Comments Received during the Public Review Period on the Methane Challenge Supplemental Documents

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COMMENTER:

American Carbon Registry (ACR)

November 13, 2015

Carey Bylin
Natural Gas STAR Program
Global Methane Initiative
U.S. Environmental Protection Agency
Mail Code 6207M, 1200 Pennsylvania Avenue NW
Washington, DC 20460

RE: Comments on Natural Gas STAR Methane Challenge Program

Dear Ms. Bylin:

The American Carbon Registry (ACR) respectfully submits comments herein on the proposed Natural Gas STAR Methane Challenge Program ("Methane Challenge Program"). Founded in 1996 as the first private voluntary greenhouse gas registry in the world, ACR has nearly twenty years of unparalleled experience in the development of rigorous, science-based standards and methodologies to quantify GHG reductions. Indeed, all methodologies published by ACR are subjected to public comment and blind scientific peer review. Additionally, ACR has operational experience in project registration, verification oversight, and credit issuance. ACR is a pioneer in harnessing the power of markets to realize emissions reductions without burdening the economy. We appreciate EPA's increasing focus on emissions of methane, a short-lived climate pollutant whose aggressive mitigation would buy valuable time to comprehensively address climate change.

While the proposed Methane Challenge Program is laudable, providing flexibility and meshing with an existing industry initiative, we believe an opportunity exists to achieve steeper cuts in emissions, engage more industry participants, and minimize costs. Consistent with EPA's Clean Power Plan, which encourages trading of credits created by emissions reductions within the power generation sector, we suggest a similar, albeit more limited, approach be incorporated within the One Future emissions intensity commitment option. Specifically, retrofitting high-bleed pneumatic controllers with low-bleed pneumatic controllers is known to offer substantial emissions reduction potential, and such reductions can generate verified credits. One Future Coalition partners could be allowed to generate such credits, saleable to other Coalition partners to retire and count towards their emissions reduction commitments.

Among the benefits of allowing trading of emissions reduction credits are the following:

- The disparity in cost-effective emissions reduction opportunities available to companies operating in different stages of natural gas supply and delivery – a key concern within the One Future Coalition – is addressed.
- More companies may find it attractive to join the Methane Challenge Program, knowing they could generate revenue from selling excess emissions reductions or limit costs of meeting commitments by purchasing and retiring credits.
- Average cost of meeting commitments will be reduced. Through credit trading, we will see capital allocation to pneumatic valve retrofits when this is less expensive than other options to reduce emissions.

- Greater aggregate reductions can be achieved. The opportunity to trade credits offers the potential to attract more participants to the Methane Challenge Program, as well as making participants comfortable committing to more ambitious emissions reductions.

Understanding that a great deal of valuable work has no doubt already gone into design of the One Future commitment option, we are not advocating a revamp. We are suggesting the addition of a single tool – emissions reduction credits from pneumatic controller retrofits – that would only increase the likelihood that the Methane Challenge Program will engender wide industry participation and achieve meaningful emissions reductions. Later development of methodologies for other emissions reduction practices would depend on interest of EPA and One Future Coalition partners, compatibility with a credit-based approach, and the size of the mitigation potential.

The applicable methodology from ACR, "Conversion of High-Bleed Pneumatic Controllers in Oil & Natural Gas Systems"[1] quantifies emissions reductions in carbon dioxide equivalent. It would be a minor issue to instead quantify the avoided methane emissions. In addition, neither the EPA nor the One Future Coalition would need to establish infrastructure for tracking and retiring emissions reductions. With respect to ensuring sufficient transparency, so that EPA and One Future Coalition partners are assured that emissions reductions are counted only towards the commitments of parties retiring the credits, ACR would be pleased to work with you. We do not expect this to be a significant hurdle.

Achieving emissions reductions at greater scale than in the past requires a fresh approach. Decoupling the claim on an emissions reduction from the party implementing a reduction will introduce market efficiency with the potential for faster and more substantial reduction in methane releases. Please feel free to contact myself or Arjun Patney (916-296-9032, arjun.patney@winrock.org) for further discussion. Thank you for the opportunity to comment on EPA's Methane Challenge Program.

Respectfully,

John Kadyszewski
Director, American Carbon Registry
an enterprise of Winrock International
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[1] http://americancarbonregistry.org/carbon-accounting/standards-methodologies/conversion-of-high-bleed-pneumatic-controllers-in-oil-natural-gas-systems

December 11, 2015

Carey Bylin
Natural Gas STAR Program
Global Methane Initiative
U.S. Environmental Protection Agency
Mail Code 6207M, 1200 Pennsylvania Avenue NW
Washington, DC 20460

RE: Comments on Methane Challenge *Draft Supplementary Technical Information for ONE Future Commitment Option*

Dear Ms. Bylin:

Following on our recent comments on the proposed Natural Gas STAR Methane Challenge Program, the American Carbon Registry (ACR) respectfully submits comments herein on the *Draft Supplementary Technical Information for ONE Future Commitment Option* ("Technical Information").

We note that the Technical Information does not propose to include reporting requirements, under "Natural Gas Pneumatic Device (Controller) Vents," related to emissions reduction credits. As we highlighted previously, retrofitting high-bleed pneumatic controllers with low-bleed pneumatic controllers can generate verified credits. Allowing for credit trading offers the potential to achieve larger reductions in methane emissions more quickly and at lower cost than otherwise possible. In addition, inclusion of this flexibility mechanism may attract greater industry participation. The approach is also consistent with EPA's Clean Power Plan, which encourages trading of credits created by emissions reductions within the power generation sector. It is our belief that failure to include a credit trading option would represent a missed opportunity to maximize emissions reductions.

We appreciate that the program was not initially envisioned to accommodate trading, and thus has not been structured as such. The short timeframe to launch may further inhibit material design changes. However, the credit trading option can be phased in at a later stage. Including simple reporting requirements now, which quite likely would incur no additional reporting burden in the near term, would facilitate later inclusion of credit trading. Specifically, we suggest the Technical Information solicit collection of the following data, perhaps as the last two lines under "Natural Gas Pneumatic Device (Controller) Vents, Voluntary action to reduce methane emissions during the reporting year" (p. 23):

- Number and vintage year of GHG offsets, derived from conversion of high-bleed to low-bleed pneumatic controllers, that were retired (self-generated or purchased)

- Number and vintage year of GHG offsets, derived from conversion of high-bleed to low-bleed pneumatic controllers, that were generated and not retired

Simply allowing for collection of these data will augment any later decision to incorporate emissions trading.

We reiterate that ACR would be pleased to work with you. Please feel free to contact me for further discussion (916-296-9032, arjun.patney@winrock.org). Thank you for the opportunity to provide comments.

Respectfully,

Arjun Patney
Policy Director, American Carbon Registry
an enterprise of Winrock International

COMMENTER:

American Gas Association (AGA)

Comments of the American Gas Association

On EPA's Proposed Voluntary Methane Challenge Program

November 13, 2015

The American Gas Association (AGA) submits these comments to support EPA's flexible approach to the proposed voluntary Methane Challenge Program and to provide our suggested changes to help improve the program described in your Framework document and the more recent Supplementary Technical Information Document released on October 19, 2015.

AGA has been a partner in EPA's voluntary Natural Gas STAR program since its inception, and many of our member companies have participated in that program over the past two decades. Their actions have helped reduce natural gas emissions from distribution systems by over 17 percent since 1990, even as the miles of distribution mains expanded 30 percent to serve nearly twice as many customers. AGA looks forward to working with EPA and our members on the new enhanced Methane Challenge program. Given our long partnership with you in the goal of reducing emissions, we appreciate your willingness to listen to our concerns and ideas as you craft your new enhanced voluntary program to reduce methane emissions from the natural gas value chain, and in particular from natural gas transmission, storage and distribution operations.

The American Gas Association, founded in 1918, represents more than 200 local energy companies that deliver clean natural gas throughout the United States. There are more than 72 million residential, commercial and industrial natural gas customers in the U.S., of which 94 percent — over 68 million customers — receive their gas from AGA members. AGA is an advocate for natural gas utility companies and their customers and provides a broad range of programs and services for member natural gas pipelines, marketers, gatherers, international natural gas companies and industry associates. Today, natural gas meets more than one-fourth of the United States' energy needs.

I. GENERAL COMMENTS

A. AGA Supports the Overall Structure of Methane Challenge

i. Choice – BMPs or One Future Pathways

AGA appreciates the proposal to allow a company to choose either the best management practice (BMP) pathway, the One Future pathway, or both. It seems likely that most natural gas utilities will find that the BMP pathway is the most workable option, but there are some that will prefer the potential flexibility to mix and match emission reduction methods in different parts of their system to achieve the One Future emission goal for their company in a cost-effective manner. In fact there may be some companies that would like to participate and seek the next level of emission reductions, but that would be precluded from doing so if they were limited to the BMP option. The reverse appears to be true for other companies that can apply at least one of the BMPs but could not participate through the One Future pathway. Still others may find that the BMP pathway is the most workable option for their distribution operations in one state, but the One Future pathway – once the details are available – may seem more workable for their operations in another state.

AGA therefore strongly encourages EPA to retain both options. A company should be able to choose either the BMP pathway or the ONE Future pathway – or at its option, follow both pathways in the final Methane Challenge program.

ii. Goals & Recognition for Early Action

We agree with the goals you have listed on page 5 of your Framework proposal, and we support having the new program:

- encourage ambitious commitments to reduce methane emissions,
- offer flexible mechanisms to achieve the commitments,
- promote innovative approaches,
- provide accountability and transparency through robust annual reporting that utilizes EPA's Greenhouse Gas Reporting Program (GHGRP) to the extent possible,
- recognize progress of companies that have been proactive in reducing methane emissions (early actors), and
- recognize improved environmental performance through quantitative assessment of emission reductions.

In order to ensure that the program promotes these worthy goals, AGA has some suggested changes or enhancements to the Framework proposal as well as the Supplementary Technical Information Document, as discussed in the relevant sections below. AGA particularly urges EPA to find ways to recognize early actors. For example, several of our member companies have already replaced all or most of their cast iron and unprotected steel mains, and they should be recognized for this impressive feat in the Methane Challenge. EPA will also need to recognize that these companies will not be able to commit to a significant percentage reduction beyond what their pipe replacement has already achieved, since the BMPs remaining for them to apply would achieve relatively modest incremental reductions compared to pipe replacement. This should not diminish their stature, but if anything, should enhance it. Early actors should be welcomed into Methane Challenge with a special award for their early action.

iii. Name – Methane Challenge

We support the proposed name. "Methane Challenge" is short, pithy, and it recognizes that it will indeed be a challenge to get to the next level of methane emissions reduction.

B. Defining Sectors – Distribution, Transmission, Storage

EPA has proposed definitions for the different industry segments and facilities in Appendix C of the Supplementary Technical Information Document. We appreciate the clarification that a "natural gas transmission pipeline" for purposes of Methane Challenge includes interstate, intrastate, and Hinshaw transmission pipelines. Thus, as we understand it, a gas utility could opt to participate in Methane Challenge for its distribution system, but not its intrastate transmission pipelines or for its transmission compression. We also understand the definition of Underground Natural Gas Storage to mean that a gas utility that operates underground storage facilities could participate in Methane Challenge for distribution, but not for its underground storage. Please confirm that our understanding is correct.

AGA appreciates EPA's proposal to follow the Subpart W definition of a natural gas local distribution company (LDC) regulated by a state public utility commission. We request an additional change however to recognize that some states have a different method for utility rate regulation. For example, in "home rule" states, utility rates and conditions are established by local or regional regulatory agencies. Please use the following definition: "A natural gas local distribution company (LDC) as regulated by a single state public utility commission or analogous regulatory structure within a single state."

AGA requests a similar revision of your proposed definition of natural gas transmission pipeline in Appendix C. You have proposed to define natural gas transmission pipeline to include "a state rate-regulated Intrastate pipeline." We request that you revise this definition to include "an intrastate transmission pipeline subject to state, local or regional rate regulation." With this change, the definition will be sufficiently broad to cover both rate regulation by state utility commissions and analogous home rule local or regional agencies.

C. Program Reporting

In addition to the reporting called for in the BMPs, EPA proposes to collect a list of information from partner companies as part of annual reporting. The Supplemental Technical Information document explains the purpose is "to provide context for participation in the Program and facilitate annual tracking of programs."[1] EPA proposes to ask for annual reporting to include:

- List of included facilities that report to Subpart W (providing the facility ID);
- List of included facilities not reporting to Subpart W;
- Applicable air regulations for included facilities, including a listing of the sources covered in the partner's Methane Challenge commitment that are affected by each regulation; and
- List of facilities acquired or divested during the reporting year.

AGA opposes requiring annual reporting of applicable air regulations for sources included in the voluntary program. The requirement to conduct a regulatory analysis and applicability determination within the context of a voluntary program is unnecessary and far more burdensome than the agency may realize. Further, to the extent there are applicable air regulatory requirements for natural gas distribution, transmission or storage operations, most will pertain to conventional pollutants rather than greenhouse gases such as methane. The reporting called for under the BMP pathway or ONE Future pathway will provide any data needed to assess how the partner's voluntary measures are contributing to methane emission reductions.

D. MOU – Proposed Partner Agreement

AGA is reviewing the proposed Memorandum of Understanding (MOU) EPA recently released, and we plan to provide comments by the November 20, 2015 deadline. We will evaluate whether the MOU addresses the following concerns.

i. The MOU should clearly recognize that participating companies are industry leaders acting voluntarily to set ambitious commitments to reduce methane emissions.

ii. There should be a mechanism to add, remove, and adjust commitment goals from the MOU, including modification of the scope, endpoint and timing when necessary to reflect realities not anticipated in the original commitments.

iii. There should be no penalty or regulatory enforcement provisions in this voluntary program. EPA's main recourse would be to deny Methane Challenge status, and the

[1] STI p. 4.

terms of the MOU should spell out the circumstances that would trigger the loss of Methane Challenge recognition.

iv. Participants should be allowed to set individual endpoint and timing goals that are anticipated to be aggressive yet reasonably expected to be achievable as allowed by the applicable regulatory structure (i.e. by the state public utility commission or analogous regional or local regulatory body within a single state).

v. Progress toward meeting goals with an endpoint that exceeds one year, such as pipe replacement, should be viewed as a multi-year rolling average to account for unanticipated events or annual variability.

vi. If an LDC selects the pipe replacement BMP for its commitment, the MOU should make it clear that the tier and associated percentage reduction commitment will be based on the inventory of cast iron and unprotected steel distribution pipelines in service in the LDC's distribution system as of January 1, 2015. In other words, the MOU should make it clear that the baseline inventory will not be a moving target that could suddenly catapult an LDC into a more onerous (and unachievable) category as a perverse 'reward' for its progress in replacing pipe. We do not believe it was EPA's intent to set moving targets within any given commitment period, but our members are concerned that the proposal does not clearly explain how the Inventory Tiers would be determined for the distribution pipe replacement BMP.

E. Reporting, Updating Emission Factors, Data Summary Accuracy, Public Access

AGA agrees that the current eGRRT reporting software system should provide a generally acceptable and efficient reporting platform, if EPA makes the necessary modifications in a "user-friendly" format and keeps the Mandatory Reporting Rule (MRR) restricted-access data separate from the more visible data that will be posted under the voluntary Methane Challenge program.

There are limitations in the current Subpart W formulas and outdated emission factors that prevent them from reflecting the true levels of natural gas emissions. For example, systems that replace cast iron or unprotected steel mains with modern polyethylene (PE) plastic or protected steel pipe do not get credit for the full value of their emission reductions because EPA is still using emission factors that are based on the 20 year old limited data collected in the GRI-EPA study. This could be remedied if EPA would revise its emission factors to reflect the far more robust and recent data provided in the Washington State University (WSU) distribution methane measurement study published March 31, 2015. An additional improvement would be to allow an emission factor based on the number of reported non-hazardous leaks rather than simply based on the number of pipe miles. This would help demonstrate improvements in reducing leaks that do not show up when using just miles of pipe times an emission factor. Otherwise, using the existing formulas in the Subpart W eGRRT system will mean that even if an LDC makes significant investments and improvements by implementing BMPs in the Methane Challenge, the true levels of methane reduction will not be fully reflected in the reported Subpart W values. AGA urges EPA to update its emission factors on an expedited schedule. This will help support all of EPA's methane programs as well as provide a more accurate assessment of total emissions in the annual GHG Inventory.

Access security in eGGRT should be modified slightly to make it easier to make the necessary adjustments to the authorized agents and designated representatives.

AGA members' experience with eGRRT indicates that it can be overly complex and difficult to use – particularly for users that are not required to be in the system often and thus are less familiar with how to navigate in eGRRT. Some tailoring is needed for the voluntary program. We suggest creating a separate Methane Challenge module for eGRRT that is streamlined so that Methane Challenge-only users can enter their voluntary data more easily. This ease of reporting could increase the number of companies willing to participate in Methane Challenge.

After a participant submits its data, the participant should have an opportunity to review and comment on the accuracy of reports summarizing the participant's progress toward meeting its goals. EPA should delay public access to Methane Challenge information until 30 days after the submittal deadline to allow the participating company time to review and correct the data displayed on EPA's web platform for accuracy. We request this one month timeframe given that this is a voluntary program and other priorities may arise or staff vacation schedules could limit a thorough review within a shorter timeframe.

EPA should ensure that the public does not have access to raw data. The public should have access to Methane Challenge data by company *only in summary form* that focuses on the participants' progress toward meeting its goals, but it is very important that EPA should not give the public access to a company's voluntarily provided detailed raw data such as component counts. Otherwise, the agency will set up a very strong disincentive for company participation in the program. In addition, to create an incentive to accelerate or expand BMP implementation, EPA's public progress summaries should emphasize participant progress that exceeds commitment goals and give that participant special recognition.

To avoid unnecessary burdens on EPA and participants, the Methane Challenge reporting deadline should be 60 days after the MRR reporting deadline.

F. Implementation Plans

We have been pleased with EPA's willingness to seek our input to craft the basic framework for Methane Challenge and that you continue to do so as you fill in the details, including what you expect companies to include in their Implementation Plans. AGA will review the recently released guidelines for developing company implementation plans and will provide comments by the November 20, 2015 deadline.

In the meantime, we offer the following preliminary comments on implementation. We request that EPA allow companies, at their option, to combine reporting entities within their parent company umbrella and have the option to develop an implementation plan and report at the parent company level. This would provide a company with more flexibility with respect to the measures implemented and potentially allow participation of a greater number of its subsidiaries.

Each implementation plan should include a "start date" for each BMP and a corresponding data collection procedure that may vary depending for example on the need to purchase additional equipment or to train personnel for a particular BMP.

G. ONE Future Option

Some AGA member companies are founding members of the ONE Future initiative, and other members are interested in participation. AGA supports EPA's proposal to give companies this option in addition to the BMP option.

II. DETAILED COMMENTS ON BMPS

A. Distribution BMPs

i. <u>Distribution Mains - Pipe Replacement Tiers</u>

AGA appreciates EPA's attempt to establish more workable annual replacement goals and a tiered set of goals based on a company's starting inventory. In the Supplementary Technical Information Document, EPA added a proposed Tier 5 as suggested on a recent stakeholder call. AGA appreciates and supports this addition.

We would also like to suggest a few adjustments to the tiers and goals to avoid unintended and unachievable "cliffs." In addition, since companies report their mileage on an annual basis to the U.S. Department of Transportation (DOT), we urge EPA to set the baseline inventory as of January 1 of the year in which a participant adds the pipeline replacement BMP to their commitment under Methane Challenge.

We ask EPA to revise the pipe replacement BMP Chart as follows *(changes in red font and underlined):*

Tier	LDC's Inventory as of Jan. 1, 2015* of Cast Iron and Unprotected Steel Mains and Other Prioritized Pipe	% Annual Replacement/Repair (or at the company's option such higher rate as approved by the State or equivalent rate regulator) Note: LDC remains in same goal tier throughout commitment period.
1	<500 miles	5%
2	500 – 1,000 miles	4%
3	1,001-1,500 miles Or over 2 miles/1000 customers	3%
4	1,500 miles-3,000 miles Or over 3 miles/1000 customers	2%
5	>3,000 miles	1.5%

***Or January 1 of the year in which a participant adds this BMP to their commitment.**

The above chart also adds an optional metric that would tie the replacement rate to the rate of "capital spend" per thousand customers. This is an important option for smaller LDCs that have a smaller base of customers over which to spread the costs of replacement.

Once a participant makes a commitment to replace (or line, seal or protect) pipe under this BMP, the participant should remain in the same tier until the commitment (e.g. a Tier 3, five year goal to replace pipe at 3% per year) is complete. In other words, EPA should make it clear that this BMP would not be a "moving target" that could ratchet up the annual percentage replacement requirement within the timeframe of a given 5-year commitment as the partner company successfully reduces its inventory of leak prone pipe. This is important, because an LDC cannot commit to do more than its state utility commission (or home rule equivalent) approves. However, if a utility has approval from its regulator for cost recovery supporting a more accelerated mileage rate, the utility should be allowed the option to use that more accelerated rate when the company sets its Methane Challenge goal.

Mergers and acquisitions can increase a company's pipe inventory. Some procedure is needed to address these changes. AGA recommends one of two options. One option would be to enter into a revised MOU to address the inventory changes due to M&A activity. The other would be to use a formula as described below.

EPA could allow companies to either choose the tier goal as above, or to choose using an optional equation to calculate their annual replacement goal based on the amount of cast iron and unprotected steel inventory in relation to the company's total inventory of distribution pipe in service. This would help eliminate a large gap in replacement miles for companies that are on the line between EPA's suggested tiers. It would also reflect the fact that the relative effort and expenditures change proportionately as system size increases or decreases through mergers and acquisitions. In addition, if an LDC acquires and merges with another older distribution system in the same state, its inventory of cast iron and unprotected steel pipe may increase, despite its ongoing efforts to replace pipe and its likely future acceleration of pipe replacement in the acquired, older system. The formula below could address such M&A changes, since it would be scalable as system size increases or decreases:

% Annual Replacement = 0.2(Total Pipe Inventory/CI + US Inventory)

Where CI = Cast Iron, and US = Unprotected Steel (and 'Replacement' includes other measures such as lining, internally or externally sealing CI, or adding cathodic protection)

In addition, the program should recognize that public safety risk or regulatory drivers may cause the need to modify pipe replacement priorities and schedules.

For DOT reporting, wrought iron and ductile iron are included in the "cast iron" category. The Methane Challenge pipe replacement BMP should clearly use the same definition of cast iron to align with the DOT reporting category, which is also used in the EPA Greenhouse Gas Inventory.

As with other BMPs, we will need to see EPA's more detailed description. One of the issues we hope to clarify is the term "seal." There are methods to seal joints externally as well as internally (CISBOT). It should also be noted that lining is a very costly method and has limited application, as we have described in our previous meetings with you. We look forward to working with you to flesh out the details of this pipe BMP.

ii. Distribution Services, Service T's and Relocating Customer Meters

AGA appreciates the addition of unprotected steel and cast iron service lines as a new BMP option. (STI pages 17-18). This BMP should be based on the number of services by material rather than their length. This would better align with the way that gas utilities and the Energy Information Administration (EIA) account for services.

Utilities have programs to replace unprotected steel and cast iron services with PE plastic services to enhance pipeline safety, and these actions also help reduce emissions. We believe unprotected steel distribution service lines *and service T's* where the service connects with the main should be included.

AGA also urges EPA to include relocating customer meters as an option. This could allow participants flexibility to establish goals and commitments that are above what is required by regulation but are approved by the state public utility commission (or home rule equivalent) for cost recovery in the LDCs rate treatment. For example, such commitments could include:

- Relocating customer meters from the property line to the house according to individual company triggers, and then adding these service lines to the leak survey program – thereby facilitating leak detection and repairs, or
- Setting annual numeric goals for service line replacements, particularly focused on service line materials found to be more prone to emissions, or
- Performing leak surveys and repair customer service lines prior to turning on gas service, or
- Replacing all unprotected steel and cast iron services when an associated main is replaced.

iii. Metering & Pressure Regulating Stations (M&Rs)

In the original Framework document, EPA proposed a BMP to "undertake monitoring and repair activities, at specified minimum levels, following defined parameters governing repair activities." We understand EPA is now considering whether to drop this BMP from the program. EPA's Technology Support Document released on October 19 acknowledges that Subpart W reporting data "indicates a low level of emissions from this source relative to other distribution sources." The document also recognizes that recent studies such as the multi-city distribution study by Dr. Brian Lamb of Washington State University "indicated that upgrades to M&R Station/City Gates that have been implemented in recent years have resulted in lower emissions from this source." AGA welcomes this recognition of the WSU data by EPA. You have asked for our feedback on "whether there is a significant population of M&R Stations/City Gates that have not made upgrades, and whether to include this source in the Program."

While there are a limited number of remaining M&R stations that have not made upgrades such as replacing high-bleed with low-bleed pneumatics and implementing robust leak detection and repair programs, AGA encourages EPA to retain this BMP option because the companies that operate these few remaining older M&Rs would appreciate the option to include a goal for upgrading them in their Methane Challenge commitments.

Here are our general thoughts, in the event that you decide to retain the monitoring and repair BMP.

This BMP should allow a participant to incorporate actions consistent with what they are already required to do under Subpart W, understanding that you are looking for additional actions beyond what is already required by regulation. This could include the following actions, at the company's option:

- Increase the frequency of Subpart W-style monitoring and measurements at Transmission to Distribution pressure reduction stations (TDs), or

- Expand the monitoring program from TDs to a larger population of M&Rs (e.g. surveying a statistically representative sample), or
- Repair leaks detected as soon as practical but within 30 months of discovery, subject to the following two exceptions:
    - where conducting the repair alone will result in greater methane emissions than if left leaking until the next time that segment is de-pressurized; and
    - where the cost exceeds a 5-year payback relative to the cost of lost gas.

iv. Distribution Main (>60 psi) Blowdowns BMP

In the October 19th Supplementary Technical Information Document, EPA lists four options for reducing blowdown emissions related to *non-emergency* work on distribution lines operating at 60 psi or more "by at least 50% from total *potential emissions* each year." AGA urges EPA to set the threshold for the blow down BMP at greater than 60 psi.

It is important for EPA to note that early actor companies that have already implemented best practices to limit blowdown emissions would not be required to reduce their already low blowdowns by an additional 50%. Instead, early actors could participate using this BMP because the 50% reduction is from "potential" uncontrolled blowdown emissions.

The four BMP blowdown control options are to: (1) route gas to a compressor or capture system for beneficial use; or (2) route gas to a flare; or (3) route gas to a low pressure system by taking advantage of existing piping systems; or (4) use hot tapping. For purposes of this BMP,

> *"total potential emissions would consist of calculated emissions from all planned maintenance activities in a calendar year, assuming the pipeline is mechanically evacuated or mechanically displaced using non-hazardous means down to atmospheric pressure and no mitigation is used."*[2]

Some of our members were confused by this reference to evacuating a line down to atmospheric pressure, so AGA suggests that EPA add a clarification that the blowdown BMP does not require a company to reduce pressure down to atmospheric pressure for every blowdown. Instead, the reference to atmospheric pressure is simply to assist in defining total *potential emissions* in the absence of mitigation. The BMP calls for reducing the total potential emissions by 50% - not 100%, which would be unachievable.

AGA believes that pressures greater than 60 psi provides an acceptable category of higher pressure distribution main for deploying methods for reducing planned, non-emergency

[2] STI p. 14.

blowdowns. It is helpful to have a clear cutoff level to know what types of distribution mains are eligible for credit under this voluntary blowdown reduction BMP.

AGA supports the list of options available for achieving such reductions. It would be helpful to add a note that a company making a commitment to deploy this BMP across its operations would *not* be limited to picking one method to apply to all future jobs, but instead could pick the method(s) best suited for each maintenance job at the time of that job. We also recommend allowing an option to use a pre-event checklist of potential options to reduce emissions from a particular planned blowdown or venting that documents that the best level of control, if any, is used for that event.

We agree that flaring also should be included as an option to control methane emissions and appreciate its inclusion in the Supplementary Technical Information Document. Our members would also appreciate EPA's help in explaining to the public that flaring is actually environmentally beneficial. Community members sometimes are concerned about the appearance of flaring and do not understand how it benefits the environment as well as public and worker safety in some instances. In fact our members have sometimes heard community members say they would prefer the LDC just to vent the gas. If EPA explains the benefits of flaring compared to venting, that could help gain community acceptance.

v. Excavation Damage Prevention BMP

EPA has provided more detail to describe the voluntary BMP for reducing emissions caused by third party excavation damage in the October 19th Supplementary Technical Information Document. The STI provides a good definition of "excavation damage,"[3] however, it should be expanded to recognize that such damage occurs not only when excavators fail to call before they dig but also when they call – but then ignore the utility markings.

AGA agrees with the list of options a company could commit to deploy as appropriate to their circumstances, including either or all of the following and to set company target rates in consultation with EPA:

1. "Shorten average time to shut-in for all damages, or"
2. "Reduce the number of damages per thousand locate calls, or"
3. "Undertake targeted programs to reduce excavation damages, including patrolling systems when construction activity is higher, excavator education programs (811, call before you dig), identifying and implementing steps to minimize repeat offenders, and stand-by efforts, or"

[3] STI pp. 19-20.

4. "Conduct incident analyses (e.g. by identifying whether excavation, locating, or One-Call practices were not sufficient)"

We appreciate EPA's effort to refer to AGA's Voluntary Guideline for Reducing Natural Gas Emissions as a starting point and for listening to our ideas. AGA supports the proposed metric for reducing damages per thousand locate calls. This is the metric used by many companies through their Common Ground Alliance DIRT programs.

Our members also support and appreciate the option to set goals for "leading indicators" that exceed regulatory requirements for damage prevention and to allow setting company-specific goals in order to be effective given different demographics (urban vs. rural), geographic differences, and regulatory environments – notably the relative strength and enforcement of state ONE-Call laws, which our members have found is the most critical factor in reducing third party damage.

The SDI sets out a daunting table of metrics for use in documenting and reporting their progress in implementing the damage prevention BMP. EPA explains that for the BMP pathway, a company would "use the collected data to set a company-specific goal for reducing methane emissions from excavation damages by implementing" the listed mitigation options.

AGA supports efforts to measure and estimate natural gas emissions from across the value chain more accurately and credibly, and we believe this new data on emissions from incidents caused by third party excavation damages will facilitate greater accuracy and fact-based decisions.

B. Intrastate Transmission & Underground Storage BMPs

AGA appreciates the clarification in the STI document that this set of BMPs applies to both interstate and intrastate transmission lines. However, AGA recommends that EPA create two subcategories for FERC-regulated interstate vs. state-regulated intrastate transmission and underground storage. State-regulated LDCs operate "transmission lines" (as defined by PHMSA and Subpart W) within a single state as part of their systems for delivering natural gas to residential and commercial customers. These transmission lines are usually at lower pressures than one would find in large interstate pipelines, and the compression stations that LDCs operate are usually smaller than their interstate cousins. In addition, unlike interstate pipelines that have one federal rate regulator (FERC), companies that include several affiliated LDC subsidiaries in different states probably cannot commit to apply the same measures across all transmission lines in all states, because each state's regulatory commission must approve such actions and they may not all agree. These differences warrant creating a separate category for Intrastate Transmission & Storage BMPs.

i. Reciprocating Compressors – Rod Packing Vent

We understand that the BMP options for compressors would apply in several industry segments, including interstate and intrastate transmission compression. Appendix 2 in the July Framework proposal describes this BMP as: "Route rod packing vent to capture/use or route gas to flare or replace rod packing every 26,000 hours of operation or every 36 months." The October 19th STI document provides further detail,[4] including a source description and listing four alternatives for mitigating emissions from wear and tear on the flexible rings in reciprocating engine compressors:

1. Replace the rod packing every 26,000 hours of operation, or
2. Replace the rod packing prior to every 36 months, or
3. Route the rod packing vent to a capture system for beneficial use to reduce methane emissions by at least 95%, or
4. Route the rod packing vent to a flare or control devise to achieve at least a 95% reduction in methane emissions.

These BMP options are fine, but they are missing one important element. AGA urges EPA to add an option for "condition based maintenance" of the equipment, since other compressor cylinder issues could be responsible for an excessive leak, and those other issues would not be addressed by replacing the rod packing.

In a "condition-based maintenance" program, the operator determines when to perform rod packing or other maintenance. With this approach, the rod packing leak rate is periodically monitored, and an increase in rod packing leak rate above a defined level triggers rod packing maintenance.

An EPA Natural Gas STAR lessons learned document, "Reducing Methane Emissions from Compressor Rod Packing System,"[5] provides an example of condition-based maintenance practices. In the STAR program example, rod packing gas leaks are periodically monitored and the value of the incremental leaked gas (relative to post-maintenance/replacement leak rates) is tracked. When the incremental lost gas value exceeds the maintenance/replacement cost, the rod packing maintenance/replacement is cost-effective. This same philosophy can be applied in Methane Challenge but the maintenance decision should be based on a defined leak rate or change in leak rate over time indicative of degradation in rod packing performance. In California, the Air Resources Board (ARB) is contemplating similar regulations for reciprocating compressor rod packing leakage. Draft regulatory language from ARB allows condition based maintenance with a leak threshold of 2 scfm.[6]

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[4] STI pp11-12.

[5] http://www.epa.gov/gasstar/documents/ll_rodpack.pdf

[6] http://www.arb.ca.gov/cc/oil-gas/meetings/Draft_Regulatory_Language_4-22-15.pdf . §95213(e).

Flexibility to use condition-based maintenance is warranted because rod packing performance may be perfectly adequate when the prescribed time interval elapses. This approach avoids unnecessary costs and down time to replace packing that is still functional. In addition, it provides the ability to identify packing that degrades prematurely. Rod condition can also lead to leaks that will degrade packing at an accelerated rate and not be minimized by changing packing. A condition-based maintenance program allows operators to address underlying causes in a cost-effective manner.

ii. Centrifugal Compressors – Venting

For centrifugal (turbine) compressors, the Supplemental Technical Information document describes mitigation options to reduce emissions associated with wet seal oil degassing vents. There are three alternative mitigation options:

- Route wet seal degassing to a capture system for beneficial use to achieve at least a 95% methane emissions reduction; or
- Route wet seal degassing to a flare or control devise to reduce methane emissions by 95%; or
- Use centrifugal compressors with dry seals.

Recent studies indicate that emissions from this source category are lower than originally assumed. However, some companies may wish to retain this as an option for voluntary measures.

iii. Compression Station Equipment Leaks/ Fugitive Emissions

EPA's original Framework document describes this proposed BMP to require a participant to "undertake monitoring and repair activities, at specified minimum intervals, following defined parameters governing repair activities." The STI document does not provide any further detail, but we assume this "voluntary" measure would align with the leak detection and repair (LDAR) requirements in the Subpart OOOOa proposed new source performance standards (NSPS).[7] AGA will comment on the LDAR proposed rule requirements in that proceeding. In brief, we believe the proposed LDAR requirements miss the mark and would better achieve EPA's goals if the leak detection program were focused instead on finding and fixing the few "gross emitters," which recent studies have shown to contribute a majority of the emissions from compression.

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[7] 80 Fed. Reg. 56593 (Sept. 18, 2015).

iv. Transmission Pipeline Blowdowns from *Non-Emergency* Maintenance Projects Between Compressor Stations

The STI document lists four mitigation options for reducing blowdowns from transmission lines:

- "Route gas to a compressor or capture system for beneficial use, or
- Route gas to a flare, or
- Route gas to a low pressure system by taking advantage of existing piping connections… to reduce system pressure prior to maintenance, installing temporary connections… or
- Utilize hot tapping…"

We agree that these are reasonable voluntary measures that can help reduce methane emissions from maintenance blowdowns. Further, the TSI explains that if a company decides to select this BMP, the company would commit to maximize blowdown gas recovery or emission reductions by using one or more of the above options to reduce methane emissions "from non-emergency blowdowns by at least 50% from total potential emissions each year" calculated based on all planned maintenance activities in a calendar year. The original Framework document also explicitly states that this BMP "excludes emergency blowdown situations." AGA strongly supports this exclusion to ensure pipeline safety. The blowdown BMP should only apply to non-emergency maintenance blowdowns.

v. Pneumatic Controllers

For transmission and storage, EPA's Framework and STI documents use the same description of the pneumatic controller source and mitigation options as the BMP for production and gathering pneumatic controllers. The Framework document contains an important exclusion: "For gas-driven pneumatic controllers, use low (defined as gas bleed rate <6 standard cubic feet/hour) or no bleed controllers for all applications except those requiring high-bleed controllers for certain purposes, including operational requirements and safety." The STI further notes that the pneumatic controller BMP "does not cover operational situations in which pneumatic controllers with a bleed rate greater than 6 standard cubic feet (scf) per hour are required based on functional needs, including but not limited to response time, safety and positive actuation."[8] AGA strongly supports this critical exception for operations and safety.

[8] STI p. 6.

III. CONCLUSION

We are pleased with the overall structure of the proposed Methane Challenge program, and we believe that working together with EPA, we can fill in the remaining details in a manner that is workable and will encourage participation in the new enhanced program.

AGA appreciates the opportunity to comment. If you should have any questions, please contact Pamela Lacey, AGA Chief Regulatory Counsel, at (202) 824-7340 or placey@aga.org.

Comments of the American Gas Association

On EPA's Proposed Partnership Agreement and Implementation Plan Guidelines for the Voluntary Methane Challenge Program

November 20, 2015

The American Gas Association (AGA) appreciates the opportunity to provide feedback on EPA's draft partnership agreement and guidelines for company implementation plans for the Methane Challenge program released on November 10, 2015.

The American Gas Association, founded in 1918, represents more than 200 local energy companies that deliver clean natural gas throughout the United States. There are more than 72 million residential, commercial and industrial natural gas customers in the U.S., of which 94 percent — over 68 million customers — receive their gas from AGA members. AGA is an advocate for natural gas utility companies and their customers and provides a broad range of programs and services for member natural gas pipelines, marketers, gatherers, international natural gas companies and industry associates. Today, natural gas meets more than one-fourth of the United States' energy needs.

I. Proposed Partnership Agreement

AGA believes the draft partnership agreement will meet our members' needs with a few minor adjustments. Overall, we believe the agreement is clear, succinct, and addresses our key criteria outlined in our November 13th comments.

i. **Recognize Leadership:** The agreement will allow EPA to recognize participating companies as industry leaders acting voluntarily to set ambitious commitments to reduce methane emissions.

ii. **Flexibility to Meet Future Realities:** There appears to be a sufficient mechanism to add, remove, and adjust commitment goals from the MOU, including modification of the scope, endpoint and timing when necessary to reflect realities not anticipated in the original commitments.

iii. **No Penalty or Regulatory Enforcement (Request Revision):** The agreement should be revised slightly to make it clear there would no penalty or regulatory enforcement provisions based on information or actions taken in this voluntary program. We believe this concern could be addressed by adding the following: *"By setting out a target date on this form the Company does not intend to expose itself to regulatory liability if it cannot meet the target date."*

iv. **Protect Confidential Information & Raw Data (Request Revision):** AGA requests EPA to revise the agreement to protect confidential information, with the following text*: "the information submitted through the methane challenge that is not already public will remain confidential."* AGA understands that EPA will want to provide transparency to allow the public to see the progress partner companies are making in reducing methane emissions. These competing concerns can be addressed by rolling up data in a higher level summary rather than releasing all the raw data.

v. **Flexibility to Set Goals:** We believe the agreement will be sufficiently flexible to allow participants to set individual endpoint and timing goals that are anticipated to be aggressive yet reasonably expected to be achievable as allowed by the applicable regulatory structure (i.e. by the state public utility commission or analogous regional or local regulatory body within a single state).

vi. **Multi-Year Rolling Average (Request Revision):** Progress toward meeting goals with an endpoint that exceeds one year, such as pipe replacement, should be viewed as a multi-year rolling average to account for unanticipated events or annual variability.

vii. **No Moving Target within Commitment Periods (Request Revision):** If an LDC selects the pipe replacement BMP for its commitment, the agreement should make it clear that the tier and associated percentage reduction commitment will be based on the inventory of cast iron and unprotected steel distribution pipelines in service in the LDC's distribution system as of January 1, 2015 or January 1 of the year in which the partner company joins the program. In other words, the agreement should make it clear that the baseline inventory will not be a moving target that could suddenly catapult an LDC into a more onerous (and unachievable) category as a perverse 'reward' for its progress in replacing pipe. We do not believe it was EPA's intent to set moving targets within any given commitment period, but our members are concerned that the proposal does not clearly explain how the Inventory Tiers would be determined for the distribution pipe replacement BMP.

II. Implementation Plans – Allow LDC or Corporate Level Plans

AGA generally supports EPA's brief Guidelines for developing Implementation Plans. We request one change so the guidelines clearly allow companies, at their option, **either** (1) to develop separate implementation plans for each of their LDC subsidiaries, **or** (2) to combine reporting entities within their parent company umbrella and have the option to develop an implementation plan and report at the parent company level. This would provide a company with more flexibility with respect to the measures implemented and potentially allow participation of a greater number of its subsidiaries.

Each implementation plan should include a "start date" for each BMP and a corresponding data collection procedure that may vary depending for example on the need to purchase additional equipment or to train personnel for a particular BMP.

AGA appreciates the opportunity to comment. If you should have any questions, please contact Pamela Lacey, AGA Chief Regulatory Counsel, at (202) 824-7340 or placey@aga.org.

COMMENTER:

American Petroleum Institute (API)

EPA Natural Gas STAR Methane Challenge:

Proposed Framework

November 2015

Prepared by

American Petroleum Institute (API)

Charge Questions – July 23 Proposal

> *Charge Question 1*
>
> *Please indicate whether your company has specific interest in one of the commitment options presented, including the possibility or likelihood of your company potentially making that commitment.*

Industry and EPA's incentives are aligned in desiring to keep methane in the pipeline, to reduce losses and improve product recovery. Industry members strive to evaluate options for cost effective measures to reduce emissions and implement them where they can achieve the greatest reductions. For example, EPA recently reported that total methane emissions from natural gas systems are down 11 percent since 2005 despite significant growth in production. These accomplishments are due in large part to the historic participation in the Natural Gas STAR program and industry's own voluntary measures.

API has previously shared options for achieving substantial methane emissions reductions more rapidly than regulations would allow. While the uncertainty surrounding the various pending regulatory decisions may influence individual company decisions on whether to participate in a federal voluntary program, API and its members continue to be committed to voluntarily reducing emissions, either on their own or through a government partnership.

While there is interest among API members in making a commitment under the program, there are several uncertainties that pose potential barriers to commitment. These uncertainties include:

- <u>Commitment Timeline</u>: Because the industry is facing a number of regulatory and non-regulatory initiatives from several agencies at the same time, we need more time to consider participation and level of commitment in the voluntary program. API understands that EPA will allow for ongoing partner commitments beyond early 2016, which could help encourage participation as the initial timeline for charter partners set out in EPA's proposal is very aggressive (see response to question 3).
- <u>Overlap with Regulations</u>: Lack of knowledge about the outcome of the various proposed and upcoming regulations and policies, which may impact these same facilities and emission sources, impedes the ability to make a quick commitment. The comment period for this program should be extended to stay open until industry is able to review BLM's proposed regulations and assess how this program interacts. (See comment response to question 9 below.)
- <u>Incentives tied to Regulatory Compliance</u>: Adding incentives that help achieve cost effective compliance with, or exemption from, the emerging regulations, such as the leak detection and repair provision of the proposed NSPS OOOOa and CTGs would help encourage participation. (See comment response to question 2 below.)

- Program Flexibility: The best way to obtain high levels of commitment is to make the program as flexible as possible. We appreciate the enhanced flexibility in this proposal, which allows companies to select which BMPs to include in their commitment and defines "company-wide" in a manner that aligns more closely with company decision making. The need for company-wide commitment may limit interest in company commitments, even with the relaxed definition of "company-wide" that EPA proposed. The all or nothing concept (meaning every source owned by the company must be reduced within the "company-wide" boundary) makes commitment difficult. Having the ability to target the highest emitting emission sources may result in the most cost-effective reductions. Likewise, facilities located in remote areas, with low production levels and/or characterized by low pressure production would be costly to control with minimal benefit. Allowing flexibility in implementation of the BMPs to target the sources with the highest potential for reduction at the lowest overall cost could both encourage participation and result in the highest potential reduction possible.

> *Charge Question 2*
>
> *In addition to recognition through the Program, what are the key incentives for companies to participate in this Program? Should EPA offer some partners extra recognition, such as awards?*

We appreciate EPA's consideration of incentives for industry members employing leading practices in reducing methane emissions. In light of several pending regulatory efforts aimed at reducing methane emissions from the oil and gas sector, we are very interested in incentives to achieve early, widespread reductions.

Addressing methane emissions through a flexible, voluntary program has the potential to achieve greater methane reductions at a lower overall cost to industry. Conversely, regulatory actions demand more attention and require that the companies' limited available resources be focused on addressing compliance. The program could provide a way for EPA to assure the implementation of company-wide actions, such as leak detection and repair programs, that would provide regulatory and reporting relief to companies with advanced, responsible practices. Limiting reporting and recordkeeping burden and allowing flexibility for current programs to continue would provide a strong incentive to companies and result in greater emissions reductions.

API has previously provided a document to EPA entitled, "Incentivizing Voluntary Participation in The Enhanced Natural Gas Star Program" (see Attachment A). We would appreciate the opportunity to work with EPA on crafting Program details that would help encourage participation. Recommendations on expanding the incentives to encourage broader industry participation include:

- Exemptions under NSPS OOOO and CTGs: One incentive pathway would be to consider companies with ambitious voluntary programs addressing new and existing sources to become exempt from the requirements in the New Source Performance Standards and the Control

Techniques Guidelines. EPA should consider exempting sites participating in the Program from NSPS OOOOa. EPA can include a potentially effective incentive in the Program by allowing BMP commitments to limit potential to emit (PTE) of a facility, as long as maintaining the BMP for the facility is documented. While we recognize that exemptions or credits would be reflected in the appropriate regulation and not the voluntary program, it emphasizes the need for industry to have clarity on the regulations prior to making commitments under the voluntary program.

- Limiting Potential to Emit (PTE): EPA should provide guidance to allow for limiting potential to emit (PTE) for regulatory and permit requirements based on Program participation, such as the proposed OOOOa leak detection and repair program.
- Avoidance of Regulation for Existing Sources: EPA has indicated that the big-picture incentive for the industry to have high participation in the program is to reduce the need for future regulation of existing sources (e.g., 111(d) emission guidelines). While we appreciate the flexibility that this would provide the industry, the decision would belong to future administrations and there is no certainty that this incentive would be upheld. To avoid 111(d), our preferred approach is to not regulate methane and instead continue to regulate VOC only.

> *Charge Question 3*
>
> *EPA is proposing to launch the Program with charter partners by the end of 2015, but will welcome new partners on an ongoing basis. Please comment on the likelihood of your company committing to join this Program as a charter partner, or at a future date*.

We recognize EPA's desire to enhance the Natural Gas STAR program to encourage ambitious commitments from industry participation. Member companies will individually decide whether to participate. While many companies support the principles of the Program, companies are more likely to commit to a voluntary program when there is clarity on how the program and pending regulatory actions will complement each other. Without this certainty, companies are unable to accurately assess the cost and potential benefits of implementing the Program. With current low oil and gas prices, the funding necessary for such a commitment is even more difficult to secure. Following are some suggestions that could help encourage companies to participate:

- Delay Program Implementation: Companies interested in signing up may wait until there is more regulatory certainty. We appreciate EPA's flexibility on companies joining the Program after the charter date.
- Revocable Letter of Intent: To gauge industry commitment and, thereby, inform the necessity to regulate methane from existing sources, perhaps EPA should first seek a revocable letter of intent to participate rather than a commitment to immediate implementation. This would allow

time for companies to further develop their full implementation plan as part of the MOU process.

- Phased-in Implementation: We appreciate the allowance of a phased-in approach to achieve the level of commitment over a five year period, which may help encourage participation. This flexibility to ramp up commitment levels over time within the five year period may allow more companies to commit, especially with the current low cost of oil and gas and the uncertainty of a significant rebound in the coming months.
- Scope of BMP Implementation: Another consideration that may encourage company participation as charter partners in the Program would be allowing flexibility in the commitment tied to source types for implementing BMPs. For example, rather than committing to full implementation of BMPs for a given source type, it may benefit some companies to have the flexibility to implement the most cost effective and impactful BMPs across source types to achieve a desired level of BMP implementation. In this case, the commitment might be on a percentage of total methane sources that implement BMPs. This flexibility would have the added benefit of avoiding the need to build in exemptions for implementing BMPs across all sources of a given source type.
- Mechanism for BMP Approvals: In terms of the BMP option, flexibility will rely on new BMP innovations. EPA has acknowledged that they will review new BMPs submitted by industry, but the approval mechanism to do this has not been set out.
- Goals and Commitment: If a company does decide to join the Program, the initial commitment goals (which may seem achievable at the time of commitment) may become too aggressive due to various factors, such as market conditions or significant acquisitions. Adding provisions for periodic goal re-evaluation and re-commitment would provide companies the flexibility to respond to the external factors while achieving their goals in a manner that makes business sense for the company. This type of flexibility could also encourage companies to participate in the voluntary Program.
- Public Information: The program describes EPA's plan to publish information related to the company commitments and performance toward goals. Before a company signs up, it would be beneficial to understand what level and type of information will be publicly released (e.g., will the MOU be public?) while avoiding the release of confidential business information (CBI) in the public domain. This could be a deciding factor for a company, depending on what information will be shared with the public.
- Program Exit: Clarity on the conditions and mechanism for a company to exit the Program could help incentivize companies to participate. If exit pathways are outlined, companies may feel more secure when signing up. (See response to question 1 on alignment of the voluntary participation with exemptions from regulations.)

> *Charge Question 4*
>
> *For the BMP option, how can EPA encourage companies to make commitments for*

> *sources for which they have not made significant progress in implementing mitigation options? In other words, how can companies be encouraged to participate beyond the sources for which they have already made significant progress?*

Flexibility to achieve the greatest reductions at the lowest cost could encourage companies to participate (see response to question 3, Scope of BMP Implementation). **Applying the same BMPs across a given source type makes little sense when the control will be very effective in some cases, and make little to no reduction in others.** Allowing more flexibility in selecting sources to cover under the commitment could result in higher participation as well as more overall reduction, since the largest contributors to emissions can be targeted, as opposed to a blanket approach for a given source type.

The Program can play a role in disseminating guidance and case studies and by holding technology workshops to help companies better understand how to target application of controls effectively.

> *Charge Question 5*
>
> *Please provide comments on the sources and corresponding BMPs that are provided in Appendix 2, including any recommended additions, deletions, or revisions.*

EPA should target BMPs in areas where they are cost effective and impactful to implement, as opposed to an 'across-the-board' implementation approach on a source type basis. Allowing flexibility in both the BMPs allowed and the implementation across sources will be more cost effective, result in higher methane reductions, and help encourage broader industry participation.

API has previously provided detailed proposals for a phase-out of high bleed pneumatic controllers and leak detection and repair. These proposals are attached and summarized below. Other BMP options proposed, such as gas well venting for liquids unloading, do not lend themselves to such a commitment. Source-specific comments on the sources included and corresponding BMPs are outlined below:

- <u>Equipment Leaks:</u> There is no BMP proposal for equipment leaks at this time. The attachment provided (see Attachment B) provides a basis for a future EPA leaks program. We would be happy to provide additional detail to EPA on API's proposed program, and we support API's proposal as an appropriate leak detection and repair program in the OOOOa rulemaking as well. In the absence of a BMP, companies should be allowed to proceed and specify a methodology they choose to employ (e.g., directed inspection & maintenance program).
- <u>Pneumatic Controllers</u>: Replacing continuous high bleed controllers with either low bleed or intermittent vent controllers reduces methane emissions, and is generally technically feasible. It is critical to maintain the option for replacing high bleed controllers with either intermittent vent or continuous low bleed controllers, which does not appear to be part of EPA's October proposal. In most cases, replacement with an intermittent vent device (also known as a no-

bleed controller) is the most feasible and cost effective option for replacing continuous high bleed controllers and properly functioning intermittent vent devices can be the lowest emission choice in any specific control scenario since they do not emit between de-actuation events. Intermittent vent controllers are recognized as meeting the low emission standard for continuous low bleed controllers in the Control Techniques Guidelines proposal and the existing subpart OOOO. (See Attachment C for API's suggested phase-out of high bleed pneumatic controllers.)

- Pneumatic Pumps: There is no BMP proposal for pneumatic pumps at this time. Pneumatic pumps are a difficult source to easily identify a BMP. Common suggestions such as replacement with solar pumps or electric pumps and routing exhaust gas to flare or gas capture/use have operational limitations in many applications. Electric pumps are limited by the availability of power, which is not typically available in remote locations. Solar pump applications are limited by a number of factors including, but not limited to: a) cold climates where snow cover can interrupt power causing operational issues; b) cost effectiveness – industry experience indicates that the payback period is typically longer than the expected lifespan of the pump; and c) high pump capacity and high pressure applications require more energy than is suitable for solar pumps. Additionally, many operators have experienced thefts of solar panels, which can cause shut in operations. A BMP option to route pump exhaust gas to a flare or gas capture system, or use on-site is generally not cost effective, unless a control device is already on-site and technically feasible. Pneumatic pump BMPs should be based on a site-by-site assessment and commitment. We also suggest that intermittent use, other diaphragm pumps (such as used for bulk liquid transfer) and temporary pumps be exempted from requiring a BMP solution, as these are generally not cost effective and can be technically challenging to address. We would also like to highlight that the gas-assist lean glycol pumps (often termed Kimray pumps) on glycol dehydration units are not pneumatic pumps but rather energy scavenging pumps with mechanical losses made up by gas assist. The only replacement for gas-assist lean glycol pumps is replacement with electric pumps which is dependent on reliable electric power being available.
- Liquids Unloading: Emissions from venting to assist wellbore liquids unloading are complex and actions to reduce venting must be matched with the characteristics of an individual well and reservoir combination. A key challenge is that there is no universally applicable technology to manage wellbore liquid loading without at least occasional venting. Industry is actively working on this difficult subject, including strategies that work to better manage wellbore liquid loading, and we recommend at this time that a BMP should not be drafted for liquids unloading. If a BMP is included in the final program, it should be based on a case by case evaluation which includes wellbore configuration, reservoir characteristics and time, as there is no universal approach that is appropriate for all wells. We would like to reiterate our earlier comment on the white papers that installation of plunger lift systems is not an emissions control technique, rather plunger lift systems are one tool used in managing wellbore liquids. As the API/ANGA survey data, the GHGRP data, and the UT/EDF production studies have shown, a higher percentage of plunger equipped wells vent than non-plunger equipped wells, plunger equipped wells that vent have a

much higher frequency of venting, and plunger equipped wells that vent have higher overall emissions per well than non-plunger equipped wells that vent.

- Centrifugal Compressors: This BMP should be included as an option for the gathering and boosting sector in addition to natural gas processing. The system that would be needed for capturing and recovering or flaring vent gas recovered from a wet seal degassing vent stream would be site specific. At some sites, a seal-oil/gas separation or vapor recovery system may be a very complex undertaking and introduce safety risks. Factors to consider include the current configuration of the seal-oil system and the ability to retrofit with seal-oil/gas separation or the availability of a current vapor recovery system and destination for the gas (e.g., a flare), site-specific emissions and typical unit utilization, and issues, including safety, associated with system design and the end point for usage (e.g., system pressures, compatibility with fuel gas). The BMP for a wet seal recovery system should be flexible to allow for assessment of applicability, cost, and safety considerations on a case-by-case basis due to complexity. Another option that some operators may choose is to convert or upgrade a compressor to a dry seal system, which should also be recognized as a BMP.
- Reciprocating Compressors: This BMP should be included as an option for the gathering and boosting sector in addition to natural gas processing. We suggest providing flexibility by including an additional option for the cost-effective alternative to a set time interval replacement of rod packing is a "Conditions-based Rod Packing Maintenance Program." For instance, some operators periodically measure rod packing vent rate to provide a warning of excessive rod packing leakage and repair/replace the rod packing based on vent rate increases, which can result in rod packing maintenance within a time frame that may be earlier or longer than 26,000 hours or 36 months. An example of this approach is found in the Natural Gas STAR lessons learned document "Reducing Methane Emissions from Compressor Rod Packing System (http://www.epa.gov/gasstar/documents/ll_rodpack.pdf). In addition, we offer to work with EPA to develop a simple approach to quantify emission reductions from compressors, such as a reduction factor based on Subpart W or AP-42 factors.
- Tanks: As indicated in EPA's proposal, acceptable BMPs for tanks are to route gas to a vapor recovery unit (VRU), flare or combustion control device. EPA already requires new, modified, or reconstructed storage vessels with greater than 6 tons per year (TPY) of VOC emissions to be controlled by 95% (NSPS OOOO). Many states have adopted these rules for storage vessels. In general existing tanks have lower emissions due to the decline in production that occurs over time, and existing tanks will typically not exceed emissions of even 6 TPY. At any point where tank controls are no longer a regulatory requirement, operators should be able to add tanks to the Methane Challenge program. The costs to control are significantly higher for an existing tank retrofit than new tank. The applicability for tanks should recognize the appropriate cost effectiveness threshold to reduce methane for existing tanks. Recordkeeping for voluntary actions on tanks can be particularly onerous if companies must assure that tank controls are not required by any federal, state or local rule or permit condition.

EPA should also include a process for companies to take credit for actions that might not be specifically adopted by EPA as BMP.

> *Charge Question 6*
>
> *Please comment on the proposed definitions of the companies or entities that will make BMP commitments, per Appendix 3.*

We appreciate EPA's flexibility in understanding that company structures vary and it would be impossible legally for some companies to make a corporate-wide or national commitment. Since companies have different structures, we would like more flexibility so that companies can choose the appropriate level of signatory based on operational and legal structure, including joint ventures. For example, EPA should allow flexibility to also consider the boundary for implementation to be aligned with state/agency, production area, subsidiary, and division boundaries. This flexibility should also be extended to allow for alignment with the definition of facility under EPA's Greenhouse Gas Reporting Program (GHGRP), since that is a regulatory reporting structure for most companies. Flexibility to allow different entities within the company to participate in different elements of the program could maximize participation.

> *Charge Question 7*
>
> *Is a 5-year time limit to achieve BMP commitments appropriate? If not, please provide alternate proposals. Would a shorter time limit encourage greater reductions earlier?*

We appreciates EPA's flexible structure in allowing companies to develop individual implementation plans over five years that recognize that some companies will have more work to do than others to achieve the BMPs. EPA should also consider how commitment timelines will be adjusted when assets are acquired or divested during the five year period, as this scenario is common within the industry. EPA should allow flexibility for revising MOUs to take into account acquired and divested assets.

> *Charge Question 8*
>
> *Should EPA offer the ER commitment option? If so, please provide specific recommendations for ways that EPA could address the implementation challenges outlined in this document. What is the minimum target company-specific reduction level that should be set for participation in this option? Would your company use this option if it were offered?*

At this time, we do not anticipate many members joining an emission reduction (ER) commitment due to the many issues outlined in the proposal related to developing baseline data and the frequent changes in exploration and production portfolios. Other sectors along the oil and gas value chain may find this option attractive.

> *Charge Question 9*
>
> *To what extent is differentiating the voluntary actions from regulatory actions important to stakeholders? What are the potential mechanisms through which the Program could distinguish actions driven by state or federal regulation from those undertaken voluntarily or that go beyond regulatory requirements?*

The voluntary program should be coordinated with other regulatory action, including any Control Techniques Guidelines for the states, to preserve industry's ability to generate Emissions Reduction Credits (ERCs) for VOCs to the maximum extent permissible under the Clean Air Act and to preserve any existing credits. Voluntary reductions of other ozone precursors such as NOx currently generate ERCs. EPA may want to consider incentivizing further reductions with credit for precursor reductions in its voluntary framework to make the program appealing to producers who may not have VOC-rich gas.

The Bureau of Land Management (BLM) is considering control requirements on the same sources EPA has historically addressed and plans to address these in its revised rules. It is possible that the BLM efforts will discourage participation in the voluntary Program, if those requirements overlap or conflict with the Program. A clearer understanding is needed of how BLM's and EPA's efforts differ and whether there is need for supplemental rulemaking from BLM in order to harmonize these rulemakings.

Several states have programs that increase complexity of determining whether reductions are voluntary or regulatory, especially when conditions are written as permit conditions. If the due diligence and paperwork required to determine whether reductions are voluntary or regulatory are too onerous, companies will be dis-incentivized from participation.

> *Charge Question 10*
>
> *EPA plans to leverage existing reported data through the GHGRP (Subpart W) in addition to supplemental data that partners would submit to EPA. Would the e-GGRT system be an appropriate mechanism to collect the voluntary supplemental data?*

The GHGRP e-GGRT tool is not ideally suited for reporting progress under the Program. Some challenges with the e-GGRT tool that should be taken into consideration include:

- Organizational Boundary Alignment: Reporting under GHGRP is on a facility basis, and may not align with the reporting structure under the Program, which may be centered more on emission reductions from select sources. This potential misalignment between the reporting boundaries of the GHGRP and the Program would add a level of complexity for reporting without added benefit.
- Operational Boundary Alignment: Some sites/sources which may be part of the BMPs are not included in the GHGRP reporting program and would likely require supplemental reporting (e.g., gas processing facilities that are currently exempt from GHGRP but may be included in the Program).
- Management of Change: The e-GGRT tool has changed over time as the GHGRP has progressed, and will likely continue to change over time, making year to year comparisons difficult to interpret. Addition of reporting under the Program would necessitate even more change to the e-GGRT tool, requiring additional time and training for participants and a strong QA/QC process before EPA requires using it. Additionally, in the past, EPA has changed xml files up to a few weeks before reports are due. These changes add complexity to reporting and companies usually dedicate resources to compliance before voluntary programs.
- Other Considerations: In addition, there are other considerations that would need to be addressed to make the GHGRP program reporting suitable for reporting progress under the Program. These considerations include, but are not limited to:
    - How would emissions be quantified?
    - Will sources be able to modify the emission factors used in Subpart W reporting to account for reductions achieved through the Program?
    - Would sources be able to document increased efficiencies – and lower relative emissions – even when production is increasing?
    - How would changes to submissions be handled?
    - Will data reported under the Program be subject to audits?

Instead of reporting Program performance using GHGRP tools, it would be preferred to use a modified version of the current Natural Gas STAR reporting mechanism, with realistic emissions factors.

> *Charge Question 11*
>
> *Would companies be willing and able to make commitments related to emission sources where EPA has proposed, but not yet finalized, new GHGRP Subpart W requirements?*

For gathering and boosting stations proposed to be included in the new GHGRP Subpart W requirements, it is difficult to determine whether companies would be willing to make commitments related to BMP implementation without more details of the suggested BMPs and regulatory certainty regarding reporting from relevant sources.

> *Charge Question 12*
>
> *EPA seeks feedback on potential mechanisms for encouraging continued, active participation in the Program once a company's initial goals have been achieved.*

Some BMPs, such as the high bleed pneumatic phase out, are time-bound. Others, such as leak detection and repair, are essentially continuous, and will therefore require active participation throughout the life of the agreement with EPA. Over time, as technologies are developed, tested and deployed, new BMPs could be drafted and companies could choose to add additional BMPs to their agreements with EPA. To help encourage continued active participation in the Program, EPA should provide regulatory relief for companies that make ambitious commitments and should consider a series of incentives and awards to commend continued participation.

> *Charge Question 13*
>
> *EPA is proposing to call this new voluntary effort the "Natural Gas STAR Methane Challenge Program", and welcomes comments and suggestions on this name.*

The name is acceptable.

> *Additional feedback*
>
> *In the proposal, EPA has indicated that they would like feedback on allowing an exemption to the full implementation of a given BMP. How should the exemption option be structured?*

See response to Question #2 above.

Charge Questions – October 19 Proposal

Charge Question 1

Are potential partners interested in reporting measured methane emissions from any sources that currently don't include measurement in the quantification options? Please comment on this and, if so, provide information on recommended measurement protocols for sources of interest.

Measuring emissions can be very costly and, if required, a disincentive to participate. When appropriate factors are available, they should be utilized. For pneumatic devices, when using field gas, it may be possible to measure instrument gas at the site level (not device level) to determine overall usage. If operators have these data available, it could be an option for operators to utilize although should not be required.

Charge Question 2

Should intermittent pneumatic controllers be included in the Pneumatic Controllers source? EPA seeks recommendations on whether and how to include intermittent controllers.

Intermittent pneumatic controllers should be a mitigation option, in addition to the options listed in the proposal, for replacing continuous high bleed pneumatic controllers. For a specific control application, setting, and service, intermittent vent controllers may be the lowest emission choice due to not emitting between de-actuation cycles and are the lowest emission and most flexible option for replacing high bleed pneumatics.

Charge Question 3

For Tanks, EPA seeks comment on whether additional elements collected under GHGRP should be considered for tracking purposes for the Methane Challenge Program.

The EPA should keep flexibility in voluntary program by keeping the definition of beneficial reuse technologies broad. VRUs are one of the most common technologies, but some operators may wish to pursue other options, such as VRTs, low pressure secondary separation with gas recovery, or bio-based vent scrubbers. In the proposal, the EPA is tracking the voluntary efforts (i.e., beneficial uses or flares) that are completed in a given year. The EPA should be asking for the total installed in the basin as part of the voluntary program since devices installed in previous years would continue to provide emission reductions. Installations under the program in a given year could be tracked as the difference in counts from the previous year for the same reporter.

In current Subpart W reporting, the control fraction associated with VRUs and flares are left to the discretion of the reporter. This should continue in the voluntary program since some operators are choosing to install and operate control technologies in a manner that exceeds typical industry applications. The EPA may wish to add a default control fraction for VRUs (0.95) and flares/combustion control devices (0.95) that are widely accepted in the industry but should offer operators to include their own control fractions if tracked internally. The EPA proposal to add a count of VRUs/beneficial reuse, flare/control devices, and emission reductions from voluntary actions should be sufficient for tracking program progress provided that the scope is extended from an annual basis to the program lifetime.

Charge Question 4

What types of situations require operators to vent to the atmosphere instead of capturing emissions during liquids unloading? How could this information best be captured in the reported data?

This charge question is not asking quite the correct question in that emissions are not captured during venting associated with liquids unloading - rather emissions are avoided by unloading the wellbore liquids without venting. The question should be "What types of situations require operators to vent wells to atmosphere to aid in unloading wellbore liquids?"

Venting of wells to aid in unloading wellbore liquids is done to remove the surface backpressure imposed by the production equipment and collection line. Venting either increases the flow volume and velocity up the tubing for wells without a plunger lift system installed or increases the differential pressure between the bottom of a well and the surface to provide enough energy to lift the plunger and liquid load. For more information, refer to attached API document, "Liquids Unloading Final.pdf", specifically Slides 11-13 in Attachment D.

For wells without plunger lift systems, the ability to lift liquids is dependent on the flow up the production tubing being at or above the critical velocity required for gas flow to drag liquid droplets up the wellbore. The critical velocity for any given well is a function of the amount and type (water or hydrocarbon) of liquids produced, the droplet size and shape flowing from the formation, and the depth of the well. The velocity up the production tubing is a function of the volume of gas flow and the tubing inside diameter. The volume of gas flow is dependent on the in-flow rate from the producing formation, the pressure differential between the bottom of the well and the surface pressure on the tubing, and the amount of tubing friction which inhibits flow. When the volume of gas produced falls below that necessary to maintain velocity above the critical flow velocity liquid droplets "fall" back into the wellbore and a liquid column begins to build in the wellbore which imposes additional backpressure on the producing formation and further reduces flow volume and hence velocity. (For more information, refer to attached API document, "Liquids Unloading Final.pdf", specifically Slides 15-19 in Attachment D)

A number of different techniques/technologies are used to help manage wellbore liquid buildup for wells without plunger lift systems. These include shutting a well in to allow the formation to "build-up" pressure and volume near the wellbore (often termed intermitting) and hence increase flow/velocity when production is started, smaller diameter velocity strings that increase the velocity for a given flow rate but impose additional friction loss and foaming agents/soap that increase the surface area of liquid droplets and lower the velocity necessary to drag them up the wellbore. If these techniques are not adequate to manage the build-up of liquids in a wellbore the well may be vented to atmosphere to increase the flow volume and velocity above that necessary to drag the liquids. (For more information, refer to attached API document, "Liquids Unloading Final.pdf", specifically Slides 21-22, 34 and 36-37 in Attachment D). This can occur sporadically if a reservoir produces a large amount of liquids unexpectedly which "loads" the wellbore with liquids or more frequently if a well is producing very close to the volume necessary to maintain critical velocity.

For wells with plunger lift systems, the ability to lift liquids is dependent on the differential pressure between the bottom of the well (under the plunger) and the top of the well (surface pressure) being high enough to provide the energy to lift the plunger and wellbore liquid above the plunger. Normal plunger operations incorporate a well shut-in period to enable the plunger to drop to the bottom of the well and for the formation pressure to build-up enough to lift the plunger and liquid. If the energy needed to lift a plunger and liquid load (height of the liquid column above the plunger) is larger than the formation pressure then it may be necessary to vent the well to atmosphere to achieve the necessary differential pressure. (For more information, refer to attached API document, "Liquids Unloading Final.pdf", specifically Slides 24-31 in Attachment D). This can occur if the formation unexpectedly produces a large amount of liquids or the production rate declines and liquids build-up faster than expected.

It is not necessary or relevant for the Program to understand or track the reasons for venting wells to assist with unloading liquids. What matters more are the emissions that result from venting associated with the management of wellbore liquids.

Charge Question 5

For liquids unloading, are there additional supplemental data elements or quantification methods needed to demonstrate that operators are minimizing emissions during liquids unloadings?

For liquid unloading, emissions can be reduced by changing the frequency of unloading (i.e., venting to the atmosphere fewer times per year) or by reducing the length of each venting cycle (i.e., for manually controlled events, the operator shuts off as soon as the well is unloaded). The GHGRP already captures the number of events, the length of time venting occurs, and the resultant emissions. Determining progress in minimizing emissions can easily use this information to illustrate a reduced frequency of venting, a reduction in venting time, or simply a reduction in emissions from venting associated with wellbore liquid management.

There is no study that links the installation of plunger lift systems with lower venting emissions associated with liquid unloading. In fact, the API/ANGA survey data, the GHGRP data, and the UT/EDF production study show the opposite that a higher percentage of wells with plunger lift systems vent, vent more frequently, and have higher emissions per venting well than wells without plunger lift systems.

Charge Question 6

EPA seeks feedback on methodologies for calculating and tracking centrifugal compressor seal oil degassing and reciprocating compressor rod packing methane emissions for the following operational situations:

a) *Compressors that route seal oil degassing/rod packing vents to manifolded vents that include sources other than seal oil degassing (e.g. blowdown vents) or seal oil degassing/rod packing emissions from multiple centrifugal compressors.*
b) *Compressors that route seal oil degassing/rod packing vents to flare, a thermal oxidizer, or vapor recovery for beneficial use other than as fuel.*

Subpart W reporting currently contains emission factors for wet seal degassing and rod packing venting for compressors on production sites. For this segment, the default emission factors could be used to determine the volume of gas captured or flared in this segment. Companies should have the flexibility to measure or meter the gas independently if desired. The additional reporting would be the number of compressors with each type of installation and the volume of methane emissions reduced. It would be very expensive to require direct measurement of emissions in all cases.

Charge Question 7

EPA seeks feedback on methodologies for calculating methane emission reductions for centrifugal compressors that convert from wet seals to dry seals.

Emissions factors should be utilized wherever possible. There may be a need to conduct studies to refine emissions factors for this source.

The industry standard is to assume 88% control for the conversion from wet seal to dry seal. Wet seal emission factors are available in current Subpart W reporting methodologies. The needed tracking for conversion would simply be the number of wet seal to dry seal conversions covered under the program and the methane emission avoided. The BMP should include the flexibility for a company to perform a "before" and "after" conversion measurement to determine emission reductions.

Charge Question 8

For transmission and distribution blowdowns, EPA requests feedback on the proposal of 50% as the minimum reduction percentage commitment, and whether the minimum commitment should be adjusted to serve as an appropriate stretch goal for partner companies. Is the proposed methodology for calculating potential emissions from this source appropriate? The proposed methodology assumes full evacuation of the pipeline to atmospheric pressure; are there circumstances in which companies don't lower pipeline pressure all the way to atmospheric levels, such that using this basis for calculating potential emissions could overstate potential emissions?

Pipeline segment blowdowns are undertaken as a part of a company's safety management program, and are required to perform maintenance, testing, pipe replacements and for safe pipeline operations. The ability to reduce the pipeline pressure to minimize blowdown emissions may be limited by several factors. Examples include pipeline configuration, customer impacts, available compression, weather, and emergency situations. For example, pipeline operators frequently cannot control the timing and need for blowdowns in emergency situations to maintain pipeline integrity and assure safety.

The ability to meet a specific minimum blowdown reduction goal will vary depending on the circumstances. Therefore, expecting companies to assure a 50% reduction from blowdown events may be unrealistic.

Charge Question 17

The Natural Gas STAR Program Annual Reporting Forms specify Sunset Dates (the length of time a technology or practice can continue to accrue emission reductions after implemented) for mitigation options (http://www3.epa.gov/gasstar/tools/program-forms.html). Should the Methane Challenge Program create a similar structure to establish Sunset Dates for designated mitigation options?

Reductions will be realized for the life of the well, and therefore operators should receive credit for the mitigation option as long as the emissions reductions remain.

Charge Question 18

The Methane Challenge Program seeks to stimulate new action to reduce methane emissions while also recognizing past actions undertaken by partners. For some sources, such historic action will be clear through proposed reporting (e.g. facilities that have converted high-bleed pneumatic controllers will show a low number of high-bleeds relative to low-bleed and zero emitting controllers). For other sources, such as cast iron pipe, a low level or nonexistent cast iron could reflect a historic replacement program or the fact that the facility never had such pipe. For practice-based programs, such as that proposed for excavation damages, companies may already have taken steps to reduce damages such that they cannot expect to achieve significantly lower levels. Should the Methane Challenge Program create a mechanism to specifically recognize historic action for certain sources? If so, how could the Program recognize such previous action (for example, by allowing these companies to join the Program and collecting and posting relevant details on previous action prior to joining the Program)?

Operators should not be disqualified from the Methane Challenge if they have already taken the mitigation options identified prior to the adoption of this program. Credit should be given for prior leading practices to reduce emissions. For example, companies that have existing leak detection programs already and can demonstrate low leak rates should receive credit for their programs as they have already invested in reducing emissions. Companies that have already incurred costs for replacing high bleed pneumatics should not be penalized for taking early action.

Attachments

A. Feldman, Howard, "Incentivizing Voluntary Participation in the Enhanced Natural Gas Star Program", American Petroleum Institute, Attachment to letter to Janet McCabe, June 12, 2015.
B. A detailed plan for an equipment leak "find and fix program" to effectively minimize leaks at oil and gas facilities.
C. A detailed plan for a phase-out of high bleed on-shore pneumatic controller valves.
D. API Presentation Slides on Liquids Unloading

EPA Natural Gas STAR Methane Challenge:

Proposed Framework

Attachment A

November 2015

Prepared by

American Petroleum Institute (API)

INCENTIVIZING VOLUNTARY PARTICIPATION IN THE ENHANCED NATURAL GAS STAR PROGRAM

One important element of EPA's methane reduction strategy is the development of the Enhanced Natural Gas STAR (ENGS) program, the agency's voluntary program to reduce further methane emissions from existing sources across the oil and gas sector. Successful implementation of the ENGS program, however, is dependent on the willingness of oil and gas producers to participate. A critical consideration will be whether participating companies will receive emissions reduction credits (ERCs) under the Clean Air Act (CAA or Act) for the voluntary VOC emission reductions achieved as a co-benefit of controlling methane under the ENGS program.

The incentive for companies to participate in the ENGS program could be significantly undercut by EPA's proposed plan to issue Control Technique Guidelines (CTGs) that would require state regulation of VOC emissions from existing oil and gas sources located in ozone nonattainment areas (classified as moderate and above) and potentially transport regions. As described below, if the VOC reductions accompanying methane reductions under the ENGS are considered "mandatory" because they are required by states pursuant to the CTGs, then they would not be available to use as ERCs for meeting CAA requirements in areas designated nonattainment for ozone. This would eliminate an important benefit that industry could obtain from voluntary reductions under the ENGS and thereby create a major disincentive for participation in the voluntary program.[1]

EPA has the ability to address these concerns. The discussion below outlines a federal framework for ensuring that companies can participate in a voluntary methane reduction program and, at the same time, generate VOC ERCs that can be used for CAA compliance.[2] These comments reflect our initial thinking; we expect to have further input once we have had the opportunity to review the design elements of the upcoming EPA proposals for establishing the ENGS program and CTGs for the oil and gas sector.

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[1] The importance of generating VOC ERCs will not only be for the benefit of permitting new oil and gas projects in nonattainment areas, but also for the benefit of other industrial sectors that may need these ERCs for CAA compliance. While many new minor source oil and gas projects may not need VOC emission offsets as condition for obtaining their air construction permits, ERCs generated by existing oil and gas sources could be useful to other sectors that need them and have limited opportunities to generate ERCs.

[2] The federal framework proposed in this paper would apply equally to oil and gas sources located on either state or tribal lands.

CAA REQUIREMENTS

The CAA establishes specific rules for the generation of ERCs. One key requirement is that the emission reductions must not otherwise be required by some other CAA program or regulation.[3] EPA has also established federal guidance providing that to the extent that the emission reductions are in fact required by CAA, those reductions are not "surplus" and consequently may not be used to generate ERCs.[4]

As discussed below, there is concern that voluntary VOC emission reductions achieved under the ENGS program will not be considered surplus if they are made now or in the future by existing oil or gas sources that are subject to new VOC emission reduction requirements over the next few years.

In releasing its methane strategy of January 14, 2015, EPA announced its plan to develop CTGs that will guide states toward adopting VOC controls for those existing sources located in ozone nonattainment areas under the CAA. In particular, section 182(b)(2) of the CAA requires states to set performance standards based on "reasonably available control technology" (RACT) for each category of existing VOC emission sources for which EPA has developed CTGs for controlling VOC emissions. These RACT requirements would then be incorporated in State Implementation Plans (SIPs) and be enforceable against covered sources. EPA is now working on draft CTGs and intends to release them for comment in the next few months.

Viewed in this context, there is concern that the voluntary VOC reductions achieved under the ENGS program may not be surplus and thus be ineligible for the generation of ERCs. This could occur if EPA or states were to determine that these voluntary VOC reductions were otherwise required by another provision of the CAA – specifically, as discussed above, the VOC RACT requirements imposed through section 182(b)(2) of the Act.

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[3] Section 173 (c)(2) of the CAA (providing that "Emission reductions otherwise required by this chapter shall not be creditable as emissions reductions for purposes of any such offset requirement"). *See also* Emissions Trading Policy Statement; General Principles for Creation, Banking and Use of Emission Reduction Credits, 51 Fed. Reg. 43,814, (December 4, 1986) [hereinafter "EPA ERC Policy"].

[4] EPA ERC Policy at 43,832. In addition to being surplus, the emission reductions must meet other criteria in order for the emission reductions to generate ERCs. These criteria include requirements for the reductions to be actual, quantifiable, enforceable, and permanent. *Id*.

PROPOSED FRAMEWORK FOR GENERATION OF VOC ERCS

So that EPA's development of the CTGs does not undermine the incentives for industry participation in the ENGS program, EPA should provide clarification that VOC reductions that occur as a co-benefit of voluntary methane reductions under the ENGS program will be deemed to be "surplus" and thereby be able to generate VOC ERCs under the CAA.

The most straightforward way for providing certainty on this issue is through the definition of the CTG source category. Specifically, EPA should define the oil and gas source category covered by the CTGs to exclude those existing oil and gas sources that have implemented "best management practices" (BMPs) for methane under the ENGS program and have thereby reduced their VOC emissions to low levels that would meet or exceed the minimum VOC RACT control levels that, as noted above, states would need to adopt in response to the CTGs under CAA section 182(b)(2).[5]

In this case, the establishment of an exemption for existing sources controlling VOCs through ENGS-specified BMPs would mean that states would not be required to set VOC RACT standards for these sources based on the control measures specified in the CTGs. Since such sources would be excluded from the oil and gas source category to which the CTGs would apply, states would have no legal obligation to establish VOC RACT standards for these sources under the CAA. This means that the VOC emission reductions achieved by these sources would not result from the imposition of any mandatory CAA reduction requirement imposed by states or EPA. Rather, the reductions will be achieved through the voluntary implementation of BMPs or other equivalent work practice measures under the ENGS program and thereby would be "surplus" reductions for purposes of generating ERCs under the CAA.[6]

In addition to demonstrating that the emissions reductions are surplus, owners and operators of existing oil and gas sources would have to meet the other criteria for generating creditable VOC ERCs under the CAA. These other criteria include

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[5] Notably, this approach is similar to the exemption that EPA has provided for new and modified sources under the NSPS Subpart OOOO regulations. In the case of the Subpart OOOO regulations, EPA has defined the "affected facility" to exclude "highly-controlled" sources that meet certain performance criteria specified in the NSPS regulation.

[6] Furthermore, by providing this guidance in the CTGs, states would also have the assurance that EPA would approve their nonattainment SIP RACT provisions with respect to the adoption of a BMP exemption for ENGS participation. It would also provide EPA regions with oversight of tribal lands needed assurance to include equivalent provisions in nonattainment federal implementation plans that EPA must adopt for ozone nonattainment areas.

requirements for the associated VOC reductions to be actual, quantifiable, enforceable, and permanent.[7] For companies participating in the ENGS program that wish to generate creditable VOC ERCs as co-benefits of methane reductions, a process for quantifying and documenting these voluntary VOC reductions would be helpful and reduce uncertainties down-the-road. EPA should, therefore, develop federal guidance for the quantification and accounting of voluntary VOC reductions from oil and gas sources that could be used to generate ERCs under the CAA. This guidance would not only be helpful to companies wishing to obtain VOC ERCs but would also encourage consistency in quantifying and crediting VOC reductions by states (and EPA regions managing tribal lands) that are responsible for establishing ERC programs as part of NAAQS implementation. Adherence to these procedures in the federal guidance could then be considered sufficient for generating creditable VOC ERCs so long as the reductions also voluntarily become federally enforceable through a permit condition or other applicable regulatory requirement imposed by the state or EPA.

VOLUNTARY METHANE EMISSION REDUCTIONS

The primary objective of the ENGS program is to encourage participating companies to achieve significant voluntary reductions in methane emissions from their existing oil and gas sources. To encourage maximum participation under the ENGS program, EPA should establish a clear and straight forward process for participating companies to receive ERCs for the co-benefit VOC emissions reductions achieved under the ENGS program. The generation of such VOC credits is therefore a critical component of the ENGS program that should be included in order to preserve industry's ability to meet its ozone compliance obligations under the CAA.

In addition to the ability to generate VOC ERCs, the extent to which companies participate in the voluntary program will depend on a variety of other important considerations, including the overall mix of incentives and benefits provided for achieving voluntary methane emissions reductions. Although outside the scope of this paper, there will undoubtedly be further dialogue regarding these incentives and benefits once the draft ENGS program is released for comment with the goal of crafting a program that encourages robust industry participation in the ENGS program and thereby the achievement of substantial methane reductions. We look forward to discussing with EPA possible approaches to achieving this important objective once we have had the opportunity to review the proposed design elements of the ENGS program.

[7] EPA ERC Policy at 43,832.

EPA Natural Gas STAR Methane Challenge:

Proposed Framework

Attachment B

November 2015

Prepared by

American Petroleum Institute (API)

Voluntary Leak Program for Oil and Gas Production Sources - Implementation Principles

General

- Targeted toward higher emissions sources
- Applies to new and existing onshore sites upstream of gas processing plant (as defined in OOOO)
- Applies to onshore production sites with onsite storage vessel or compressor
- Incorporates five-year phase-in schedule to implement initial monitoring for participating existing sites based on individual company plan
- Instrument-based monitoring programs within existing state regulatory and permit requirements or participation in voluntary program should satisfy future regulatory requirements (i.e., NSPS OOOO)
- Allow flexibility in leak detection methods and technologies (e.g., Method 21, IR camera, or other equivalent) to satisfy the voluntary program requirements
- Committed to reasonable, cost-effective reporting that tracks progress

Program Specifics

Target	Broad facility survey
Target Components	Significant emission sources such as malfunctioning fugitive emission components, pneumatic controllers not functioning as designed, and controlled hydrocarbon storage vessels
Method	IR camera, or equivalent
Initial Survey	
Existing Site	Phased in, initiated within no later than 18 months and concluded over no more than a 5 year period
New Site	Within 180 days of start of production following installation of new hydrocarbon storage vessel or compressor
Subsequent Surveys	Annual after initial survey
Repair Period	• 1st attempt within 15 days • Repair within 60 days (pending part availability) • Delay of repair (at next shutdown or pending part availability)
Reporting	
Frequency	Annual
Contents	• Number of new sites monitored • Number of existing sites monitored • Number of leaks repaired (excluding those repaired during survey) • Number of leaks not repaired and reason for delay
Tagging/Other Identification	Only of leaking components not repaired during survey

EPA Natural Gas STAR Methane Challenge:

Proposed Framework

Attachment C

November 2015

Prepared by

American Petroleum Institute (API)

Program to Phase-out High-bleed Pneumatic Controllers - Implementation Principles

General

- 5-year replacement goal for all onshore continuous high-bleed pneumatic controllers
- Create a new and separate Gas STAR Pneumatics Program (separate from the proposed Gas STAR Gold program and the old Gas STAR program)
- Work together to develop the program specifics

Participation

- Industry leadership would publically endorse and promote the program to other trade associations
- Individual company participation

Program Specifics

- Replace all onshore continuous-high-bleed controllers with one of the following:
    - continuous–low-bleed controllers,
    - intermittent-vent controllers,
    - electrically operated controllers and valve actuators or mechanical controllers,
    - convert to instrument air to replace natural gas as the motive gas, or
    - remove from service where feasible with no replacement.
- Support annual reporting and alignment with timing of GHG reporting – March 31st reporting deadline for the previous calendar year. Reports would include the following regarding a company's onshore continuous-high-bleed controllers:
    - Number replaced
    - Number swapped to instrument air
    - Number eliminated
    - Number remaining
- Individual company commitment/annual targets to meet 100% replacement goal within 5 years
- Only affects controllers located at upstream onshore production and gathering facilities as well as natural gas processing plants.
- EPA may make program details and submitted company-specific data publically available
- Maintain Subpart OOOO exemption based on functional needs, including but not limited to response time, safety, and positive actuation.

EPA Natural Gas STAR Methane Challenge:

Proposed Framework

Attachment D

November 2015

Prepared by

American Petroleum Institute (API)

Gas Well Liquids Unloading

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Key Message

The US gas supply is dependent on the industry's continued ability to use the best and most cost effective technologies and practices to manage wellbore liquids

American Petroleum Institute

Webinar goals

- Seek common understanding of deliquification technologies
  - How they operate
  - Applicability constraints – when do they work
  - What role venting to atmosphere has in each technology
- Seek common understanding of key principles
  - Critical flow – what it is and why it is important
  - Limitations of “artificial lift” technologies applied to gas wells
  - Individual well variability and necessity for appropriate choices for deliquification

Gas well liquids unloading

- Introduction
- Wellbore dynamics
- Unloading with reservoir energy
- Unloading with added energy
- Emerging Technologies

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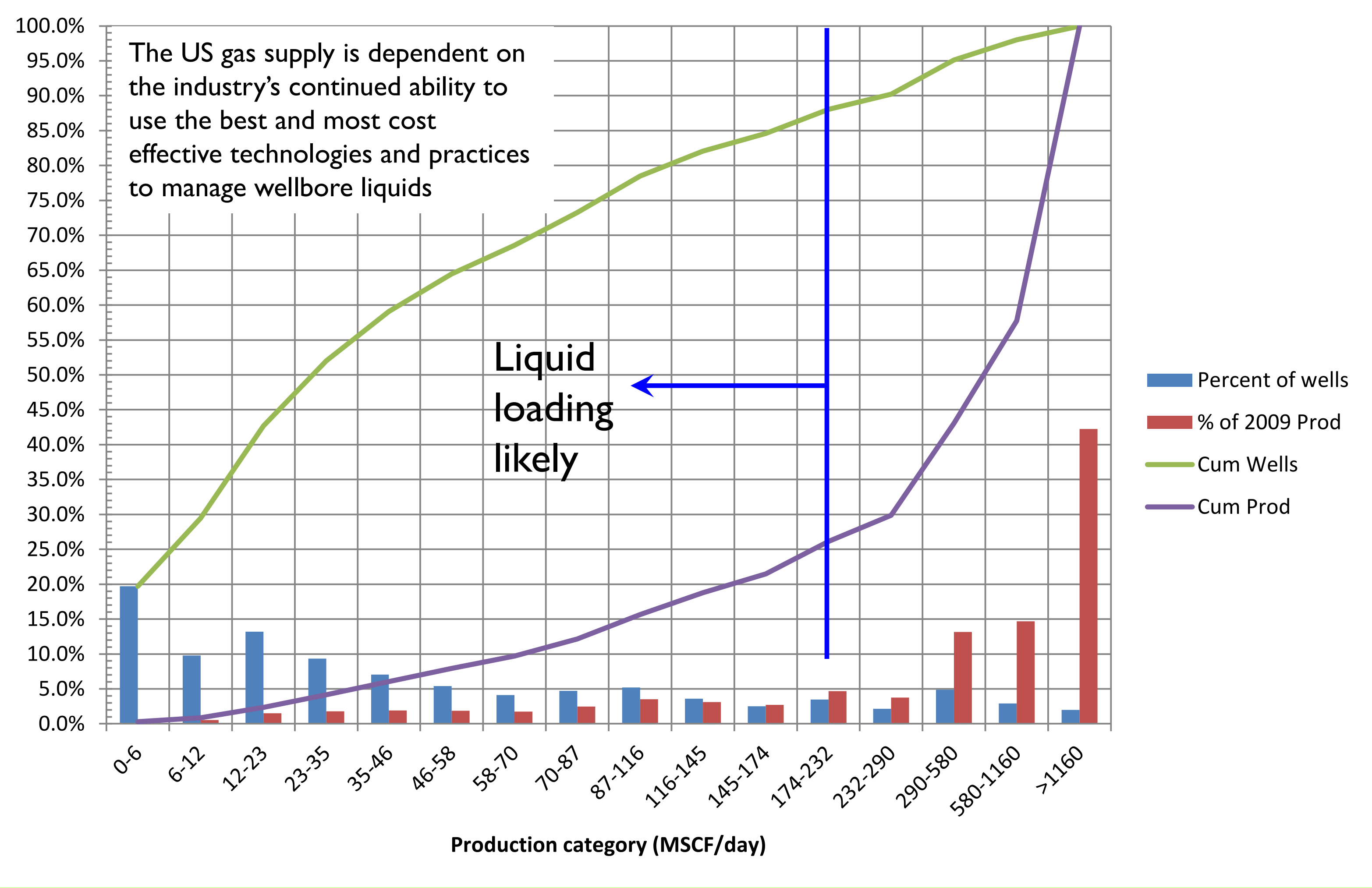
Key points

- Liquids unloading (deliquification) is not synonymous with venting
  - Venting of gas wells to assist liquid unloading is the source of emissions – not deliquification
  - Deliquification techniques that do not vent do not create emissions
- Well-bore liquid management is a complex field with a large amount of on-going research and improvement
  - There is no single answer to well-bore deliquification or to minimize venting to assist liquid unloading.
- U.S. gas well data:
  - Approximately 85% of onshore gas wells have tools or techniques to manage liquid loading
  - Only 13% of onshore gas wells reported venting associated with liquids unloading in 2012
  - More of the venting wells were equipped with plungers than were not equipped with plungers; Plunger equipped wells accounted for ~70% of emissions
  - Reported emissions are dominated by a small number of reports (3.6% = 75%)

U.S. gas well count and production



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Introduction to Deliquification

- In the last 50 years, gas has gone from being a waste product that hindered oil production to a primary, sought after product
  - Gas prices have caused operators to rethink "abandonment pressure" and "economic limit"
  - Wells/fields are reaching original abandonment pressure while fields are still profitable
- What do they have to do differently to remain profitable down to very low reservoir pressures?
- The biggest challenge is "Deliquification"

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Working Definitions

- *Artificial Lift*: application of external energy to lift a <u>commercial product</u> from reservoir depths to the surface
- *Deliquification*: application of energy to remove an <u>interfering liquid</u> to enhance gas production
- The key difference is that it matters where and in what condition artificially-lifted oil ends up, but water just needs to be gone
  - Evaporation is a reasonable deliquification method, but it would be an artificial-lift failure
  - "Upside down" pumps that discharge liquids below a packer into a deeper formation are available (although rarely used). These pumps can be very effective in deliquification, but not in artificial lift

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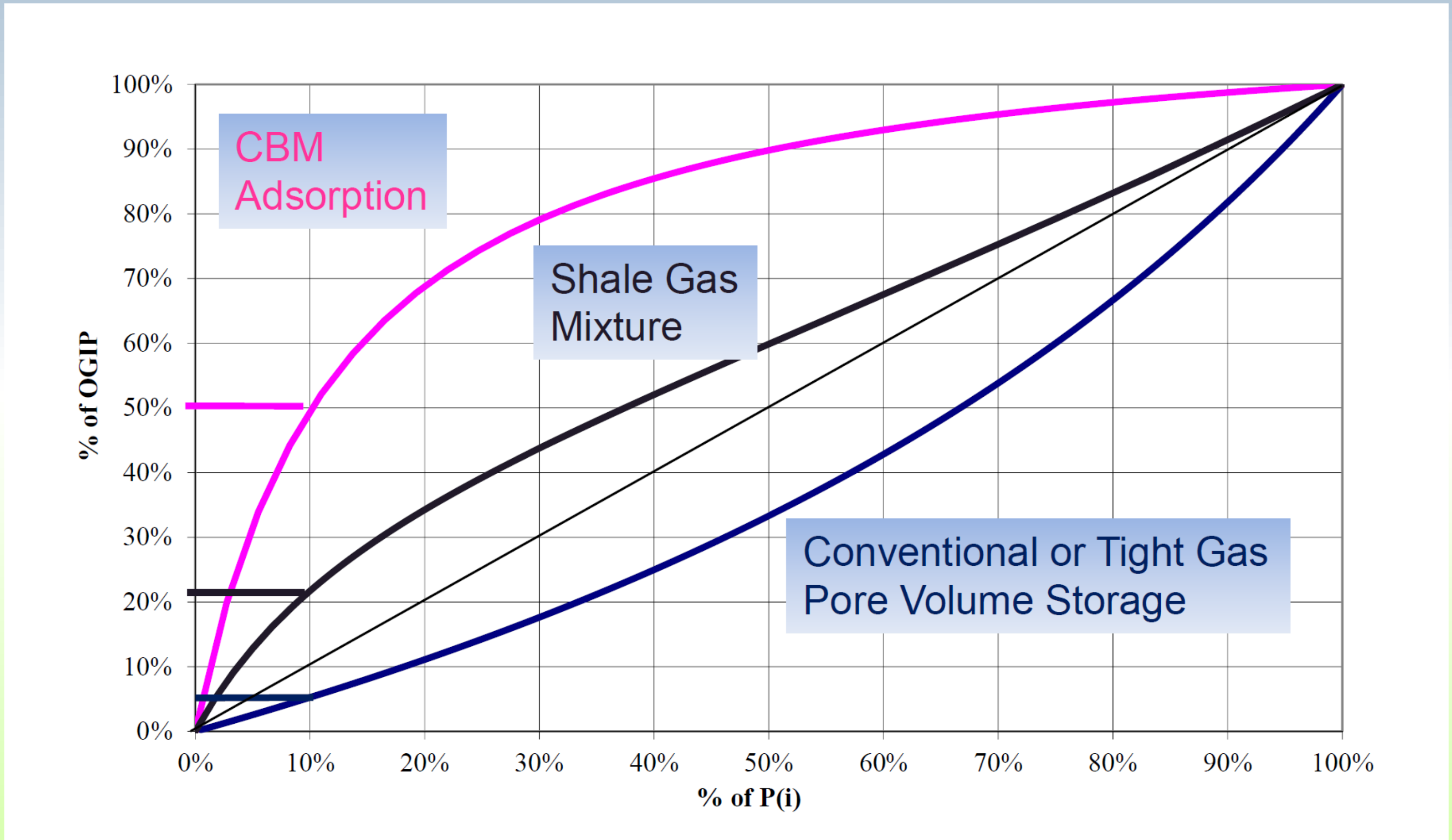
Why Reservoir Pressure Matters

Reservoir Pressure vs. Oil and Gas In Place



American Petroleum Institute

Wellbore dynamics

American Petroleum Institute

Gas well flow – what matters

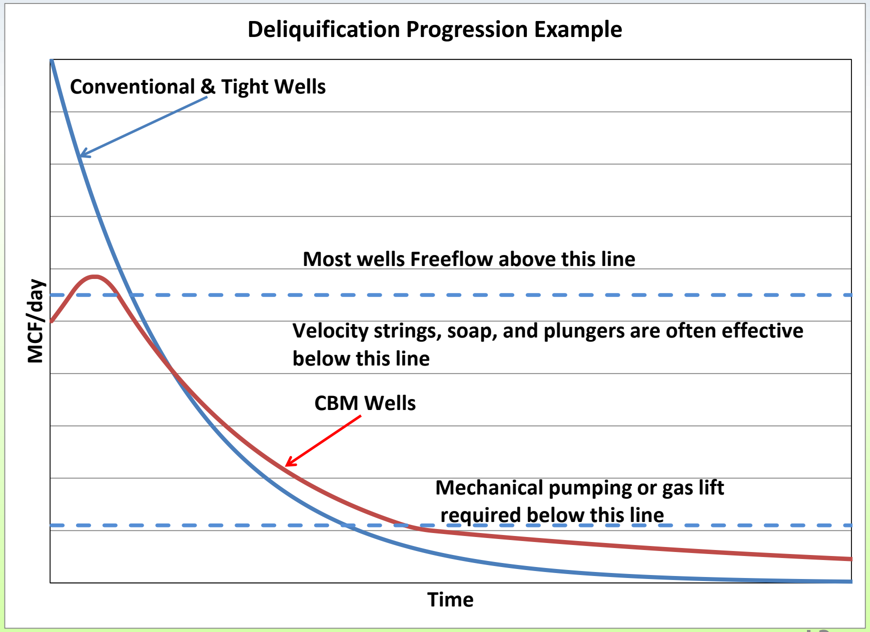
- With given reservoir and wellbore characteristics:
  - Flow rate into the wellbore is a function of differential pressure between the reservoir and the wellbore
  - Flow rate out of the well is a function of the differential pressure between the bottom and top of the wellbore
  - The ability of the flowing gas to drag liquid along with it is a function of the gas velocity which is a function of the flow rate and tubing size
- This pressure and flow management is one of the primary jobs for production teams

Gas well flow – what matters

- Formation pressure provides the energy for flow
- The differential pressure between the bottom of the wellbore and the tubing pressure is made up of:
  - Weight of the fluid column in the wellbore;
  - Flowing friction in the tubing;
  - Surface equipment pressure drop;
  - The collection system pressure the well is flowing into.

Gas well life cycle

- Early in a well's life it will tend to free-flow without added assistance
- Once a well declines it will enter a period where liquids loading is an issue but lifting liquids still relies on reservoir energy
- Once reservoir energy is no longer adequate mechanical lift will be needed
- Decline in reservoir energy and production begins when a reservoir is put on production.
- The ability of a well to economically support deliquification defines its economic life



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Vertical multi-phase flow

- All other things being equal, gas will tend to flow at a higher velocity than liquids in the same stream
- At the gas/liquid interface the “no flow boundary” requires that either
  - The gas is slowed to the speed of the liquid,
  - The liquid is accelerated to the speed of the gas, or
  - Some combination of gas slowing and liquid accelerating
- In vertical flow,
  - Gas velocity will tend to drag the liquid up the hole
  - Buoyant forces will tend to lift the liquid up the hole
  - Gravity will tend to push the liquid down the hole
- The major variables are
  - Drop size (bigger makes gravity > buoyancy)
  - Drop shape (affects droplet drag)
  - Gas velocity (higher allows drag + buoyancy to exceed gravity)

Critical Flow

- Critical Flow—R.G. Turner et al published a *Journal of Petroleum Technology* paper in November, 1969 coining the term "Critical Flow"
  - He showed that the liquid volume that reached surface was a function of gas velocity which was a function of interfacial tension and fluid density
  - Critical Flow is that gas flow rate up an individual well that results in a velocity just sufficient to drag the produced liquid up the wellbore with the gas
  - It will vary from well to well and depends on the amount of water a well makes, the tubing size, the water droplet size and shape, and changes it over time for any individual well
  - At flow rates less than critical flow liquids will build up in the wellbore
- Many other researchers have built on this concept with new interpretations of Turner's data and some new data sets
- The magnitude of "critical velocity" and the method of determining it continues to be a source of heated academic debate

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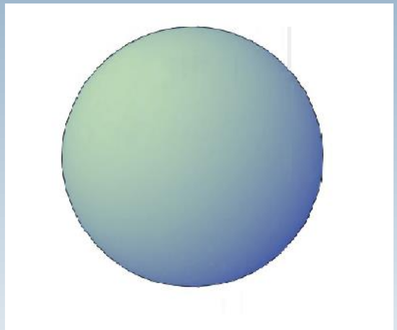
Selected Critical Flow Theories

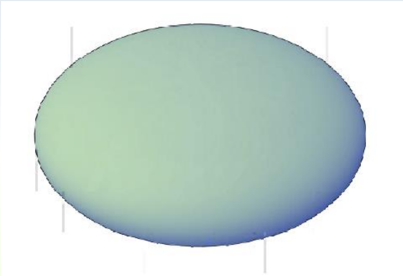
Turner, 1969

$$v_{Turner} = 1.912 \frac{ft}{sec} \left(\frac{\sigma_{gasLiq} \left(\rho_{liq} - \rho_{gas} \right)}{\rho_{gas}^{2}} \right)^{1/4}$$



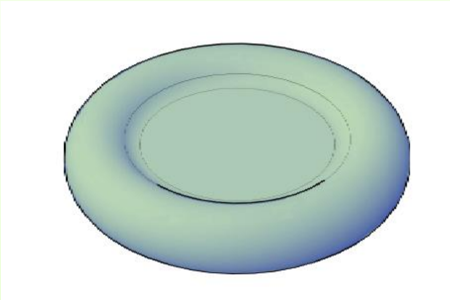
Coleman, 1991

$$v_{Coleman} = 1.593 \frac{ft}{sec} \left(\frac{\sigma_{gasLiq} \left(\rho_{liq} - \rho_{gas} \right)}{\rho_{gas}^{2}} \right)^{1/4}$$



Li, 2002

$$v_{Li} = 1.322 \frac{ft}{sec} \left(\frac{\sigma_{gasLiq} \left(\rho_{liq} - \rho_{gas} \right)}{\rho_{gas}^{2}} \right)^{1/4}$$



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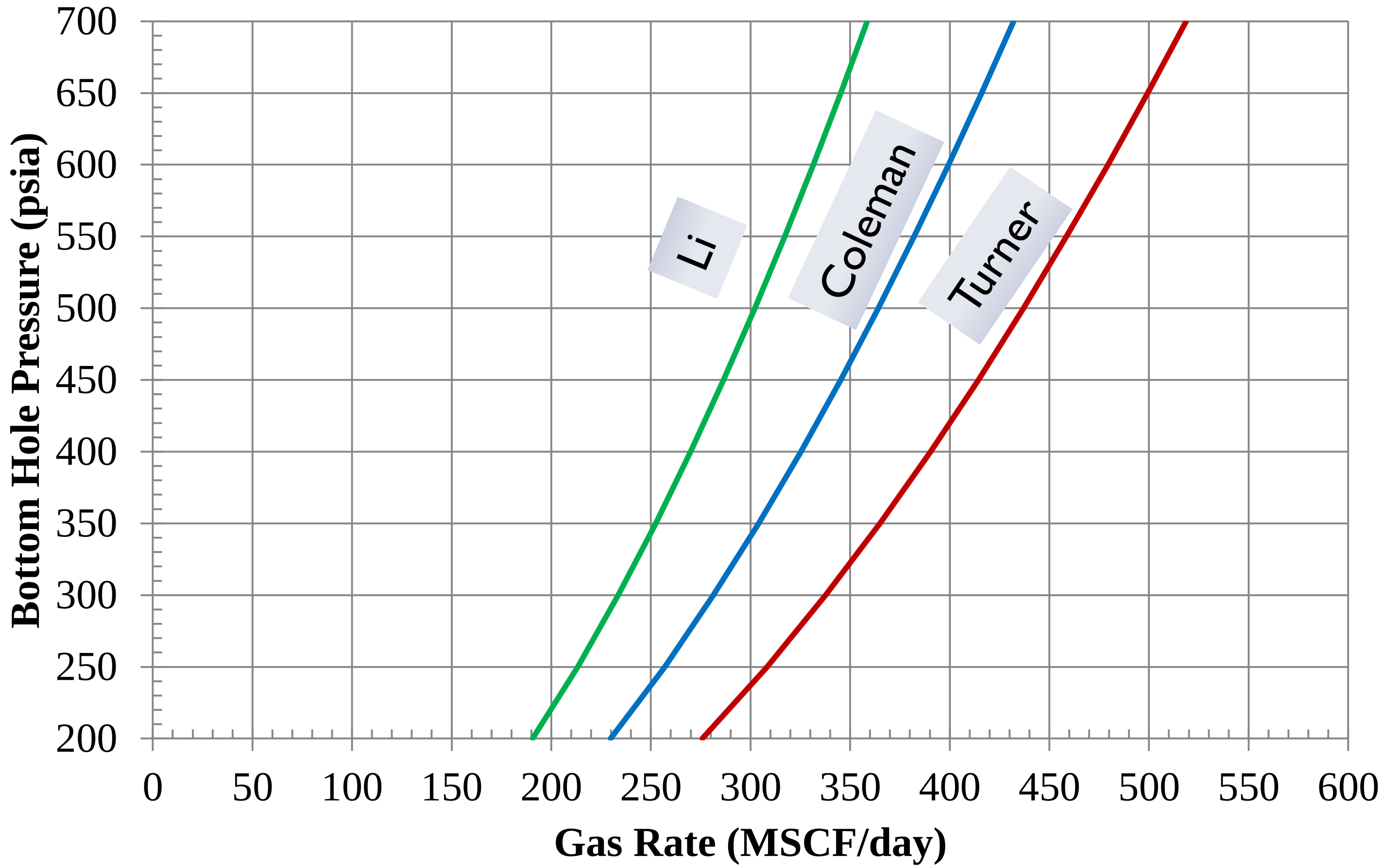
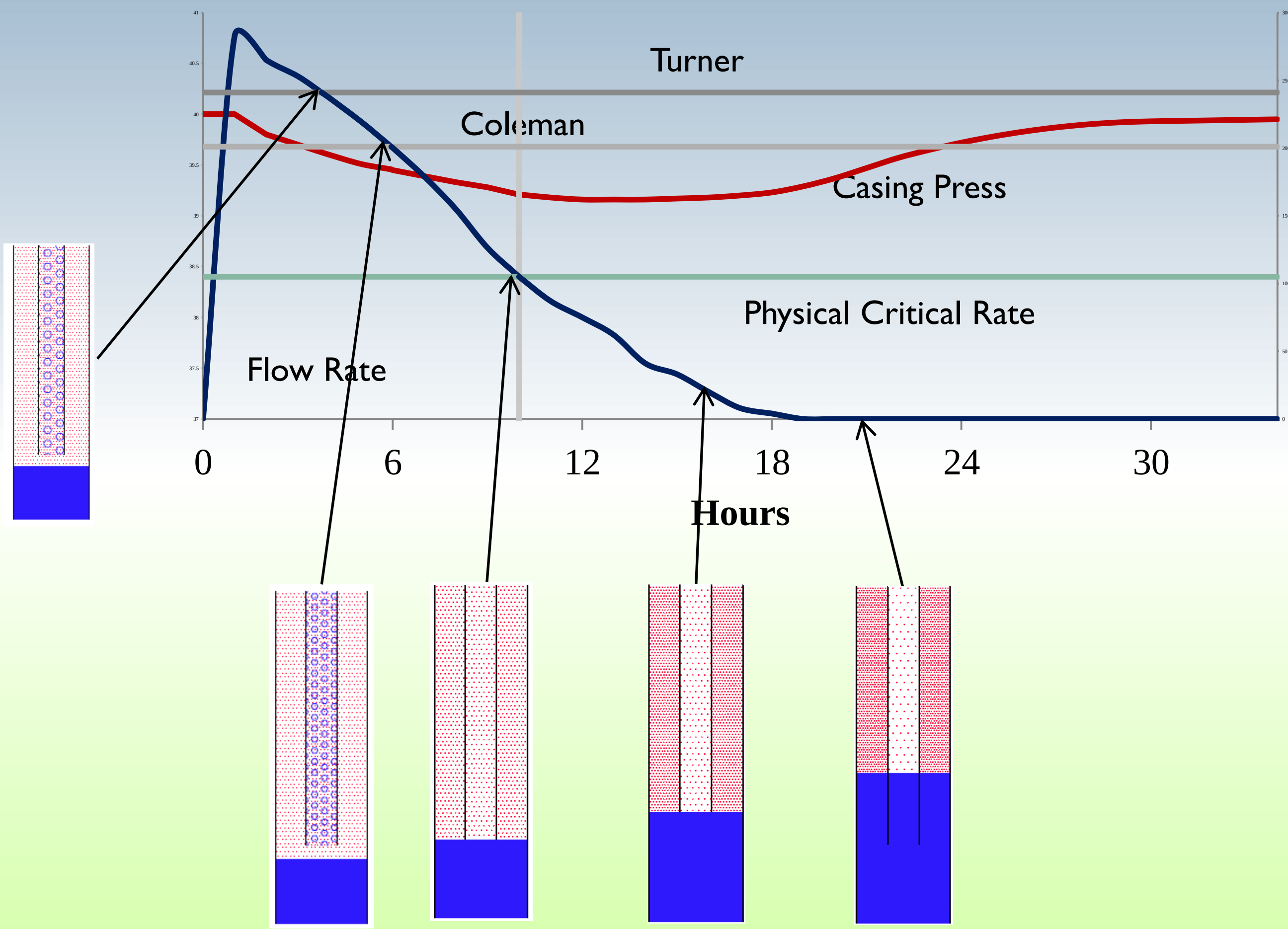
Flowing bottomhole pressure vs. gas rate



A non-theoretical method to determine critical flow



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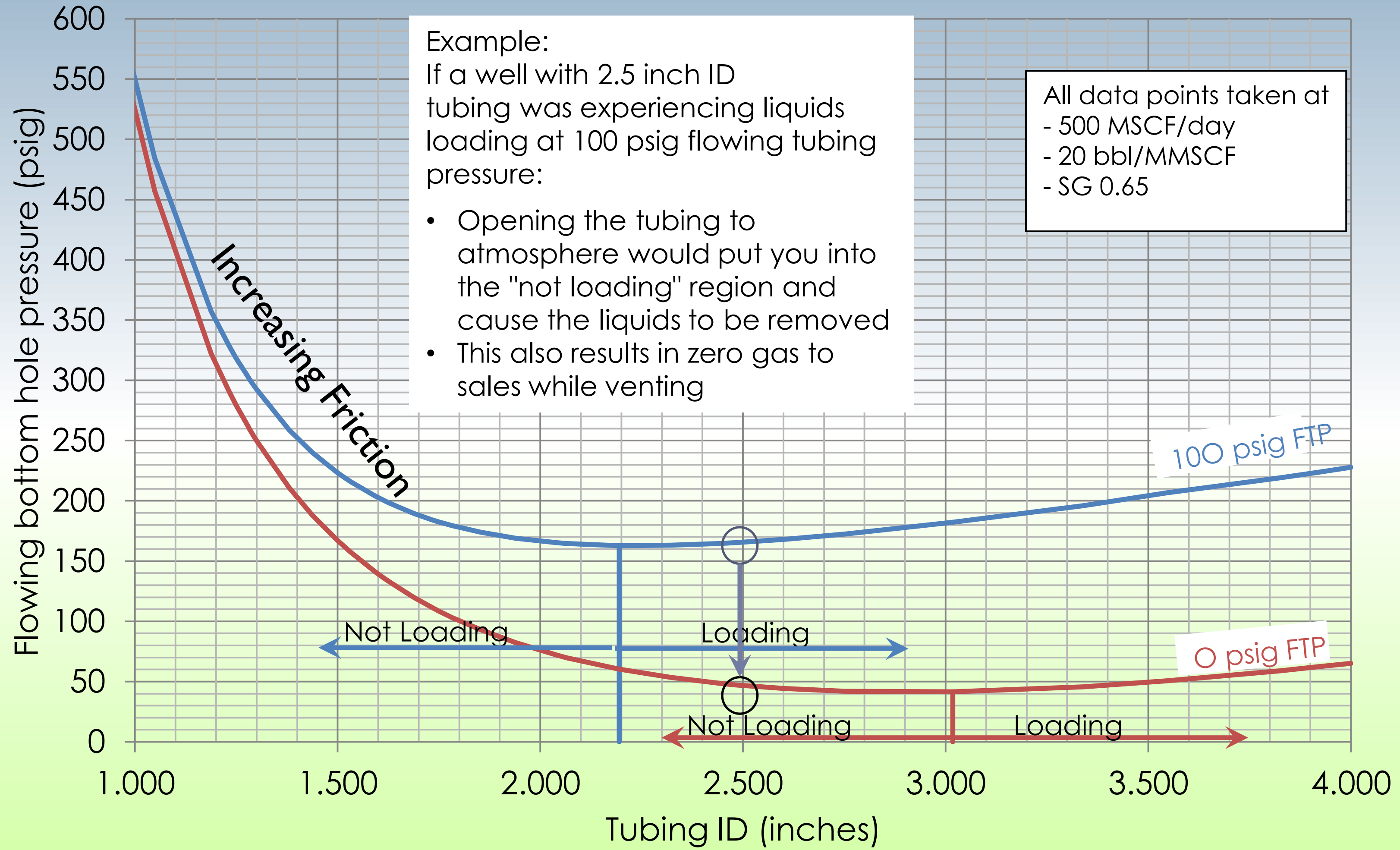
Unloading with Reservoir Energy

- Velocity Strings
- Plunger Lift
- Soap/Surfactants
- Intermitting
- Vent cycles

Velocity String

- A "velocity string" is a smaller diameter string of tubing that forces a normal gas flow rate to have a velocity greater than the "critical velocity"
- Higher velocity equates to higher friction – there is a tradeoff
- Wells with velocity strings are very unforgiving:
  - If rate increases, friction will rapidly raise FBHP
  - If rate decreases slightly, you can drop below the critical rate and load up very quickly – 1 bbl water = 1,030 feet in 1" ID tubing ~ 500 psi backpressure
  - A cold section in the wellbore can condense water vapor and upset the balance on a near-critical well
  - Small diameter velocity strings preclude both plungers and swabbing
- It is not a good idea to fully open the casing with a velocity string
- Venting is occasionally used in conjunction with velocity strings

Pipe Size vs. Flowing Bottom Hole Pressure



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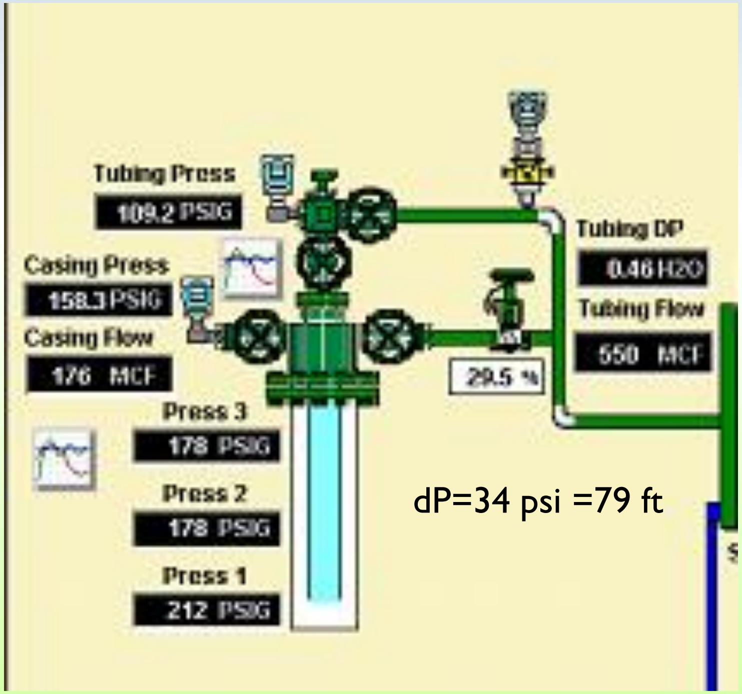
Tubing/Casing-Flow Controller

- If you're using a velocity string and the tubing/casing differential pressure is "excessive" then you can alleviate high friction drop by allowing some casing flow:
  - Must monitor tubing flow to make sure you stay above critical
  - Must throttle casing flow carefully to ensure that you don't upset the tubing flow too much
- A number of wells have seen sustained performance improvements with this configuration over several years
- Wells on flow controllers do not vent



Plungers

- A plunger operates like a pipeline pig
  - Differential pressure across the plunger moves it up the wellbore
  - Any solids or liquids it encounters are pushed in front of it
- Differential pressure determines how much liquid a given well can lift
  - Disregarding friction, 10 psid [68.9 kPad] can move:
    - No more than 2.5 gallons [9.5 L] per trip in 2-3/8
    - No more than 4.4 gallons [16.6 L] per trip in 2-7/8
  - To move 5 bbl/day [794 L] with 10 psid in 2-3/8 requires at least four trips per hour (closer to 6 with a safety factor)

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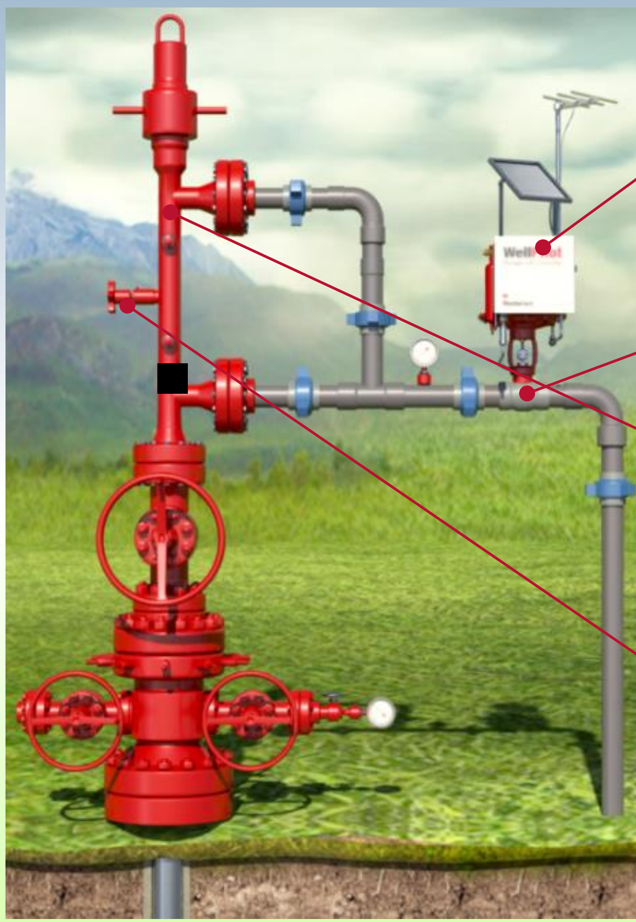
Components / Parts



- **Controller:** Electronic-based system with control parameters for opening and closing motor valves
- ***Motor Valve:*** Diaphragm-operated device controlled by controller to open/close sales/tank line
- ***Lubricator:*** Uppermost stopping point for plunger
- ***Plunger Sensor:*** Magnetic device strapped around lubricator to detect plunger arrivals

Components / Parts

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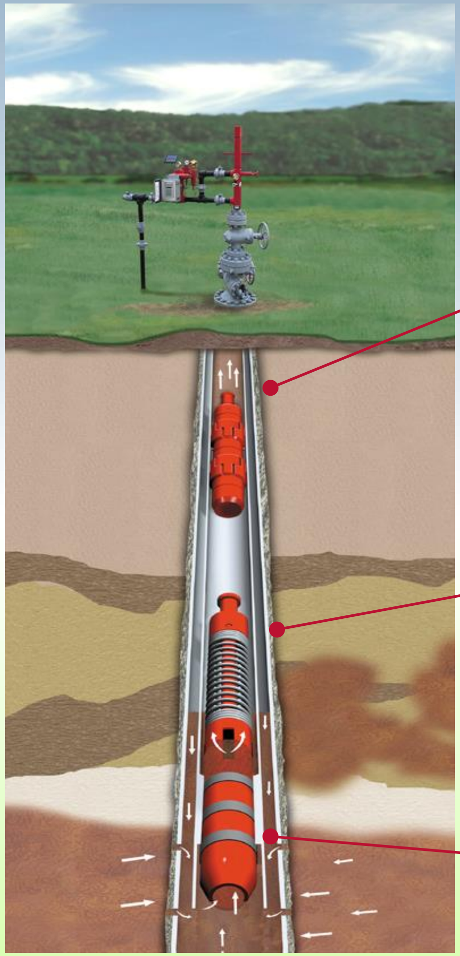

- ***Plunger:*** Pig-type device that provides seal inside tubing to deliver fluid to surface
- ***Bumper Spring:*** Shock absorber at plunger's deepest stopping point
- ***Landing Tool:*** Locates bumper spring in profile or lands elsewhere

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Plunger operations sequence

- Drop plunger
  - Conventional plungers cannot fall against tubing flow so the tubing flow is stopped for some period of time to let the plunger fall to bottom
  - Bypass plungers allow gas to flow through the plunger body while flowing so the tubing flow is not stopped
- Keep well shut in until your process shows adequate pressure build up
- Plunger rise (open well to sales)
  - Force required to lift plunger is a function of
    - The weight of the plunger
    - The weight of the liquid load
    - Friction with the tubing walls
  - Force is provided by differential pressure between BHP and FTP
- Plunger arrival and after flow
  - After the plunger arrives the well flows to sales – called "after flow"
  - When the flow rate drops to some "critical rate", the cycle repeats

Plunger selection

Plunger Type	Use	Shut In required	Gas Velocity	Fall velocity
Conventional	Depleted wells, late life	Y	<3 m/s	50 m/min
Bypass	Onset of loading	N	3-4.5 m/s	250 m/min
Plunger configuration (each configuration is used with both bypass and conventional)				
Ring	Solids (paraffin, scale) handling			
Pad	Low solids, better seal			
Brush	Cleaning pipe			

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Plungers

- Early in life, there tends to be enough FBHP that the well doesn't need assistance
- Late in life the pressure required to lift a plunger plus a load of water may be greater than the differential pressure available
  - Operators may vent wells to atmosphere to increase the force available
  - In that case, the tubing is shut in for a drop time, the vent is then opened until plunger arrival is sensed
  - The vent is then shut and the sales line is open to allow after flow to sales

Plunger controls

- One of the fastest evolving areas of gas well deliquification is control of plungers
- Controls range from
  - Simple clock timer
  - Rigid algorithm to use timers to control drop time, shut in time, and some form of “critical flow” calculation to control after flow
  - Flexible algorithm to “learn” the well’s flow characteristics, critical flow rate and adjust drop time, after flow time, and the need for vent-assist on plunger travel time (smart automation)
- Sophisticated vendor controls are becoming very common and are starting to be seen as a viable alternative to “design your own” controls that are proprietary to a specific operator.

Plunger Operation

- Plungers are operated more as “art” than “science”
  - Some operators shut the well in for extended period to build up pressure
  - Other operators use bypass plungers to let the plunger fall against flow
  - Some operators wait until tubing/casing differential is “big enough” to run the plunger
- One technique that works well (with automation control):
  - As soon as a plunger arrives, shift flow to tubing/casing annulus and drop the plunger
  - Let it fall for a set time, then shut the annulus until the plunger arrives again and start over
  - This technique will reduce slugging, move more liquid, and access more of the reservoir

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Plunger operational risk examples

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Surfactant

- Soaps, foamers, and other surfactants are designed to foam and:
  - Introduce voids that lighten the liquid column
  - Reduce the surface tension of the liquid drops to minimize their size/weight
- All soaps have to be activated by agitation
- Care must be exercised to ensure that the soaps are activated downhole
  - Unactivated liquid soap will often activate and foam in the production/measurement equipment
  - Foaming in the gathering system will tend to increase the condensation surface and increase water problems
  - Liquid soap is “gummy” and can increase skin
- Different formulations are effective on different fluids
  - Each condensate mix requires unique formulation (rarely successful)
  - Each water mix requires adjustments to standard formulations
- Occasionally, surfactants are used in conjunction with vent cycles

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Intermitting

- When a well is shut in, the pressure deep in the reservoir will tend to migrate towards the near-wellbore rock
- This observation has been used to "intermit" wells
  - Shut in the well until shut-in tubing pressure reaches a pre-determined value
  - Open the tubing to sales and flow until the flow rate declines to the critical rate
  - Shut the well in again
- This technique does not result in any vented gas

Vent cycles

- For the weakest wells with marginal economics, vent cycles are occasionally used
  - The well is shut in for a period (either based on time or based on surface pressures building up to some pre-determined value)
  - The well is opened to atmosphere for a time to “lift the liquid load” (but it is exceedingly difficult to determine when all of the interfering liquid is removed)
  - The well is then sent to sales until loading starts again (either time based or based on a flow rate)
  - The cycle starts again
- The industry has recognized that this practice is very imprecise, not particularly effective, and significant saleable gas is vented instead of sold
- Vent cycles are generally seen as an alternative to abandonment, not as an alternative deliquification method

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Unloading with added energy

- Methods
  - Surface compression
  - Sucker Rod Pumps – Walking Beam & Linear Drive
  - Progressing Cavity Pump
  - Electric Submersible Pumps
  - Jet Pumps
  - Gas Lift
- In general – pumps designed for artificial lift (oil pumping) require changes in configuration and/or procedures to work at all in gas-well deliquification applications

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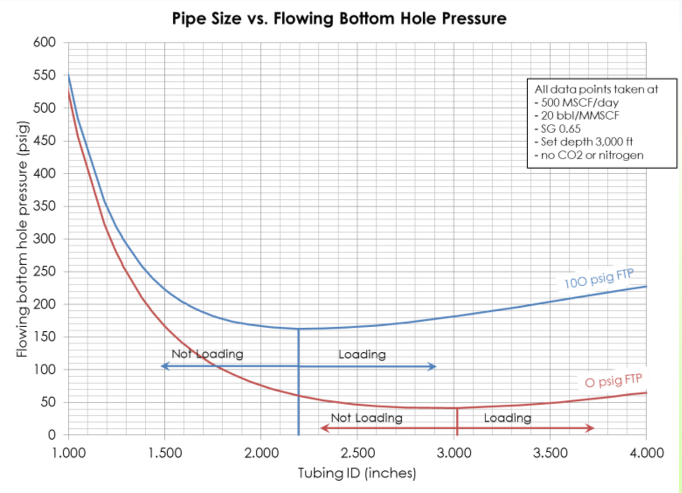
Emissions issues with adding energy

- None of the techniques in this section directly vent gas to the atmosphere
- They all require some external motive force and have some amount of offsetting emissions
  - On-site engines – normal engine exhaust emissions
  - Electric motors – emissions associated with power generation
- Emissions associated with added-energy deliquification are not considered as "unloading emissions"

Surface Compression – Lower Surface Pressure

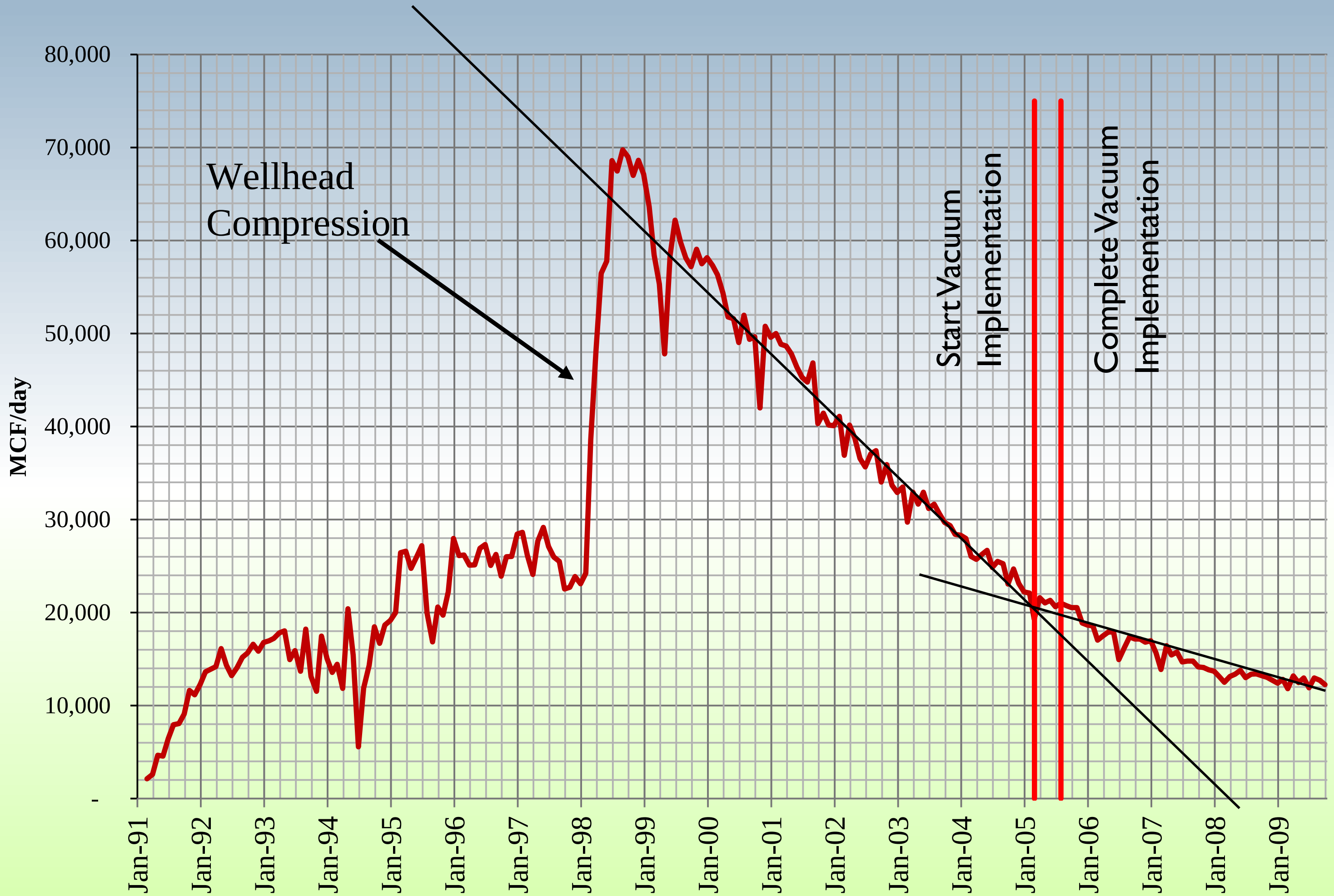
- As has been seen earlier, critical flow rate can be altered by changing flowing tubing pressure
- Lower surface pressures can also increase the differential pressure between the reservoir and the flowing bottom hole pressure, which can increase flow into the well
- Wellsite or lateral compression is a useful tool for reservoir management in many situations
- Compression is often used in conjunction with other deliquification techniques



Evaporation as Deliquification

- If your pressure is low enough, then it is sometimes possible to evaporate all of the liquid that flows into the wellbore
- This technique works, but it requires that you:
  - Be willing/able to operate under vacuum conditions
  - Remove production tubing to maximize the flow area (and minimize velocity)
- One major concern is that the evaporating water will leave salt behind that can plug the formation
  - There is no theory that would predict this won't happen
  - Experience to date has not shown it to be a problem
- Another concern is the risk of accelerated corrosion from oxygen incursion
  - This risk can be mitigated by using oxygen sensors on surface

Evaporation Example
(22 wells on vacuum)



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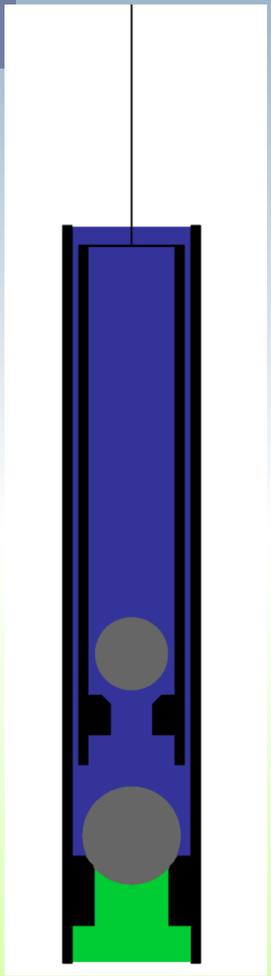
Sucker Rod Pump (SRP)



- Simple chamber with two valves
  - Chamber empties on downstroke
  - Chamber fills on upstroke
- With the pump liquid-filled, very little plunger movement is required to start pumping
- The Artificial Lift version of SRP uses “Pump Jacks”, “Beam Units” or “Nodding Donkey’s” on the surface
- The artificial lift version of SRP is a poor choice for deliquification
  - Pump Jack moves at constant speed
  - Time at top of travel is too short to facilitate refilling the barrel through leakage at minimum engagement – Gas locks the pump
  - Pump-off controls may help avoid gas lock
  - Electric VFD’s may vary pump speeds

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Sucker Rod Pumps - Linear

- The deliquification version of SRP uses linear rod drivers
  - Allows programming pauses and different speeds on the up stroke than the down stroke
  - Programming options allow pauses/variable speed
    - Pause at top of stroke to allow leakage to fill barrel and let any gas out of the barrel
    - Slow down the upstroke to help with filling barrel
    - Speed up the downstroke to keep traveling valve open
  - If the barrel is full at the start of every upstroke, then the standing valve opens and lets in whatever is there—water gas, froth, etc. and prevents gas lock

Progressing Cavity Pump (PCP)

- Rotor has a profile with a slight pitch.
- Each revolution causes the liquid in the cavities to move up the pump barrel.
- PCP’s are positive displacement pumps and can develop very high discharge pressures
- Pumps turn fairly slowly (60-300 rpm):
  - Very resistant to damage from solids in a slurry.
  - Not resistant to damage from running dry which is common in gas wells with low amounts of liquid production.
- Variable speed pump-off controls significantly improve run life in gas wells

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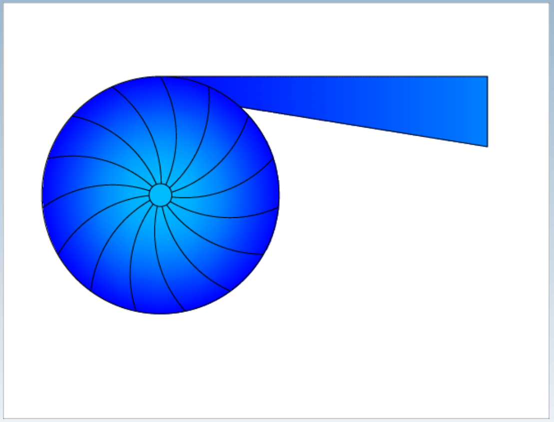
Electric Submersible Pump (ESP)

- Multi-stage centrifugal pump
- The impellor slings water from the eye at the center to the volute at outside edge to trade decreasing pressure for increasing velocity



- The volute has an increasing cross section to trade decreasing velocity for increasing pressure
- Intermediate stages discharge into next stage
- ESP have a narrow flow rate that allows them to function. When the rate falls below that value they stop pumping
- Gas wells tend to produce liquids inconsistently and frequently fall outside the operating envelope of the ESP

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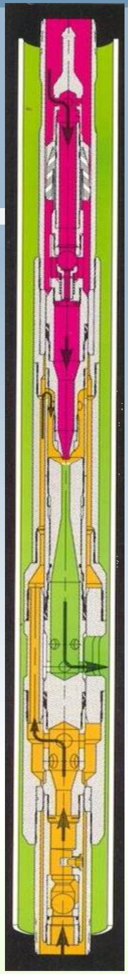
Jet pump

- Transfer some momentum from a "power fluid" to raise the pressure of a "suction fluid"
- Tubing-Free jet pumps
  - Two tubing strings (usually concentric)
  - Power liquid down inner string
  - Well liquid and exhausted power liquid up tubing/tubing annulus
  - Gas production up casing/tubing annulus
- Minimum suction pressure varies by nozzle/throat combination, but it is seldom less than 460 ft [122 m] or 200 psig [1380 kPag]



- High minimum suction pressures result in very high quantities of abandoned gas at the end of life
- Pump can be floated to surface without need for slick-line unit

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Gas Lift

- High pressure/high velocity gas is injected into annulus above a packer through gas-lift valves in tubing
- Very popular in oil operations
  - Hydraulic fluid-level in reservoir tolerates the high minimum BHP achievable
  - Flow interference is minimal when the only gas in the tubing is gas-lift gas

- Rarely successful in gas operations
  - Energy requirements about 5 times larger than SRP and PCP’s
  - Gas wells cannot tolerate very high minimum FBHP-achievable
  - Significant interference between injected gas and produced gas
  - Balance between injection and production VERY sensitive to small changes

Emerging Technologies

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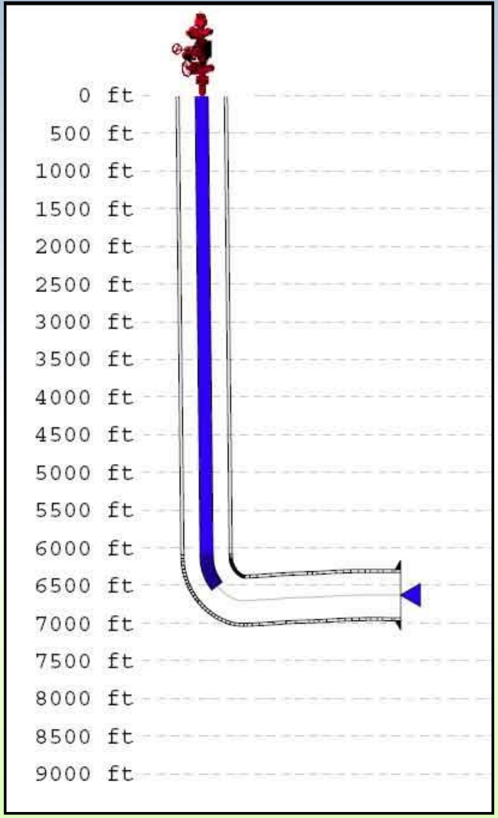
Implications for Horizontal Wells

- Most of today's pumps will not traverse the bend in a horizontal well
- If a pump is set in straight pipe, minimum reservoir pressure is determined by pump technology minimum suction pressure:
  - If a Jet Pump requires 600 ft [183 m] suction pressure, then minimum flowing bottom hole pressure is about 270 psig [1861 kPag] (with zero psig on surface)
  - With 50% drawdown, minimum abandonment pressure is 550 psig [3.8 MPag]
  - In unconventional reservoirs something like 50-75% of OGIP will be left in the ground at 550 psig.
  - Changing from Jet Pump to PCP lowers min suct to around 30 psig [207 kPag], minimum abandonment pressure drops to around 70 psig, [621 kPag] and recovery goes to over 85%.
- Advances in Deliquification technology are underway and more will be required to meet the needs of the industry in the future



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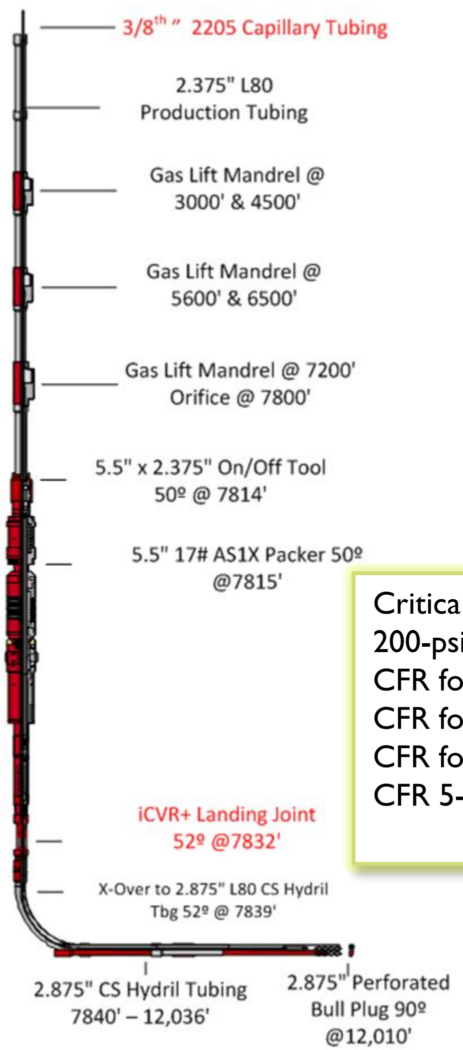
Hybrid Lift Gas Deliquification Example



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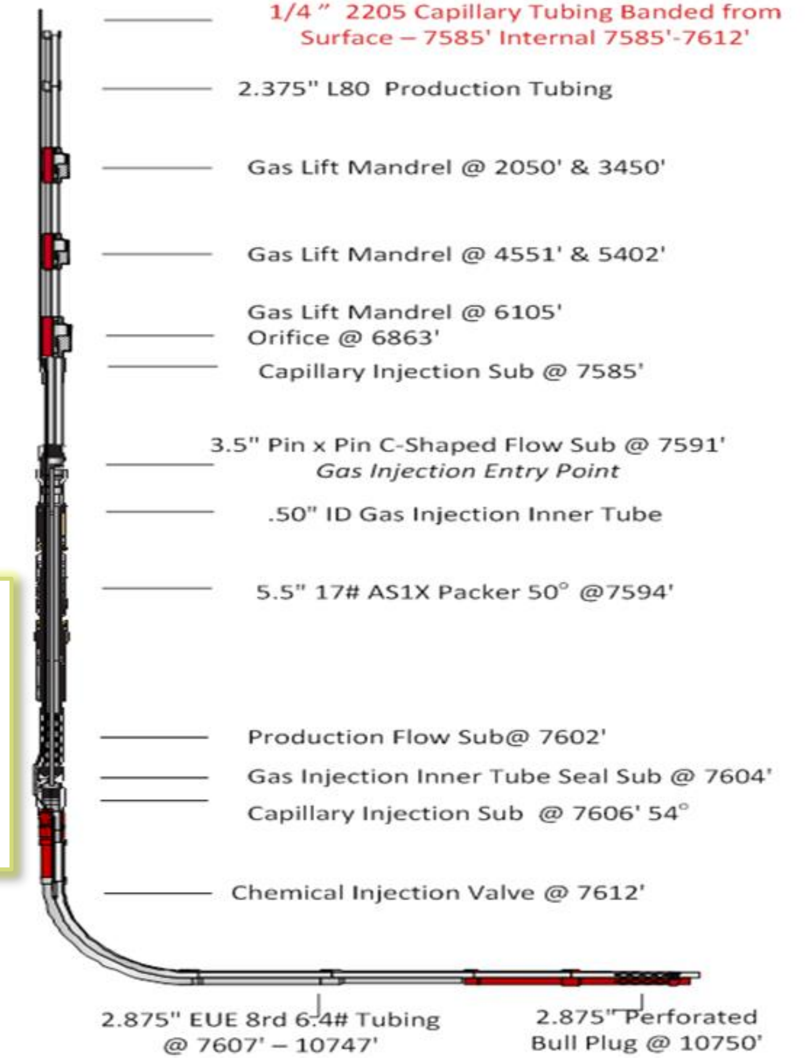
Critical flow requirements for
200-psi WHP in vertical:
CFR for 2-3/8 in. = 406 mcf/d
CFR for 5-1/2 = 2445 mcf/d
CFR for 5-1/2 x 2-3/8 = 1869 mcf/d
CFR 5-1/2 x 2-3/8 = 774 mcf/d foamed



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Emerging Technologies

- Research directions seem to be toward adapting gas-compression equipment to moving liquid
  - Liquid quantities pretty low (5-200 bbl/day [0.8-32 m^3/day])
  - Varying strategies to manage discharge pressure
  - Depth limitations somewhere between 2,500 and 5,300 ft [760 – 1600 m] (but everyone is working on extending this)
- Several people are working on thermocompressors
- Submersible hydraulic pumps that look similar to a reciprocating compressor are becoming available – hydraulic power unit @ surface.
- More research and refinement of technologies is needed before widespread adoption occurs.
- Ongoing improvement of existing technologies is widespread

Deliquification Conclusion

- Deliquification is different from Artificial Lift and it requires different:
  - Tools (gas wells want much more attention)
  - Mind set (e.g., pipeline operation is a valid tool of production, pigging is not a "necessary evil", it is critical)
  - Staffing levels (more stuff to do takes more folks)
- No technology is set-and-forget:
  - Be prepared for any given technology to work or fail to work on any given well (regardless of "similar" wells in the same field)
  - Expect to spend considerable field and engineering effort to "get it right" only to find that as pressures change it doesn't work any more
- The only "silver bullet" for deliquification is great data, appropriate staffing, and a flexible approach

Additional slides

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Plungers

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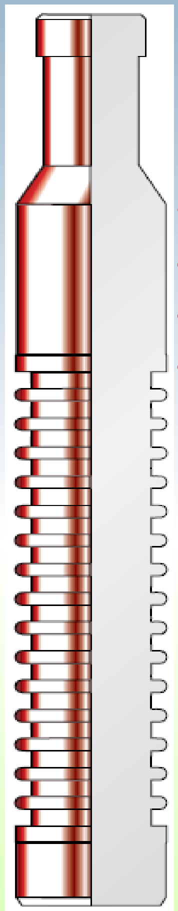
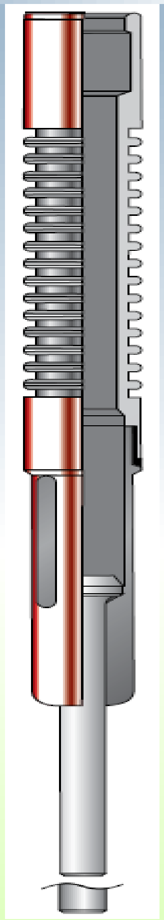


Conventional

- Used on depleted wells
- Shut-in well for plunger to fall
- Gas velocities below 3 m/s
- Fall time average 50 m/min

RapidFlo (Continuous)

- Used at beginning of loading
- Minimal or no shut-in time
- Gas velocities 3 - 4.5 m/s
- Higher amounts of fluid
- Fall time average 250 m/min



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Plunger Types

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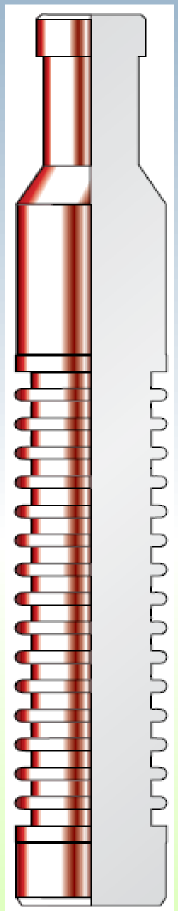
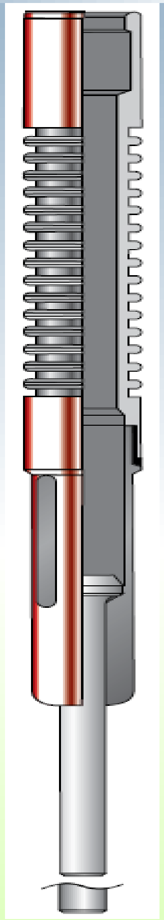


Ring Plunger

- Available in Conventional & RapidFlo
- Common / Very simple
- Longest Life
- Great paraffin handling
- Good scale handling
- Conventional Ring is most inexpensive lift
- Least sealing efficiency (requires higher flow rates)



Plunger Types

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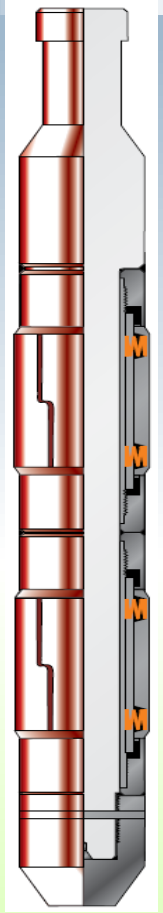
Padded Plunger

- Most popular plunger
- Higher sealing efficiency than Ring Plungers
- Second best longevity
- Available with one, two, or three, sets of sleeves (each sleeve has four pads on it)
- Not good with movement of solids or paraffin



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Plunger Types

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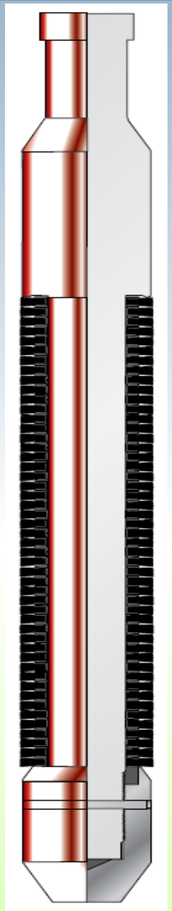

Brush Plunger

- Highest sealing efficiency
- Has application to move solids
- No moving parts
- Has lowest longevity of all plunger types

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Drilling Evaluation Completion Production Intervention

POGO Test Plunger

- **No-Go Shoulder and Bumper Spring Built Into Plunger**
  - Designed For 1 25/32”(1.781”) Pump Seat Nipples
  - Designed for X-Nipple Profiles (1.875”)
  - Plunger No-Go is 1.895”
- **Eliminates Flow Restrictions Over Conventional Springs**
  - Reduced Back Pressure on Formation
  - Eliminated Scale Issues With Conventional Springs
- **All Components Serviceable At Surface**
- **Spirals, Single and Double Pad Plungers Available**
- **Reduced Cost of Test Equipment**
- **Reduced Installation Costs**

Capabilities / Product Offering

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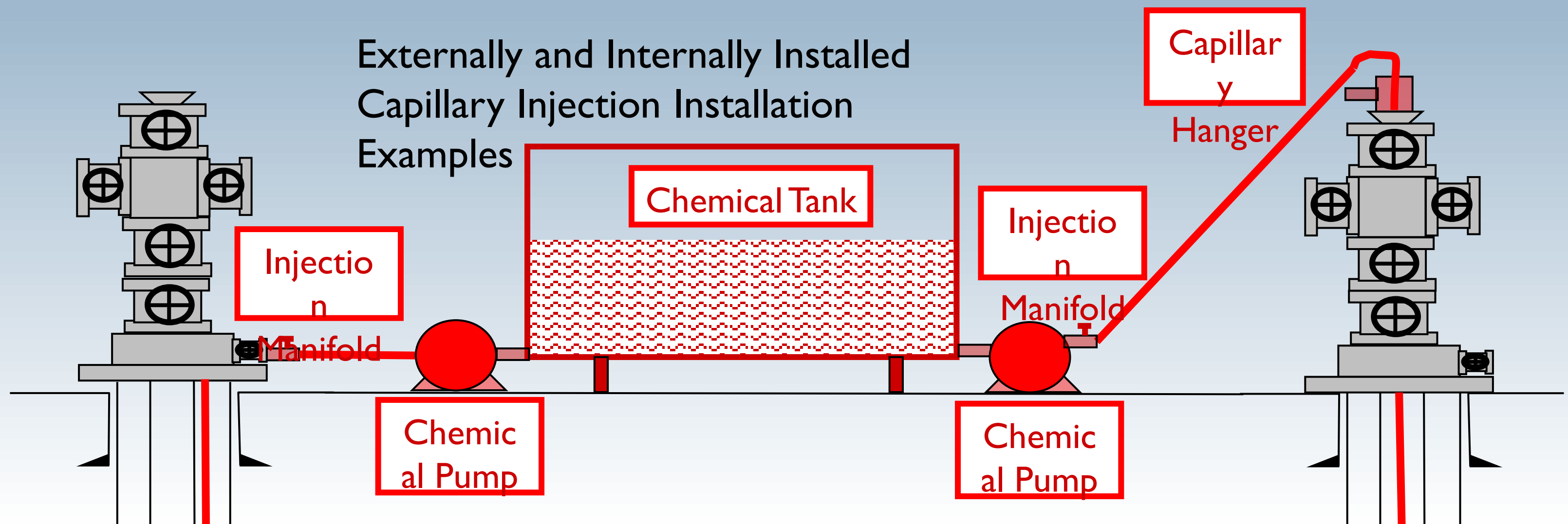
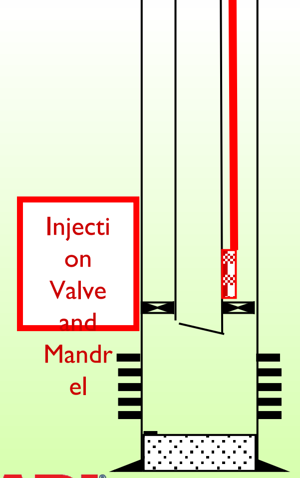
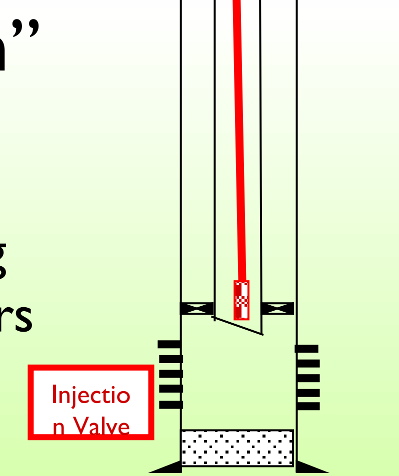
Externally and Internally Installed
Capillary Injection Installation
Examples



"A Chemical Delivery System"

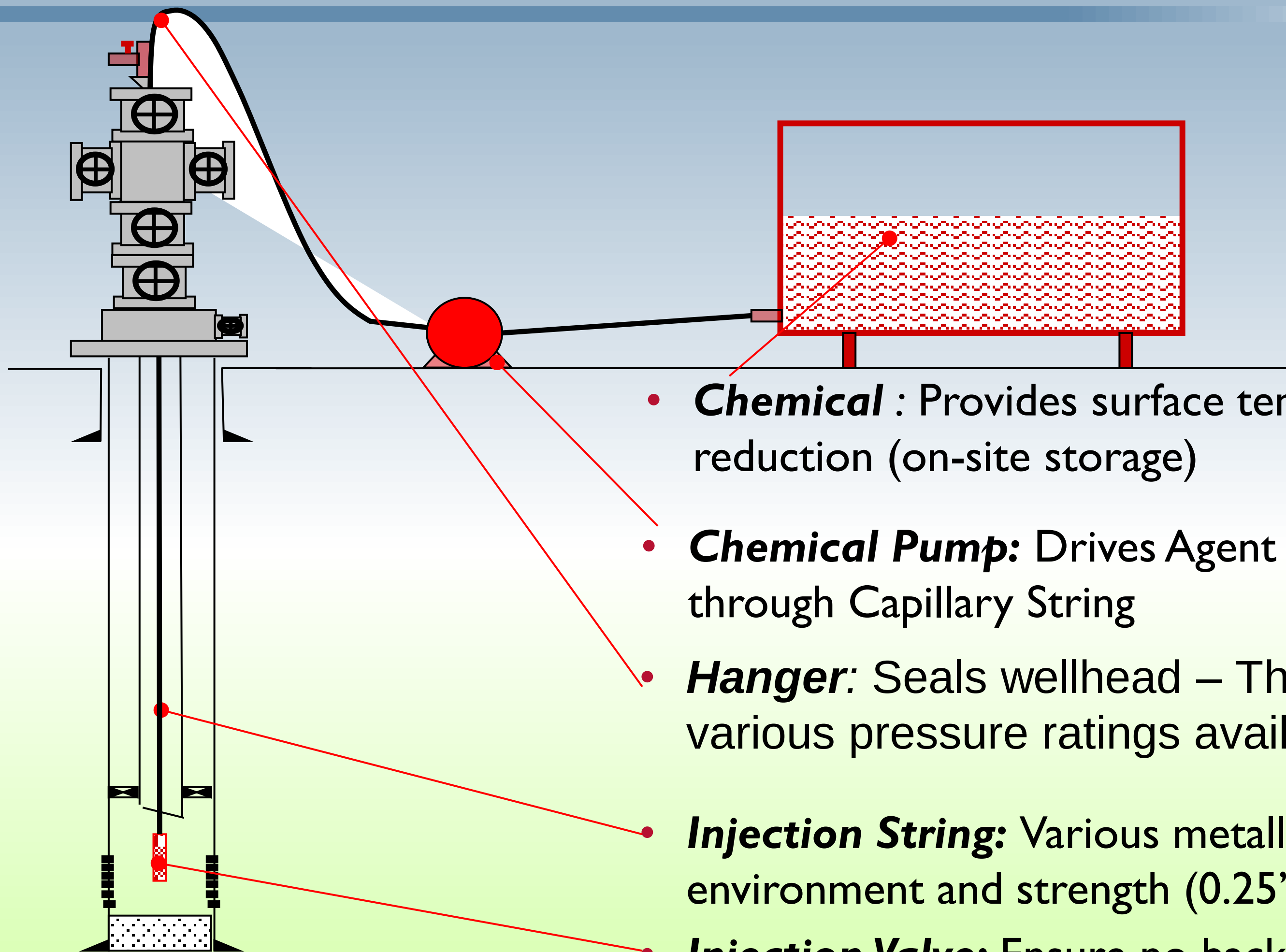
- ¼" or 3/8" Capillary Injection Tubing
- Internally or Externally Installed
- Installed Near End of Production Tubing
- Primarily Used for Foamer and Inhibitors





Courtesy Of Weatherford

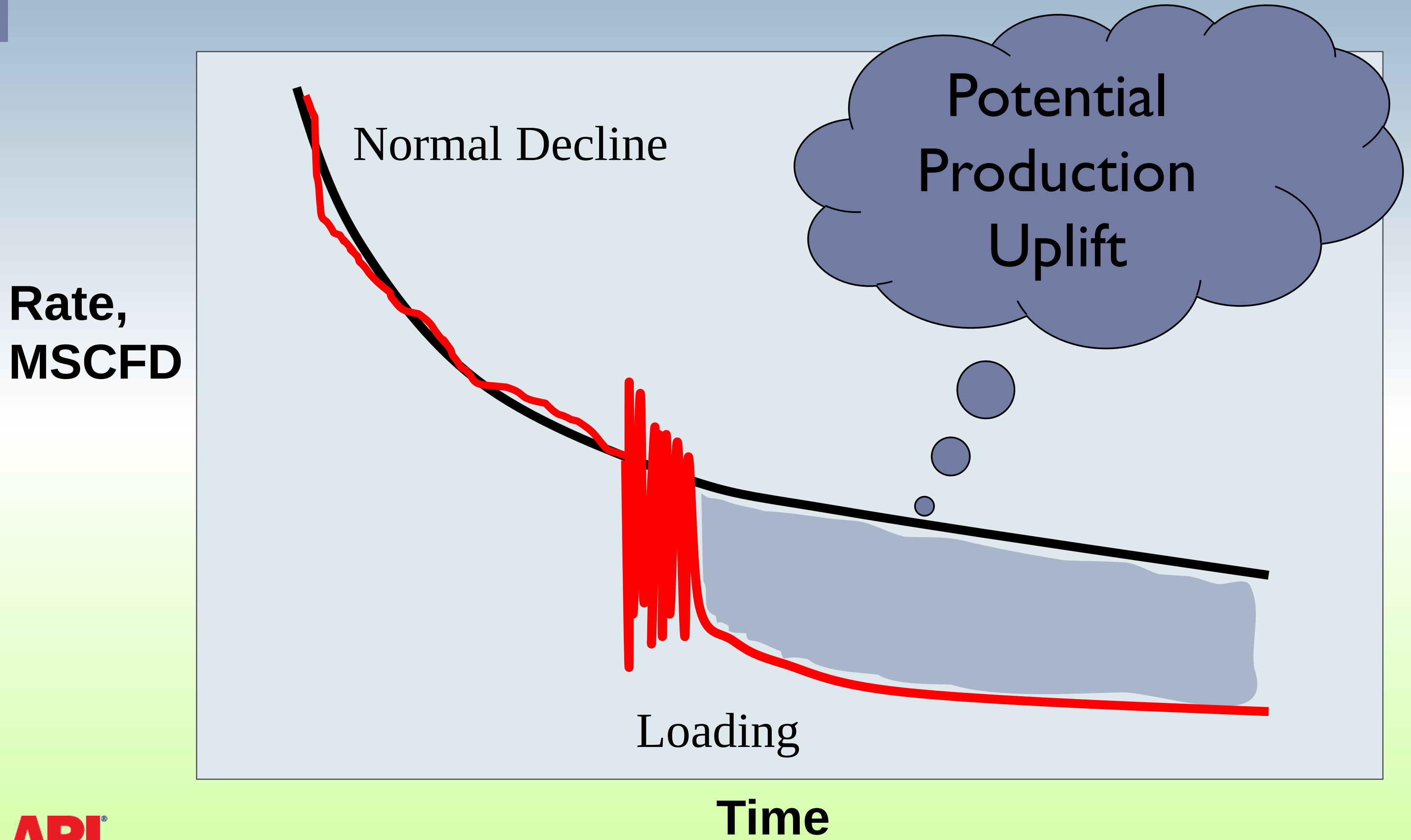
General Summary of Equipment



- ***Chemical*** *:* Provides surface tension and density reduction (on-site storage)
- ***Chemical Pump:*** Drives Agent under Low pressure through Capillary String
- ***Hanger****:* Seals wellhead – Threaded, flanged, various pressure ratings available
- ***Injection String:*** Various metallurgies for environment and strength (0.25" + 0.375" OD)
- ***Injection Valve:*** Ensure no back flow of fluid or gas

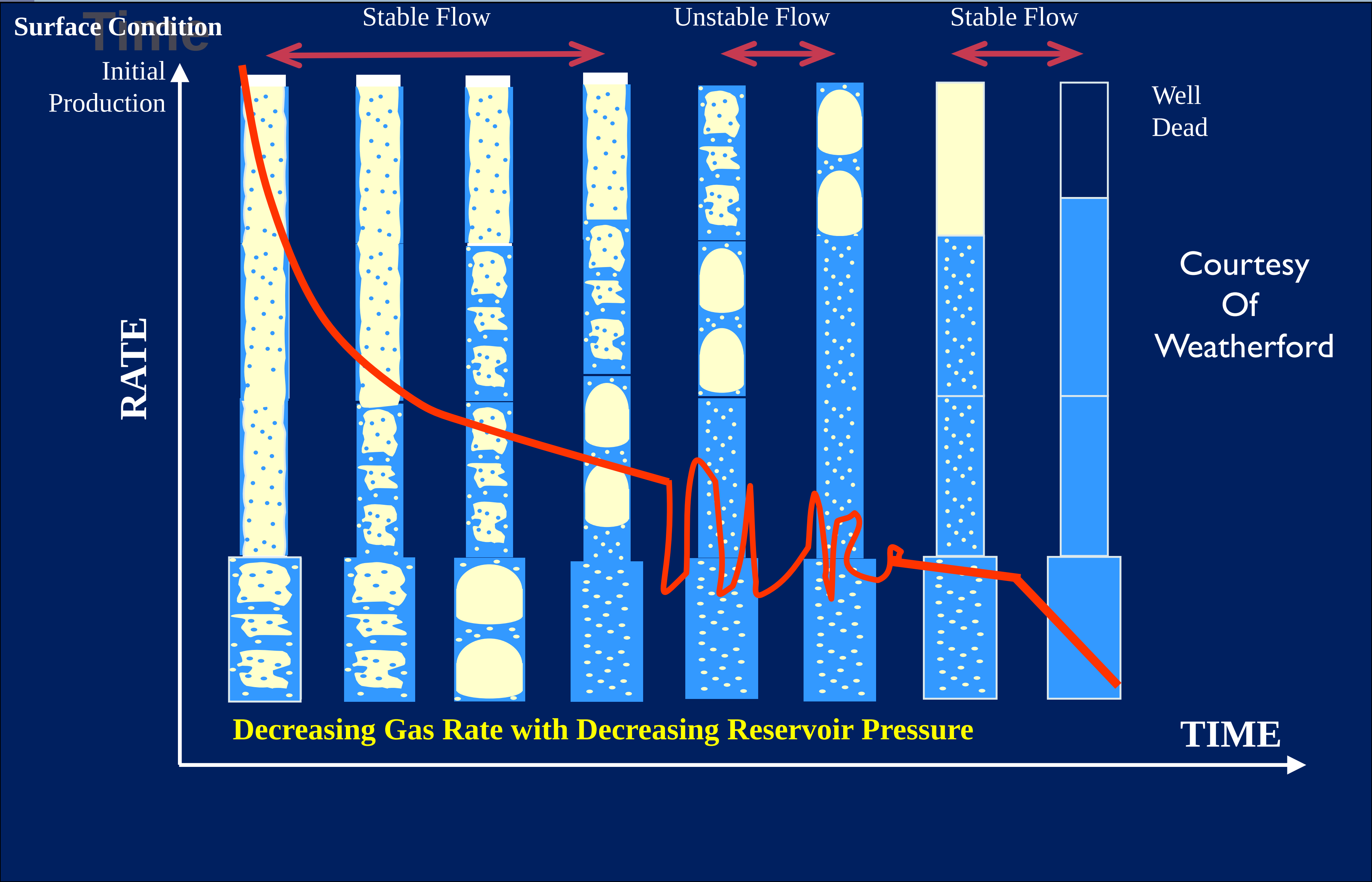
Courtesy Of Weatherford

Effects of Loading on Production Decline



API
American Petroleum Institute

History of a Gas Well – Loss of Velocity Over Time



November 13, 2015

The Honorable Janet McCabe
Acting Assistant Administrator
Office of Air and Radiation
U.S. Environmental Protection Agency

Also via Electronic Mail to methanechallenge@tetratech.com

Re: Comments on the *EPA Natural Gas STAR Methane Challenge Program: Proposed Framework*

Dear Ms. McCabe:

The American Petroleum Institute (API), America's Natural Gas Alliance (ANGA), and the Independent Petroleum Association of America (IPAA) appreciate this opportunity to provide our comments to EPA regarding the Natural Gas STAR Methane Challenge program proposed by EPA on July 23, 2015. We value our long-standing relationship working with EPA on a number of air-related programs and stand ready to help shape a flexible program that achieves EPA's goals while attracting substantial participation from industry partners. EPA has taken into consideration many of the recommendations that we have discussed in past meetings, including the incorporation of a Best Management Practice (BMP) option into the Methane Challenge proposed framework. The BMP option is the preferred option for the majority of our member companies; therefore, the BMP option is the primary focus of the comments contained herein.

Building from the success of the Natural Gas STAR Program and industry's significant accomplishments in reducing methane losses, we remain interested in further addressing methane emissions through voluntary action. We would like to work with EPA to structure a program that is flexible for partners while achieving the aggressive methane reductions that EPA seeks. The limited resources available for companies to invest due to current market conditions should be deployed where the greatest benefit in reductions can be achieved. Providing more flexibility in implementing cost effective emission reductions, especially focusing on sources with the highest reduction potential, will not only achieve EPA's goals more quickly, but could also appeal to more companies. Further, coordination with other regulatory actions, including any Control Techniques Guidelines for the states, could encourage broad industry participation. These key points - flexibility, cost effectiveness, and motivation to participate - are further elucidated in the enclosed responses to EPA's thirteen questions set out in the Methane Challenge proposed framework and the eighteen questions addressing the BMPs.

Once again, we appreciate the opportunity to work with EPA to frame the details for a successful and mutually beneficial methane emissions reduction program that achieves EPA's goals through voluntary measures. We look forward to engaging with you and your staff on these initiatives. Please contact us if you have any questions.

Sincerely,

Howard J. Feldman

Howard J. Feldman
Senior Director, Regulatory and Scientific Affairs
American Petroleum Institute

Erica Bowman
Vice President, Research and Policy Analysis
America's Natural Gas Alliance

Lee O. Fuller

Lee O. Fuller
Executive Vice President
Independent Petroleum Association of America (IPAA)

Enclosures
Cc: Joseph Goffman, US EPA
Paul Gunning, US EPA
Carey Bylin, US EPA

COMMENTER:

American Public Gas Association (APGA)

BEFORE THE

ENVIRONMENTAL PROTECTION AGENCY

WASHINGTON, D.C.

COMMENTS OF THE AMERICAN PUBLIC GAS ASSOCIATION

ON THE

EPA METHANE CHALLENGE PROGRAM

The American Public Gas Association ("APGA") is the national, non-profit association of publicly-owned natural gas distribution systems. APGA was formed in 1961 as a non-profit, non-partisan organization, and currently has over 700 members in 37 states. Overall, there are nearly 1,000 municipally-owned systems in the U.S. serving more than five million customers. Publicly-owned gas systems are not-for-profit retail distribution entities that are owned by, and accountable to, the citizens they serve. They include municipal gas distribution systems, public utility districts, county districts, and other public agencies that have natural gas distribution facilities.

Public gas systems are typically much smaller than

APGA Response to EPA Questions

Following are specific areas in which EPA requested feedback and APGA's comments:

1. Please indicate whether your company has specific interest in one of the commitment options presented, including the possibility or likelihood of your company potentially making that commitment.

The American Public Gas Association ("APGA") is the national, non-profit association of publicly-owned natural gas distribution systems. APGA was formed in 1961 as a non-profit, non-partisan organization, and currently has over 700 members in 37 states. Overall, there are nearly 1,000 municipally-owned systems in the U.S. serving more than five million customers. Publicly-owned gas systems are not-for-profit retail distribution entities that are owned by, and accountable to, the citizens they serve. They include municipal gas distribution systems, public utility districts, county districts, and other public agencies that have natural gas distribution facilities.

Public gas systems tend to be smaller than typical investor-owned utilities. The average public gas system has 5 or fewer employees, approximately 5,000 customers and annual revenues of less than $1 million, the majority of which goes to pay for the gas the utility resells to its customers. Most have no in-house engineering or technical support staff. Most are too small to be required to report estimated methane emissions to EPA under Subpart W. Those that are required to report have found EPA's e-GGRT system daunting.

Many APGA members would potentially commit to one of the commitment options presented if the administrative burden of participating is reasonable for these small systems.

2. In addition to recognition through the Program, what are the key incentives for companies to participate in this Program? Should EPA offer some partners extra recognition, such as awards?

APGA believes potential partners in the Program would like to publicize their participation by being able to link their website to EPA's site for this program. A logo for the program that participants could place on their websites, hard hats, stationary, business cards, etc. A plaque that could be displayed in the utility office or city hall would be good.

3. EPA is proposing to launch the Program with charter partners by the end of 2015, but will welcome new partners on an ongoing basis. Please comment on the likelihood of your company committing to join this Program as a charter partner, or at a future date.

Many APGA members might participate if the program is not administratively burdensome for small utilities.

4. For the BMP option, how can EPA encourage companies to make commitments for sources for which they have not made significant progress in implementing mitigation options? In other words, how can companies be encouraged to participate beyond the sources for which they have already made significant progress?

No comment.

5. Please provide comments on the sources and corresponding BMPs that are provided in Appendix 2, including any recommended additions, deletions, or revisions.

No comment

6. Please comment on the proposed definitions of the companies or entities that will make BMP commitments, per Appendix 3.

EPA has proposed to define NG Distribution as "a local distribution company <u>as regulated by a single state public utility commission</u>." [emphasis added] That definition would exclude the majority of natural gas distribution utilities that are NOT regulated by state public utility commissions. Out of approximately 1,300 natural gas distribution utilities in the US, approximately 1,000 are public gas systems, e.g. owned and operated by local governments such as cities, towns, counties and gas districts. Rates charged by public gas systems are typically approved by the utility's governing body (city council, utility board, etc.) rather than a state PUC. Also, public gas utilities are not "companies."

We suggest changing the definition to read "a local distribution system whose primary business is to deliver natural gas to residential, commercial and industrial gas consumers."

7. Is a 5-year time limit to achieve BMP commitments appropriate? If not, please provide alternate proposals. Would a shorter time limit encourage greater reductions earlier?

5 years is fine.

8. Should EPA offer the ER commitment option? If so, please provide specific recommendations for ways that EPA could address the implementation challenges outlined in this document. What is the minimum target company-specific reduction level that should be set for participation in this option? Would your company use this option if it were offered?

No comment.

9. To what extent is differentiating the voluntary actions from regulatory actions important to stakeholders? What are the potential mechanisms through which the Program could distinguish actions driven by state or federal regulation from those undertaken voluntarily or that go beyond regulatory requirements?

It is not important.

10. EPA plans to leverage existing reported data through the GHGRP (Subpart W) in addition to supplemental data that partners would submit to EPA. Would the e-GGRT system be an appropriate mechanism to collect the voluntary supplemental data?

Many APGA members have found the e-GGRT system daunting. The calculations required to convert miles of main, # of leakers at M&R stations etc. are difficult even for professional engineers to comprehend, let alone public gas systems with no engineering staff. APGA has previously suggested to EPA that e-GGRT should only ask for submission of the population counts and have e-GGRT perform the calculations to convert these counts into estimated metric tons of CO_2 equivalent. E-GGRT would only be appropriate for the methane challenge if EPA simplifies the e-GGRT system as APGA has suggested.

11. Would companies be willing and able to make commitments related to emission sources where EPA has proposed, but not yet finalized, new GHGRP Subpart W requirements?

APGA is not aware of any proposed new GHGRP requirements for natural gas distribution.

12. EPA seeks feedback on potential mechanisms for encouraging continued, active participation in the Program once a company's initial goals have been achieved.

No comment.

13. EPA is proposing to call this new voluntary effort the "Natural Gas STAR Methane Challenge Program", and welcomes comments and suggestions on this name.

No comment.

APGA appreciates the opportunity to comment on this proposal. Any questions concerning these comments should be directed to John Erickson, APGA Vice President, Operations (202-464-0834) or jerickson@apga.org).

Bert Kalisch

Bert Kalisch, President and CEO

COMMENTER:

Berkshire Hathaway Energy Pipeline Group (Berkshire Hathaway)

October 13, 2015

Carey Bylin
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, DC 20460

Submitted via Email to: methanechallenge@tetratech.com

Subject: Berkshire Hathaway Energy Pipeline Group Comments on the EPA's Proposed Natural Gas STAR Methane Challenge Program: Proposed Framework

Dear Ms. Bylin:

Introduction

The Berkshire Hathaway Energy Pipeline Group (BHE Pipeline Group), consisting of Northern Natural Gas (Northern) and Kern River Gas Transmission (Kern River), is pleased to provide comments in response to the request for feedback regarding the U.S. Environmental Protection Agency's (EPA) proposed Natural Gas STAR Methane Challenge Program: Proposed Framework (Methane Challenge Program). Northern operates a natural gas transmission pipeline system, which includes approximately 14,700 miles of pipeline, five natural gas storage facilities and 48 compressor stations (634,810 horsepower) across 11 states. Northern has been an active participant in the Natural Gas STAR Program since 1994. Kern River operates a 1,717-mile natural gas transmission pipeline system, with 11 compressor stations, extending from southwestern Wyoming to Southern California; its system delivers natural gas to markets in Utah, Nevada and California.

General Comments

Northern has participated in the existing Natural Gas STAR Program for a number of years and has been able to save customers money and avoid emissions. We believe that implementation of such programs demonstrates our core principles of environmental respect and operational excellence. At the same time, the BHE Pipeline Group has questions regarding the advancement of the Methane Challenge Program, particularly given the August 18, 2015, release of the Clean Air Act Section 111(b) new source performance standards for the oil and gas sector. Once new source performance standards are promulgated for new and modified sources, the EPA may ultimately be required to propose standards for existing sources under Section 111(d). This is consistent with the approach taken for fossil-fueled electric generating units under the Clean Power Plan. The EPA's use of a 2012 baseline in that circumstance and its preclusion of credit for early action in reducing emissions ultimately penalized early and voluntary actions. While the BHE Pipeline Group supports voluntary action to reduce or avoid greenhouse gas emissions, we do not support the advancement of programs that, in the end, only penalize those who take early and voluntary action.

Specific Comments

1. Confidential or Sensitive Information Not Protected

The EPA stated that a principal goal of the Methane Challenge Program is to transparently demonstrate partner company commitments and progress, including publication of progress data, and proposes to implement a public platform managed by the EPA. Our comment to this goal is that partner companies should have the ability to identify information that should not be published, including data that it wishes to remain confidential in order to protect its assets and customer interests.

2. Use of eGGRT for Reporting Flaws Data Analysis

The EPA is proposing that annual data be reported utilizing the EPA's electronic Greenhouse Gas Reporting Tool (eGGRT) currently utilized for the Greenhouse Gas Reporting Program (GHGRP) since Subpart W of the EPA's GHGRP already collects information that would be relevant to the Methane Challenge Program. Our comment to this provision is that reporting via eGGRT would not sufficiently protect the information since eGGRT can be accessed by the public.

In addition, much of the current data collected in eGGRT is based on required EPA emissions factors and not actual measured emissions. Many current methane tracking and reduction programs are based on measured data, and methodologies should be aligned between existing and proposed programs. The reporting and publication of the incongruous data would likely result in inaccurate and misleading inferences drawn by stakeholders and the public.

Emissions factors the EPA incorporated in the GHGRP have changed since the programs implementation, resulting in incomparable and or inconsistent emissions results between reporting years, making it more difficult to demonstrate emissions reductions. Changes in emissions factors, which are outside the control of the reporting entity and solely within the control of the EPA create a significant potential for misinterpretation of actual emissions and emissions reduction progress by stakeholders and the public.

3. More Details Are Required

BHE Pipeline Group supports voluntary action to reduce or avoid greenhouse gas emissions, as evidenced by Northern's 20+ year participation in the Natural Gas Star Program. With that said, information provided for the Methane Challenge Program is at this point vague and does not impart the level of detail needed to determine if this would be an appropriate commitment. Among the stated goals is for the program to be "ambitious" and to prescribe accountability for making and achieving commitments; however, goals have not been defined and measures on how to achieve goals have not been provided. The program also proposes that a memorandum of understanding would be entered into between the participant and the EPA and the contents and objectives of the proposed memorandum of understanding have not been defined. Without specific information regarding the proposed memorandum of understanding's provisions, it is not possible to determine if the expectations of the Methane Challenge Program will be achievable, or if a partnership should be considered.

Conclusion

The BHE Pipeline Group appreciates the opportunity to provide comments on the EPA Methane Challenge Program. The BHE Pipeline Group comments are intended to seek additional data protection and project clarification. If you have any question or concerns, please feel free to contact me at (563) 333-8009 or cswoollums@berkshirehathawayenergyco.com.

Sincerely,

Cathy Woollums
Sr. Vice President, Environmental and
Chief Environmental Counsel
Berkshire Hathaway Energy
106 E. Second Street
Davenport, IA 52801

COMMENTER:

California Public Utilities Commission

Comments:

In 2014, the California State legislature passed Senate Bill 1371 which tasks the California Public Utilities Commission with the development of a program to address fugitive methane emissions from California's natural gas transmission and distribution systems. This will entail developing a leak detection and repair program as well as new monitoring and reporting requirements. These efforts seem very similar to the Methane Challenge. Would EPA be interested in partnering with the State of California to develop both programs concurrently?

COMMENTER:

Clean Air Task Force (CATF) & Natural Resources Defense Council (NRDC)

November 13, 2015

Carey Bylin
Natural Gas STAR Methane Challenge Program

Re: Comments of Clean Air Task Force and Natural Resources Defense Council on Proposed EPA Natural Gas STAR Methane Challenge Program

The Clean Air Task Force and Natural Resources Defense Council are pleased to submit comments on the proposed EPA Natural Gas STAR Methane Challenge Program. The Methane Challenge Program should be as strong and transparent as possible. Our comments focus on the following topics: (1) the limitations of the One Future Program Emission Intensity Commitment, (2) the importance of transparency, (3) the need for continuous improvement, (4) the potential of the Emissions Reduction Commitment Option, and (5) a number of specific issues with the proposed Best Management Practice Commitment Option.

At the outset, we stress that the Methane Challenge Program—or any voluntary methane reduction program—does not reduce the need or legal obligation to adopt enforceable federal standards comprehensively covering existing sources of methane in the oil and gas sector nationwide. Existing sources of methane in the oil and gas sector account for about 7 million tons of methane pollution under current estimates. Once EPA adopts standards of performance to address new and modified sources of methane pollution in the sector, as it has proposed to do, the agency has an obligation to put in place a process for controlling existing sources under section 111 of the Clean Air Act. *See* 42 U.S.C. § 7411(b) and (d). Practically speaking, the number of sources that participate—and thus the magnitude of reductions achieved—under a voluntary program will almost certainly pale in comparison to what can be achieved under federally enforceable performance standards for existing sources.

That said, a voluntary program can play a role in addressing methane pollution if it rapidly drives innovation, reduces actual emissions, and provides more detailed information on emissions, reduction potentials, costs, and implementation issues. To these ends, we support EPA's commitment to an enhanced voluntary program for methane from the oil and gas sector, with its goals of creating a program that is ambitious and achieves meaningful reductions, is transparent, and demonstrates continuous improvement.

(1) The limitations of the One Future Program Emission Intensity Commitment

As currently described in public materials, the One Future program is inconsistent with EPA's stated purpose behind the Methane Challenge, i.e., "to provide a new mechanism through which companies [can] make and track *ambitious* commitments to reduce methane emissions,"[1] due to an unambitious intensity goal coupled with an unambitious timeline for achieving that goal. By committing to achieve a modest intensity reduction from an alleged current 1.3 percent leakage rate to 1 percent and giving participants nearly a decade to do so, One Future will not necessarily address participants' methane emissions from existing sources or reduce methane pollution (in absolute terms) below participants' current levels.[2] For this reason and others, EPA should not recognize participation in the One Future program as participation in the Methane Challenge Program, or should at least require a more ambitious leak rate commitment and/or deadline.

[1] Methane Challenge at 3 (emphasis added).

[2] While the alleged 1.3 percent leak rate is likely an underestimate, this is the rate that One Future used to calculate its one percent goal, *see* One Future: *Our Goal: 99 Percent Efficiency* (available at http://www.onefuture.us/our-goal/) (Assuming that "industry's current rate of emissions is equal to approximately 1.3 percent of gross natural gas production"), and is thus illustrative of the low ambition of One Future, and the lack of evidence that participation in One Future will motivate significant pollution reductions. As noted below, if EPA chooses to recognize the One Future program in the Methane Challenge, it must hold participants to the one percent goal of One Future, even if further information (such as previously unidentified sources of methane emissions) comes to light that makes achieving this goal more difficult.

It is well established that methane emissions originating from sources currently in operation will comprise the overwhelming majority of the sector's methane pollution for many years. Thus, if One Future participants were to commit to achieving the program's modest leakage rate reduction over the next few years (say by 2017 or 2018), participants who currently emit above the One Future threshold for their industry segment would likely have to address their existing sources. But by giving participants until 2025 for meeting their goal, One Future's intensity rate would allow operators to ignore that problem while at the same time *increasing* emissions by expanding production over the coming years. An intensity rate target allows companies that experience growth to rely on new sources – many of which must comply with EPA methane performance standards (if finalized) – as a means to lower their overall intensity rate without actually reducing emissions from their existing sources. Companies could not only ignore the emissions that are causing a problem today, but also increase their total emissions, all while receiving positive recognition under the Methane Challenge Program for doing so.

Thus a possible route of "compliance" with One Future would play out in the following manner**.** ***First***, the owner/operator would focus on growth in production. ***Second***, new methane standards of performance would require sources that are installed or constructed as a result of the growth to comply with more stringent controls or work practices than the company currently utilizes, thereby reducing the company's overall emissions intensity rate. ***Third***, because of compliance with these standards, and without addressing any of the emissions from existing sources, the company would receive recognition as a participant in the Methane Challenge Program.[3]

In other words, a company with increasing production that complies with finalized methane standards of performance may very well *not* reduce actual emissions, and yet still be recognized as a company that "truly want[s] to excel and differentiate" itself.[4] This scenario is not far fetched; One Future's website notes that a primary reason for focusing on the *rate* of emissions instead of the total volume is because the member companies are "focused on achieving growth."[5] Thus, the unambitious intensity rate focus of One Future is inconsistent with the Methane Challenge Program's goal to reduce methane pollution.

Additional critiques of One Future are as follows:

- Only emission sources located in the natural gas sector are included in the calculation of the one percent target; methane emissions sources in the oil sector are ignored. According to the GHG Inventory, methane emissions from the upstream oil segment totaled over 968,000 metric tons in 2013, and there is no evidence that the One Future program will directly address these emissions. Additionally, a recent analysis found that methane emissions from oil and gas activities are projected to grow 4.5% from 2011 to 2018 and that all of the projected net growth is from the oil sector.[6]

- The structure of One Future provides no means for promotion or recognition of continuous improvement. The notion seems to be that one percent emissions is "good enough," and further improvement of environmental performance is not needed. A number of companies are (likely) already achieving an emissions rate which will meet the One Future intensity emissions rate goal for their segment, and the program gives them little to no incentive to continuously improve.

In sum, the One Future approach is not consistent with the goals of Methane Challenge, the Obama Administration and the EPA's stated goals for abatement of methane pollution, or the substantial reductions in climate pollution that are called for in light of the urgency of threats to public health and welfare from greenhouse gases. A number of studies have shown that methane pollution from oil and gas can be dramatically reduced (by more than 40%) in a few years at very low cost with straightforward, nationally applied enforceable emission standards. Given this,

[3] We note that achieving intensity rate reductions via compliance with the section 111 standards under consideration also will not drive innovation beyond that already incentivized/recognized by the proposed standards.
[4] Methane Challenge at 3.
[5] One Future (available at http://www.onefuture.us/faqs/).
[6] ICF International. 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries.

One Future's unambitious single goal of reducing the emissions rate to one percent over a decade does not rise to a level that EPA should recognize through the Methane Challenge Program.

If EPA is to retain One Future as a component of the Methane Challenge Program, we recommend the following improvements:

- Adopt a more ambitious intensity rate target or targets to be met over time
- Move up the deadline for achieving the target intensity rate
- Require yearly measurement and reporting of emissions from individual facilities, and other measures in line with the transparency goals of the Methane Challenge (and discussed below), before and after companies achieve emissions intensity rates complying with the One Future program thresholds.
- Require that One Future participants commit to reaching the emissions intensity thresholds for their segments even if new sources of emissions are identified that could make achieving the emissions intensity threshold more challenging
- Provide means to handle companies whose emissions rise above the One Future emissions intensity threshold after the deadline year (such as moving a company to provisional status). In addition to moving the company to provisional status, continued recognition by the Methane Challenge program should only be granted if companies provide information on how they will reduce emissions and avoid future emissions above the threshold.

(2) The Importance of Transparency

The Methane Challenge Program must be grounded in transparent and granular data. With its release of the "Methane Challenge Program: Supplemental Technical Information," the EPA has taken steps to make its data collection process transparent and clear. However, we have comments about the general reporting method and some specific data elements.[7]

a. Distinguishing regulatory reductions from voluntary reductions

Companies should be required to fully document all the actions they take to comply with the Best Management Practice (BMP) option. These voluntary actions should be clearly distinguished from actions the company takes to comply with EPA, BLM, state, or other regulatory requirements. As such, on page 4 of the Supplementary Technical Information, EPA states that it will collect information on "[a]pplicable air regulations for included facilities, including a listing of the sources covered in the partner's Methane Challenge commitment that are affected by each regulation."[8] Later, in the Reporting sections of the Description of Emissions Sources, the EPA proposes to collect data on "[v]oluntary action to reduce methane emissions during the reporting year."[9] EPA should also collect data on actions taken or equipment replaced to comply with applicable regulations. This is data that companies already have, so compilation and reporting will take minimal effort. Such effort is justified, as this information will significantly improve stakeholders' ability to compare the impacts of voluntary efforts with the impacts of regulatory actions.

b. Report cost information

The EPA has stated repeatedly that it hopes that the Methane Challenge Program will be an opportunity for learning and sharing information about best management practices. However, cost data - which would be instrumental in aiding this learning process - is missing from the program. Companies participating in the Methane Challenge Program should be required to report on the costs of implementing the BMPs. We suggest that this reporting take the form of annualized costs averaged across the entire facility for each form of compliance. For example, reflecting the proposed reporting format, a company choosing to adopt the pneumatic controller BMP

[7] We provide granular comments on reporting requirements in section (5) where we discuss individual BMPs.
[8] Methane Challenge Program: Supplementary Technical Information at 4.
[9] Methane Challenge Program: Supplementary Technical Information at 6, 8, 9, 11, 13, 14, 15, 17, 18, 20.

for the production segment would report three cost figures: "Average annualized cost of converting high-bleed to low-bleed," "Average annualized cost of converting high-bleed to zero emitting or removed from service," and "Average annualized cost of converting low-bleed to zero emitting or removed from service."[10]

c. Require direct emission measurement

The Methane Challenge Program should not solely rely on the standard emission factors as currently allowed for many sources in the Greenhouse Gas Reporting Program's Subpart W. In many cases, these standard emission factors are outdated or flawed. For example, the program will allow emissions from pneumatic controllers to be quantified using Subpart W's Standard Emission Factors. While it remains very clear that replacing high-bleed controllers with low-bleed controllers substantially reduces emissions, several recent studies have reported that average emissions from low-bleed controllers are higher than the emissions factor for low-bleed controllers used in the Greenhouse Gas Reporting Program.[11] This means that although replacing high-bleed controllers will reduce emissions, actual emissions after replacement may be higher than calculated emissions.. As such, using these inaccurate emissions factors could overestimate the effectiveness of the Methane Challenge Program. Recent studies have also shown that there is a high level of heterogeneity in the emissions from devices within a class, depending on the specific type of service in which the controller is employed.

EPA should replace these standard emission factors with direct emissions measurement, which can be phased in over time if needed. In any case, a full measurement approach should be in place by the end of the company's 5-year BMP implementation period.[12]

d. Additional reporting for Onshore Production

The EPA has stated that for reporting purposes, it "intends to utilize the same segment and facility definitions as Subpart W."[13] While this simplifies both the reporting and interpretation of data, the approach will lead to insufficient granularity of data reported in the Onshore Production segment. Because companies are required to report on all data associated with a given emissions source located in an entire hydrocarbon basin, it is difficult to discern the emissions of individual sites within the respective basins. The EPA should require more specific supplemental information for companies adopting BMPs in the Onshore Production segment, preferably at the well pad level.

(3) The Need for Continuous Improvement

Participants in the Methane Challenge Program should be striving for best management practices at their operations. Over time, costs will decline and technologies will advance.

We recommend a biennial review process, in which all aspects of the BMPs are reviewed in light of new data. Companies that commit to a BMP would be able to "lock in" the requirements that are in place when they make the commitment for the entire 5-year duration of their commitment. But, if they wish to remain in the program

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[10] Methane Challenge Program: Supplementary Technical Information at 6. Below, in our comments on the pneumatic controller BMP, we discuss the importance of including intermittent controllers as well. If these controllers are added to the BMP, it would add 4 additional reporting categories: "Number of intermittent-bleed controllers converted to low-bleed", "Number of intermittent-bleed controllers converted to zero emitting or removed from service", "Average annualized cost of converting intermittent-bleed to low-bleed", "Average annualized cost of converting intermittent-bleed to zero emitting or removed from service".

[11] See Allen, D.T., *et al.* (2013), "Measurements of methane emissions at natural gas production sites in the United States," *Proc. Natl. Acad. Sci. USA* **110,** 17768–17773; Allen D.T. *et al.* (2015), "Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers," *Environ. Sci. Technol*. **49**, 633–640.

[12] We note that requiring direct measurement from the start – including on the older, higher emitting devices – will yield highly useful information on the amount of emission reduction achieved by BMPs, beyond the baseline goal of the BMP Program of implementing the BMPs.

[13] Methane Challenge Program: Supplementary Technical Information at 4-5.

after this initial 5-year commitment period, they would have to commit to the adoption of the revised best management practices. Such an approach can better ensure that the practices recognized by the Methane Challenge Program advance over time so that they remain truly "best" practices.

(4) The Potential of the Emissions Reduction Commitment Option

We support inclusion of the Emission Reduction (ER) Commitment Option because it has advantages over both the One Future Option and the Best Management Practice Commitment Option. Under the ER option, companies would commit to absolute methane emission reductions, as opposed to an intensity reduction that could allow emissions to increase as production increases (as in the One Future option). The approach thus would more clearly achieve methane emission reductions from current levels. In addition, the ER option would ensure that companies develop a company-wide methane emissions reductions plan, rather than limiting their commitment to a few isolated best management practice technologies (as in the BMP option). From a company perspective, the flexibility to set a customized, company-wide goal may have significant appeal.

The Emission Reduction Commitment Option also has transparency advantages over both the One Future and BMP Commitment Options when it comes to meeting our country's greenhouse gas reduction goals. It is easier to see overall progress toward reaching a methane reduction goal such as the President's 40-45 percent from 2012 levels by 2025 when the goal is based on actual emissions, as opposed to an emissions intensity goal or individual piecemeal goals for various technologies.

In light of these benefits of the approach, we respond to the concerns that the EPA raised about implementing the ER approach, specifically that:

> *Any changes to a company's operations would need to be accounted for in an adjusted baseline, and tracking and adjusting the baseline operations and emissions could present a significant challenge, particularly in the upstream sector where acquisitions and divestitures of assets occur on a regular basis.*

Companies are well versed in keeping track of changes in their operations that result from acquisitions and divestitures in their financial statements, and we do not think it would be substantially more difficult to update their methane emissions accounting records than it is to update their financial accounting records. The Emission Reduction commitment should include provisions to allow companies to adjust their emissions baseline to reflect such changes in the company's operations.

> *EPA has already received feedback that an ER commitment could be problematic for companies that seek to expand their operations.*

As noted above, companies already have tools that allow them to account for emissions changes that result from acquisitions or divestitures. But, a company's operations may also expand through natural growth in the absence of acquisitions. Such growth could result in higher levels of production, and potentially higher levels of methane emissions. However, if the goal of the Methane Challenge Program is to be truly ambitious, it should aim to reduce absolute levels of methane emissions, not simply to reduce methane emissions as a share of natural gas production. Yes, this makes the ER Commitment more stringent than the One Future Commitment - but such relative stringency is exactly why this approach is needed. Relatedly, having to plan expansion in light of a methane emission reduction commitment could better drive innovation than either the One Future or BMP approaches.

> *Some stakeholders mentioned that the inclusion of voluntary supplemental data (e.g. for facilities below the GHGRP's reporting threshold of 25,000 metric tons CO_2e per year) will mean that companies participating in the Program may show higher total emissions levels relative to their counterparts who are not participating in the Program.*

We agree that companies should not be penalized for reporting emissions from facilities emitting below 25,000 metric tons CO2e per year to the Methane Challenge Program. However, we do not consider this to be a major problem. When companies report emissions from facilities that have emissions below the GHGRP threshold, reports of emissions from these facilities should be flagged so their emissions can be separated from emissions from facilities that are above the GHGRP threshold. As long as this distinction is made clear, we do not see significant harm associated with this additional reporting. The omission of smaller facilities from the Subpart W requirements is well understood and recognized, and the reputational benefit of participating in the Methane Challenge Program would far outweigh any concern about higher levels of reported emissions. Indeed, some entities including investors may more favorably consider a company that discloses (and commits to reduce) methane emissions from sources emitting under 25,000 tons CO2e per year, as compared to other, non-participating companies.

(5) Specifics of the Best Management Practice Commitment Option

a. General comments on BMPs

We are concerned that the piecemeal nature of the BMP Commitment option will allow companies to take credit for participating in the Methane Challenge Program while only reducing a small amount of methane emissions. As it stands now, a company could adopt as few as one BMP and get credit through the program. There should be a minimum required set of the number of BMPs adopted, or minimum potential emission reductions associated with the BMPs adopted (either in absolute terms or as a percent of total company methane emissions).

The EPA has stated that it is considering allowing participating companies to request an exemption to full implementation of the BMP. We do not think that this exemption is appropriate. If the company is unable to meet the BMP goals, its status in the Methane Challenge Program should be marked as "Provisional" until the company is able to attain full compliance. We note that for many emissions sources included in the BMP Commitment option, there are multiple technologies or strategies available to reduce emissions. BMPs should allow the use of all qualifying methods for reducing emissions in order to maximize emission reductions while providing flexibility for participating companies to select the most appropriate abatement option. For example, emissions can be reduced from reciprocating compressor seals by monitoring vents and replacing rod packing when venting exceeds a threshold, by adding gas that would be vented from rod packing to the fuel or air intake for the compressor engine, or potentially by routing the emissions to a VRU controlling emissions from a tank or other potential emissions source on the site. A similar range of options exists for other sources. In light of these options, and the proven success of existing source *standards* in Colorado and Wyoming (where few, if any, exceptions have even been *requested* to broadly applicable requirements to reduce emissions from existing equipment),[14] it would be inappropriate for EPA to grant exemptions to full implementation of the BMPs.

We are concerned that companies may only sign up for BMPs for sources from which they have already significantly reduced emissions. Thus, the commitments may represent past emissions reductions rather than new emissions reductions. While there is value in recognizing firms which have already implemented emissions reductions programs, the Methane Challenge Program intends to promote continuous improvement in performance. Furthermore, it is valuable to understand the timeline for emissions reductions and differentiate emissions reductions due to regulations. In their initial proposal to join the program, companies must describe and quantify their progress to date toward the BMP and demonstrate how participation in the Methane Challenge Program will result in new and additional methane reductions.

The issue of "progress to date" should also be part of the time allowed to achieve the BMP commitment. The current proposal allows up to 5 years for all BMPs. However, if a company has already implemented the BMP at a portion of its operations, it should not need the entire 5-year period to complete its work. Thus, the maximum allowable time period should be tied to how close the company is to achieving the BMP at the time of application. (RESPONSE TO EPA QUESTION #18)

[14] McCabe, David, et al. "Waste Not: Common Sense Ways to Reduce Methane Pollution from the Oil and Natural Gas Industry." January 2015. Pg. 26. Available at: http://www.catf.us/resources/publications/files/WasteNot.pdf.

As discussed in a previous section, it is very important to distinguish between emission reductions that result from regulatory requirements (state and federal) and emissions from these voluntary actions. EPA must ensure that the Methane Challenge Program requirements exceed all existing federal and state regulations.

Below, we provide specific comments on the mitigation options that constitute the proposed BMPs:

Onshore Production and Gathering and Boosting

- Pneumatic Controllers

An additional option should be added: "Utilize a closed-loop system to capture vented natural gas from gas-actuated pneumatic controllers and route this gas to a process or capture system."

Both replacement with low-bleed and replacement with zero-emitting controllers are defined as equal mitigation options in the proposal. The Methane Challenge Program should be more aggressive about requiring zero-emitting pneumatic controllers, or routing of emissions from low-bleed controllers to a process or capture system, such as an on-site VRU. It should require zero-emitting devices for all sites with grid access or closed-loop capture systems for all facilities that already have a capture system on site.

EPA states that "Intermittent bleed pneumatic controllers are not included in this source category."[15] This is inappropriate given the large amount of emissions that are currently vented from intermittent bleed controllers. Intermittent bleed pneumatic controllers can either be high-emitting (over 6 standard cubic feet per hour (scfh) averaged over a period long enough to capture a representative actuation cycle) or low-emitting (under 6 scfh). In order to comply with this BMP, EPA should ensure that an owner/operator's intermittent-bleed devices are low-emitting, that the owner/operator replaces intermittent-bleed devices with zero-emitting options, or that emissions from intermittent-bleed controllers are routed to a process or capture system, such as an on-site VRU. (RESPONSE TO EPA QUESTION #2)

Finally, pneumatic controllers exhibit a large amount of emissions heterogeneity. This heterogeneity is due to the specific type of service in which the controller is employed, and it also results from malfunctioning equipment. Thus, a crucial aspect of the pneumatic controller BMP must be direct measurement and monitoring of gas-actuated pneumatic controllers, for example as an aspect of leak detection and repair programs. This will ensure that controllers advertised as "low-bleed" that vent to the atmosphere are actually emitting under 6 scfh.

- Equipment Leaks/Fugitive Emissions

EPA has stated that due to the potential for overlap of this emissions source with on-going regulatory actions, including the proposed updates to NSPS and draft Control Techniques Guidelines, the BMP proposal for this source will be phased in at a later date. It stated that it intends to specify mitigation options that are consistent with regulatory approaches, with greater flexibility included in the voluntary Program as needed. This may suggest that the EPA intends to make the BMP for this category looser than whatever will be in the final NSPS. In order to fulfill the goals of the Methane Challenge Program, the BMPs for Fugitive Emissions must reflect leading practice and therefore they must be more environmentally protective than the requirements in the proposed regulation.

The BMP for a leak detection program should require that companies commit to fixed frequency monitoring and that companies repair all leaks found within a certain number of days. Inspections should be performed frequently. Following recent regulatory precedent from Colorado and Wyoming, EPA should consider monthly frequency for production sites and compressor stations to be best practice, particularly for larger facilities. Repairs should be completed within 15 days.

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[15] Methane Challenge Program: Supplementary Technical Information at 6.

- Liquids Unloading

The Supplemental Technical document lists several technologies that can be used to reduce venting from liquids unloading: plunger lifts and smart well automation; swabbing the well to remove accumulated fluids; installing velocity tubing; and installing artificial lift systems. Companies should be required to report emission reductions associated with each of these technologies separately (as opposed to simply the overall emission reduction).

The second option listed, "Track and report emissions for all wells conducting liquids unloading…"[16], should not be considered a BMP. Companies should be encouraged to track and report this information, but this should not be counted at the same level as actually minimizing venting.

The EPA should also consider setting an emissions target for wells that vent from liquids unloading. We suggest a threshold of less than 100 Mcf/well for all wells that unload, based on 2013 Subpart W data.

- Pneumatic Pumps (only Chemical Injection Pumps (CIP))

EPA has stated that due to the potential for overlap of this emissions source with on-going regulatory actions, including the proposed updates to NSPS and draft Control Techniques Guidelines, the BMP proposal for this source will be phased in at a later date.[17] It stated that it intends to specify mitigation options that are consistent with regulatory approaches, with greater flexibility included in the voluntary Program as needed. This may suggest that the EPA intends to make the BMP for this category looser than whatever will be in the final NSPS. As noted above for leak detection and repair, in order to fulfill the goals of the Methane Challenge Program, the BMPs for CIPs must reflect leading practice and therefore they must be more environmentally protective than the requirements in the proposed regulation.

The Proposal currently identifies the BMP for Chemical Injection as replacement with "no- or low-emitting pump… or route bleed gas to flare or gas capture/use."[18] However, because up to 80 percent of chemical injection pumps can be replaced with zero-emitting electric pumps, the "low-emitting" option should not be considered a "best" management practice.[19] In addition, routing bleed gas to flare should not be considered a best practice mitigation option and this language should be removed from the Methane Challenge Proposal.

The Proposal also specifies that the BMP only apply to Chemical Injection pumps, excluding Kimray pumps even though Kimray pumps are a large source of methane emissions and should also be included in this source category. According to the 2015 GHG Inventory, Kimray pumps in the production segment emitted approximately 181,000 metric tons of methane, while Chemical Injection pumps emitted approximately 113,000 metric tons.[20] And, like Chemical Injection pumps, these Kimray pumps can be replaced with zero emitting electric pumps.[21] EPA should include Kimray pumps in the Methane Challenge, using zero-emitting pumps or gas capture/use as a BMP.

- Tanks

Routing vented gas to flare should not be considered a best practice mitigation option and this language should be removed from the Methane Challenge Proposal.

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[16] Methane Challenge Program: Supplementary Technical Information at 8.
[17] Methane Challenge Program: Supplementary Technical Information at 5.
[18] Methane Challenge Proposal at 16.
[19] ICF International. "Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries." Page 3-16. https://www.edf.org/sites/default/files/methane_cost_curve_report.pdf
[20] Net emissions for Chemical Injection pumps calculated using itemized voluntary reductions reported in Inventory. Net emissions for Kimray pumps estimated from the natural gas estimated based on non-itemized voluntary reductions.
[21] ICF International. "Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries." Page 3-16. https://www.edf.org/sites/default/files/methane_cost_curve_report.pdf

- Other Missing Sources in the Production and Gathering and Boosting Segment

There is an additional emissions source that is not addressed in the Methane Challenge Proposal: associated gas venting and flaring. Venting of associated gas from oil wells (a.k.a. "casinghead" gas) is greatly underestimated in the GHG Inventory, which is reported only as venting from stripper wells. As shown by GHGRP data, venting of associated gas from oil wells is actually a large source of methane emissions, and the EPA should consider including it in its Methane Challenge Program. While *flaring* of associated gas is not strictly a methane issue (though it does result in some methane emissions due to incomplete combustion) associated gas venting and flaring are directly connected and both practices represent wasteful sources of harmful pollution. They should both be addressed in the Methane Challenge Program. As we reiterate throughout our comments, flaring should not be considered a best practice methane mitigation option.

Natural Gas (NG) Processing

- Reciprocating Compressors-venting

An additional mitigation option that should be considered is to include the monitoring of venting, with a device such as a high-flow sample which measures the emissions rate directly, from reciprocating compressors as part of leak detection and repair programs (with at least a quarterly inspection frequency). Some rod packing will have a high vent rate before its lifetime reaches 3 years or 26,000 operating hours. An infrared camera would identify which rod packing is emitting excessively. This option should be included as a BMP to significantly reduce emissions from excessively emitting rod packing that would otherwise be allowed to operate for 3 years/26,000 hours.

In addition, routing rod packing gas to a flare should not be considered a best practice mitigation option and this language should be removed from the Methane Challenge Proposal.

- Centrifugal Compressors-venting

Routing wet seal degassing to flare should not be considered a best practice mitigation option and this language should be removed from the Methane Challenge Proposal.

NG Transmission & Underground Storage

- Reciprocating Compressors-venting

See Reciprocating Compressors-venting in Natural Gas (NG) Processing section above.

- Centrifugal Compressors-venting

See Centrifugal Compressors-venting in Natural Gas (NG) Processing section above.

- Equipment Leaks/Fugitive Emissions

See Equipment Leaks/Fugitive Emissions in Natural Gas (NG) Processing section above.

- Pneumatic Controllers

See Pneumatic Controller section in Onshore Production and Gathering and Boosting section above.

NG Distribution

- M&R stations/City Gates

In its initial July 2015 Proposal, EPA included a BMP that called for monitoring and repair activities at specified minimum intervals at M&R stations/City Gates. However, in its October 2015 Supplemental Technical Information document, EPA stated that it was seeking comment on whether or not to include this source in the Methane Challenge Program. The EPA cited low emissions reported to the GHGRP Subpart W for this source and a recent study that found that upgrades at M&R stations/City Gate facilities have resulted in lower emissions. However, we think that the EPA should include leaks from M&R stations/City Gates in the Methane Challenge Proposal. LDAR should still be considered a best practice, because leaks will arise at random intervals in any real-world pressurized system. Upgraded facilities may temporarily experience lower leak levels, but as these facilities age, leaks will inevitably occur. Companies that are pursuing best management practices should adopt leak detection and repair programs proactively to show that they are committed to preventing pollution (and retaining a valuable product) now and in the future.

- Mains – Cast Iron, Not Cathodically Protected Steel (Bare and Coated)

The mitigation options for this BMP (replacing cast iron and non-cathodically protected steel pipes or rehabilitating said pipes with plastic inserts) are appropriate. However, we are concerned that these minimum annual replacement/repair rates specified are not high enough to be considered best practices.

Minimum Annual replacement/repair rate in BMP proposal		
Tier	Inventory of Cast Iron and Unprotected Steel Mains	% Annual Replacement/Repair
1	< 500 miles	6.5%
2	500 - 1,000 miles	5%
3	1,001 - 1,500 miles	3%
4	1,501 – 3,000 miles	2%
5	> 3,000 miles	1.5%

We compared the replacement/repair rates in the proposal to the current average replacement using data from the Pipeline and Hazardous Materials Safety Administration (PHMSA).[22]

Tier	Number of Companies in Tier in 2013	Miles of Cast Iron and Unprotected Steel		Average Replacement Rate between 2013 and 2014
		2013	2014	
Tier 1	248	14,029	12,963	8%
Tier 2	19	13,202	11,844	10%
Tier 3	8	10,067	9,635	4%
Tier 4	13	27,135	26,294	3%
Tier 5	3	12,385	11,838	4%

[22] Unprotected Steel data:
https://hip.phmsa.dot.gov/analyticsSOAP/saw.dll?PortalPages&NQUser=PDM_WEB_USER&NQPassword=Public_Web_User1&PortalPath=/shared/PDM%20Public%20Website/_portal/GD_BARE_STEEL
Cast Iron data:
https://hip.phmsa.dot.gov/analyticsSOAP/saw.dll?PortalPages&NQUser=PDM_WEB_USER&NQPassword=Public_Web_User1&PortalPath=/shared/PDM%20Public%20Website/CI%20Miles/GD_Cast_Iron
Note: We removed from the sample 14 companies for which mileage of cast iron and unprotected steel pipelines increased between 2013 and 2014. We consider this to be an artifact of the data, not an actual increase in mileage.

Based on this data, the BMP replacement/repair rates proposed as BMPs are lower than the actual average replacement/repair rates. Thus, the BMPs, as they are currently designed, do not represent best practices. (RESPONSE TO EPA QUESTION #9)

Furthermore it is not clear that the BMPs should be relatively less stringent for firms with larger amounts of outdated pipelines still in the ground. Firms with high mileage of outdated pipe are either large utilities with significant resources available, which should be directed to bringing their infrastructure into good repair, or, alternatively, companies that have significantly neglected the need to upgrade their infrastructure in the past, relative to their peer utilities. These companies should not be recognized by the Methane Challenge Program for replacing outdated pipe at rates significantly slower than the average utility.

If EPA feels that tiered replacement rates are needed, we suggest that the tiers be tied to rates achieved in recent years by high-performing utilities within their tier. For example, this table shows the replacement rate for the company closest to the 85th percentile within each tier in 2013. These rates, or rates determined in a similar manner, would be appropriate thresholds for the Methane Challenge Program.

Tier	85th Percentile Firm: Outdated Main Replacement Rate for between 2013 and 2014
Tier 1	13%
Tier 2	16%
Tier 3	5%
Tier 4	5%
Tier 5	7%

- Services

The EPA stated that it seeks guidance on the structure of the BMP commitment for unprotected steel and cast iron services. We reviewed the PHMSA data for number of unprotected steel and cast iron services in place currently in the country.[23] We found that the average replacement rate between 2013 and 2014 was 9%, and the average number of replacements per company was 622.

Number of Companies	Number of Cast Iron and Unprotected Steel Services		Average Replacement Rate between 2013 and 2014
	2013	2014	
316	2,262,367	2,065,762	9%

EPA could simply use data on the past performance of companies to set a BMP. For example, the 85th percentile company for outdated services replacement rate replaced 28% of their cast iron and unprotected steel services between 2013 and 2014. EPA could use this figure or a similarly derived figure to define the BMP.

While we have reservations about tiering the rate of replacement in the BMP to the number of current outdated services in a company's inventory (see above discussion of outdated distribution mains), EPA could adopt a tiered approach to this source of methane emissions while using PHMSA data on company performance in recent years

[23] Unprotected Steel data:
https://hip.phmsa.dot.gov/analyticsSOAP/saw.dll?PortalPages&NQUser=PDM_WEB_USER&NQPassword=Public_Web_User1&PortalPath=/shared/PDM%20Public%20Website/_portal/GD_BARE_STEEL
Cast Iron data:
https://hip.phmsa.dot.gov/analyticsSOAP/saw.dll?PortalPages&NQUser=PDM_WEB_USER&NQPassword=Public_Web_User1&PortalPath=/shared/PDM%20Public%20Website/CI%20Miles/GD_Cast_Iron
Note: We removed from the sample 37 companies for which number of cast iron and unprotected steel services increased between 2013 and 2014. We consider this to be an artifact of the data, not an actual increase in mileage.

to set appropriate replacement rates. These rates should reflect the actual high performance of the firms which have been aggressive in replacing outdated services. For example, EPA could use the following tiers:

Tier	Inventory of Cast Iron and Unprotected Steel Services
1	< 5,000 services
2	5,001 - 10,000 services
3	10,001 – 50,000 services
4	50,001 – 100,000 services
5	> 100,000 services

And, based on PHMSA data, the 85th percentile company in these tiers replaced the following percentage of outdated services between 2013 and 2014:

Tier	Number of Companies in Tier in 2013	Miles of Cast Iron and Unprotected Steel		85th Percentile Firm: Outdated Service Replacement Rate for between 2013 and 2014
		2013	2014	
Tier 1	252	164,297	147,182	32%
Tier 2	21	142,533	120,771	21%
Tier 3	29	634,662	550,464	14%
Tier 4	10	766,576	715,526	9%
Tier 5	4	554,299	531,819	7%

(6) Concluding Remarks

In closing, we reiterate that a voluntary methane reduction program does not reduce the need or EPA's legal obligation to swiftly address existing sources of methane in the oil and gas sector under section 111 of the Clean Air Act. That said, a voluntary program can play a role in addressing methane pollution *if* it rapidly drives innovation, reduces actual emissions, and provides more detailed information on a range of issues to inform methane practices and policies. To these ends, we support EPA's goals of creating a program that is ambitious and achieves meaningful reductions, is transparent, and demonstrates continuous improvement. These comments are intended to help EPA ensure that the Methane Challenge Program achieves these goals.

Please feel free to contact the undersigned if you have any questions about these comments.

Sincerely,

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COMMENTER:

Center for Biological Diversity

Submitted Online

October 13, 2015

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Re: Natural Gas STAR Methane Challenge Program Proposal

The Center for Biological Diversity ("Center") submits the following comments on EPA's recently proposed Natural Gas STAR Methane Challenge Program ("Methane Challenge"). The proposed program is an extension of the Natural Gas STAR program, which has been in existence for over 20 years. This voluntary methane-reduction program is available to existing oil and gas operators.

The Center is a non-profit organization with more than 900,000 members and online activists and offices throughout the United States. The Center's mission is to ensure the preservation, protection and restoration of biodiversity, native species, ecosystems, public lands and waters and public health. In furtherance of these goals, the Center's Climate Law Institute seeks to reduce U.S. greenhouse emissions and other air pollution to protect biological diversity, the environment, and human health and welfare.

The Center commends the Administration's commitment to reducing methane from the largest industrial source in the United States. We are encouraged that the EPA has issued its proposed New Source Performance Standards for new oil and gas operations.[1] With regard to existing sources, however, the proposed voluntary program is neither legally sufficient to comply with Clean Air Act requirements nor factually sufficient to achieve the necessary level of methane reductions.

Methane emissions pose both a health and climate risk. As a component of ground-level ozone, reducing methane provides significant health benefits for those affected by ozone, especially children, those with lung disease or asthma and others who are at increased risk of

[1] Oil and Natural Gas Sector: Emission Standards for New and Modified Sources, Proposed Rule, 80 Fed. Reg. 56593 (Sept. 18, 2015).

lung complications. As the Administration is well aware,[2] methane is also a greenhouse gas that plays a prominent role in any strategy to reduce global-warming induced climate change. It is potent – heating the atmosphere 87 times more than the same volume of CO_2 over a 20-year period. Methane is also "short-lived," meaning that reductions are a critical component of near-term climate stabilization.

The urgency of addressing greenhouse gas pollution is becoming more evident every day. The National Climate Assessment released in May 2014 by the U.S. Global Change Research Program states that "reduc[ing] the risks of some of the worst impacts of climate change" will require "aggressive and sustained greenhouse gas emission reductions" over the course of this century.[3] Humanity is rapidly consuming the remaining "carbon budget" necessary to preserve a likely chance of holding the average global temperature increase to only 2°C above pre-industrial levels. According to the IPCC, if non-CO_2 forcings are taken into account, total cumulative future anthropogenic emissions of CO_2 must remain below about 1,000 gigatonnes (Gt) to achieve this goal.[4] Another recent scientific report found that "[i]n all of the studies consistent with limiting warming below 2°C the energy sector needs to decarbonise rapidly and reduce to zero emissions as early as 2040 but no later than 2070."[5] Even more recently, the International Energy Agency projected that in its central scenario, the entire remaining 1,000 $GtCO_2$ carbon budget will be consumed by 2040.[6] Some leading scientists – characterizing the effects of even a 2°C increase in average global temperature as "disastrous" – have prescribed a far more stringent carbon budget for coming decades.[7]

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[2] Obama Climate Action Plan: *Strategy to Reduce Methane Emissions* (Mar. 2014) ("Obama Methane Strategy"), *available at* https://www.whitehouse.gov/sites/default/files/strategy_to_reduce_methane_emissions_2014-03-28_final.pdf.

[3] Jerry M. Melillo, et al., *Climate Change Impacts in the United States: The Third National Climate Assessment* at 14-15 (2014) ("National Climate Assessment"), *available at* http://nca2014.globalchange.gov/downloads.

[4] Intergovernmental Panel on Climate Change, *Climate Change 2014 Synthesis Report: Approved Summary for Policymakers* at SPM-10 (Nov. 1, 2014) ("Multi-model results show that limiting total human-induced warming to less than 2°C relative to the period 1861-1880 with a probability of >66% would require cumulative CO_2 emissions from all anthropogenic sources since 1870 to remain below about 2900 $GtCO_2$ (with a range of 2550-3150 $GtCO_2$ depending on non-CO_2 drivers). About 1900 $GtCO_2$ had already been emitted by 2011."); *see also* Intergovernmental Panel on Climate Change, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Summary for Policymakers* at 27 (2013) ("Limiting the warming caused by anthropogenic CO_2 emissions alone with a probability of >33%, >50%, and >66% to less than 2°C since the period 1861–1880, will require cumulative CO_2 emissions from all anthropogenic sources to stay between 0 and about 1570 GtC (5760 $GtCO_2$), 0 and about 1210 GtC (4440 $GtCO_2$), and 0 and about 1000 GtC (3670 $GtCO_2$) since that period, respectively. These upper amounts are reduced to about 900 GtC (3300 $GtCO_2$), 820 GtC (3010 $GtCO_2$), and 790 GtC (2900 $GtCO_2$), respectively, when accounting for non-CO_2 forcings as in RCP2.6. An amount of 515 [445 to 585] GtC (1890 [1630 to 2150] $GtCO_2$), was already emitted by 2011."). United Nations Environment Programme, *The Emissions Gap Report* at 13-22 (2013) (describing emissions "pathways" consistent with meeting 2°C and 1.5°C targets).

[5] Bill Hare et al., *Below 2°C or 1.5°C Depends on Rapid Action from Both Annex I and Non-Annex I Countries*, Climate Action Tracker Policy Brief at 2 (June 4, 2014) ("Hare et al. 2014").

[6] International Energy Agency, *World Energy Outlook 2014: Executive Summary* at 2 (Nov. 12, 2014).

[7] James Hansen, et al., *Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature*, 8 PLoS ONE e81648 at 15 (2013), *available at* http://www.plosone.org/article/fetchObject.action?uri=info:doi/10.1371/journal.pone.0081648&representation=PDF.

A group of leading climate scientists has calculated that developed countries like the United States must reduce their greenhouse gas emissions by 35-65 percent below 1990 levels by 2030 in order to preserve a likely chance of limiting global temperature rise to 2°C this century.[8] On an economy-wide basis, moreover, current United States climate policy will result in emissions 5 percent *above* 1990 levels by 2030.[9]

Furthermore, with international negotiations in Paris rapidly approaching, the U.S. must demonstrate its commitment to meaningful emissions reductions to assure that global commitments stay on track to meet the 2ºC goal. The United States is also a founding partner in the UNEP's Climate and Clean Air Coalition, which focuses on reducing various short-lived pollutants. The United States must do more than put forth aspirational programs: decisive, enforceable actions are the only reasonable option.

Over nearly a decade since the release of a key summary report on mitigation of short-lived pollutants,[10] the EPA has dragged its heels on implementing critically important Clean Air Act regulations for reducing methane. It is now clear that responding to the climate crisis requires faster and deeper emissions reductions than previously understood, that the majority of fossil fuels must stay in the ground, and that ongoing fossil fuel extraction must be phased out as quickly as possible and within a few decades. Nonetheless, because minimizing methane reductions from oil and gas operations can still play a part in averting the worst loss and damage from climate disruption, as detailed further below, we wish to underscore the absolute necessity of rapid implementation of meaningful and enforceable limits on methane emissions as required by the Clean Air Act.

I. THE EPA MUST REGULATE METHANE FROM OIL AND GAS SOURCES PURSUANT TO CLEAN AIR ACT § 111(D)

The proposed voluntary Methane Challenge Program does not fulfill the requirements for emission guidelines under Clean Air Act § 111(d). Furthermore, history has shown that the voluntary programs for methane emissions also fail to achieve the methane reductions necessary to meet international commitments or to avoid catastrophic climate impacts.

A. Statutory Overview of Clean Air Act § 111(b) and § 111(d) requirements

The Clean Air Act ("CAA") provides for complementary control over air pollution from new and existing stationary sources. Under CAA § 111(b), the EPA has the authority to regulate air pollutants emitted by new and modified stationary sources. Once a source category is subject to regulation for a given air pollutant, the EPA is required under § 111(d) to issue emission guidelines for that same pollutant (if it is not a criteria air pollutant or hazardous air pollutant).

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[8] Hare et al. 2014, *supra* note 5 at 12 (calculating "from the IPCC AR5 scenarios that reductions for the Annex I countries in 2025 and 2030 are 25-55% and 35-65% below 1990 levels respectively for an equity scenario based on relative capability to mitigate").
[9] *Id*. The United States' international pledge is to reduce emissions 17% below 2005 levels by 2020 and longer-term stated goal of reducing emissions 83% below 2005 levels by 2050.
[10] U.S. EPA, *Global Mitigation Of Non-CO_2 Greenhouse Gases* (2006), *available at* http://www3.epa.gov/climatechange/Downloads/EPAactivities/GM_Cover_TOC.pdf.

These emission guidelines are implemented by the states to control emissions from existing sources.

The CAA is silent with regard to the exact timing for issuance of emission guidelines, but federal regulations state that "concurrently upon or after proposal of a standard of performance" the Administrator will publish a draft guideline document regarding control of designated pollutants from existing sources.[11] In practice, New Source Performance Standards ("NSPS") are often issued concurrently, such as was the case with the recent promulgation of NSPS for electricity generating units, the "Clean Power Plan." As the EPA demonstrated, there is a congruity to addressing existing sources at the same time as existing sources, allowing for a seamless administrative process.

On August 18, 2015, the EPA proposed NSPS for methane emissions from the oil and gas sector. This was an important step to curb methane, a potent short lived climate pollutant and ozone precursor. In addition, the promulgation of final standards will trigger the requirement that the EPA promulgate emission guidelines for existing oil and gas sources. If the EPA does not issue emission guidelines for existing sources when it finalizes the NSPS, the EPA will be under an obligation to issue them in the near future.

The Center wishes to underscore the fact that a voluntary program for emission reductions is legally insufficient to comply with the requirements of the CAA. The proposed Methane Challenge is intended to "complement" the methane NSPS and VOC control technique guidelines and provide "incentives and opportunities for companies to undertake and document ambitious voluntary methane emission reductions, principally from existing methane emission sources."[12] Yet, the enrollment in the Methane Challenge Program is entirely voluntary: companies are invited to make "specific, ambitious voluntary commitments."[13] Furthermore, the Methane Challenge Framework contains several allusions to "transparency" and "robust annual data reporting." But in reality, the vast majority of "tracking" will simply be through the Greenhouse Gas Reporting Program, to which companies are already required to submit data.[14] We do support, however, the EPA's plan[15] to determine how to separate voluntary actions to reduce emissions as opposed to measures taken in accordance with regulatory requirements.

Both the voluntary nature of enrollment and lack of enforcement options are at odds with the requirements of Emission Guidelines issued pursuant to section 111(d) of the Clean Air Act. Under § 111(d), the Administrator must issue emission guidelines pursuant to which the individual states submit "SIP-like" plans that implement enforceable standards for the reduction of air pollutants from designated sources. Clearly the proposed Methane Challenge neither allows for state involvement nor provides enforceable standards. Thus, the proposed Methane Challenge cannot be treated as a regulatory substitute.

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[11] 40 C.F.R. § 60.22.

[12] U.S. EPA, Natural Gas STAR Methane Challenge Program: Proposed Framework, Proposal for Stakeholder Feedback 4 (Jul. 23, 2015) ("Methane Challenge"), *available at* http://www3.epa.gov/gasstar/documents/methane_challenge_proposal_072315.pdf.

[13] *Id.*

[14] *Id.* at 10 ("EPA proposes to rely heavily on GHGRP Subpart W data to track progress").

[15] *Id.*

B. Oil and Gas Operations Are the Largest Industrial Source of Methane in the United States and Significant Mitigation Options are Available

As the Administration has acknowledged, reducing methane is a key component of any strategy to meet international commitments and avoid the most dire effects of global-warming induced climate change.[16] Since President Obama's release of the Methane Strategy, evidence has continued to mount that rapid and sizable methane reductions are essential. To be clear, if existing sources are not addressed, the same sources that EPA has published data for to date will continue to emit at the same levels.

The oil and gas sector is the most efficient place to make substantial reductions due to both the amount of methane it emits and the significant number of mitigation options available. In 2013, the latest year for which there are data, oil and gas operations accounted for approximately 29 percent of all U.S. methane emissions, more than any other source category.[17] Furthermore, these emissions are on the rise: between 2012 and 2013 oil and gas methane emissions increased by 3 percent.[18] It is especially important to rapidly address methane emission from existing sources because these sources will account for approximately 90% of total methane emissions from this source category by year 2018.

And these data fail to capture the full picture. Numerous recent studies have undertaken estimates of methane emissions from oil and gas operations at locations throughout the United States. The overwhelming evidence indicates that methane leakage rates are much higher than assumed by the EPA for the purposes of the U.S. Greenhouse Gas Reporting Program and Inventory of U.S. Greenhouse Gas Emissions. There is compelling evidence that leakage rates from oil and gas operations are far higher than EPA emission factors suggest. For instance, Miller and colleagues recently used atmospheric measurements to estimate that actual methane emissions are about 1.5 times larger than EPA estimates.[19] Observations from oil and gas operations in Colorado indicate that inventories underestimate methane emissions by at least a factor of two.[20] Leakage rates over a Utah gas field were recently estimated at 6.2 to 11.7%, well above the rates assumed by national inventories.[21] A study of leakage rates in the Barnett Shale region of Texas indicated that leakage rates were 1.5 to over 4 fold higher than EPA estimates, especially at gathering compressor stations.[22] A more detailed study of methane emissions from natural gas gathering and processing found that methane leakage rates were double the rate EPA assumes for the U.S. Greenhouse Gas Inventory, resulting in a volume of methane that is one-

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[16] Obama Methane Strategy, *supra* note 2.
[17] US EPA, *Inventory of U.S. Greenhouse Gas Emissions And Sinks*: 1990 – 2013 ES-6 (Apr. 15, 2015).
[18] *Id.*
[19] S. M. Miller et al., *Anthropogenic emissions of methane in the United States*, 100 PROC. NATL. ACAD. SCI. 20018 (2013).
[20] G. Pétron et al., *Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study*, 117 J. GEOPHYS. RES. D04304 (2012).
[21] A. Karion et al., *Methane emissions estimate from airborne measurements over a western United States natural gas field*, 40 GEOPHYS. RES. LETT. 4393 (2013).
[22] D. R. Lyon et al., *Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region*, 49 ENVIRON. SCI. TECHNOL. 8147 (2015), *available at* http://pubs.acs.org/doi/pdf/10.1021/es506359c.

third the total emissions estimated for all natural gas operations.[23] This discrepancy was due primarily to large rates of leakage from gathering stations, which are not subject to separate emissions quantification for the purposes of the EPA's U.S. Greenhouse Gas Inventory.

Moreover, EPA's data for oil and combined oil/gas wells omit the impact of hydraulic fracturing. A recent white paper from Environmental Defense Fund summarizes findings from a number of studies to conclude that emissions factors used in EPA's current inventory underestimate methane emissions from oil wells that employ hydraulic fracturing.[24] Hydraulic fracturing and associated techniques are widespread and continue to expand at a rapid pace, making it all the more necessary that EPA update its emission factors, which were developed for conventional wells.

Another major source of methane emissions from the oil and gas sector is leaks from pneumatic devices. A recent study calculated emission factors for pneumatic devices to find that national emissions from this source are likely at least twice the amount predicted using the emission factors in the U.S. Greenhouse Gas Inventory.[25]

Recent reports have also substantiated an alarming rate of leaks from decaying gas pipeline systems across the country, creating the need for systematic, on-the-ground data collection to obtain an accurate quantification of emissions from this source. For example, according to a recent study, the two distributors of natural gas in New York City and Westchester County reported 9,906 leaks in their combined system for 2012 alone, and gas distributors nationwide reported an average of 12 leaks per 100 miles of the 1.2 million miles of gas main pipes across the country.[26] More than 5,800 leaks were detected from aging gas pipelines underneath the streets of Washington, D.C.[27] These samples indicate that EPA's data are incomplete, and we urge the EPA to note this fact.

Finally, a recent study raised the possibility that sensors used to measure methane leakage for the purpose of "bottom-up" inventories, such as those compiled by the EPA, may have fundamental flaws such that methane will be consistently under-estimated.[28]

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[23] A. J. Marchese et al., *Methane Emissions from United States Natural Gas Gathering and Processing*, ENVIRON. SCI. TECHNOL. DOI: 10.1021/acs.est.5b02275 (2015), *available at* http://pubs.acs.org/doi/pdf/10.1021/acs.est.5b02275.

[24] ENVIRONMENTAL DEFENSE FUND, *Co-Producing Wells As a Major Source Of Methane Emissions: A Review of Recent Analyses* (Mar. 2014) *available at* http://blogs.edf.org/energyexchange/files/2014/03/EDF-Co-producing-Wells-Whitepaper.pdf; see also blog post by David Lyon *available at* http://blogs.edf.org/energyexchange/2014/03/13/latest-epa-greenhouse-gas-inventory-may-not-reflect-full-scope-of-oil-and-gas-emissions/. We note that the recently released proposed updates to the NSPS for oil and gas operations would extend the green completion requirement to oil and oil/gas wells, but would not apply to existing wells.

[25] D. Allen et al., *Measurements of methane emissions at natural gas production sites in the United States*, 110 PROC. NATL. ACAD. SCI. 17768 (2013).

[26] Patrick McGeehan et al., *Beneath Cities, a Decaying Tangle of Gas Pipes*, N.Y. TIMES (Mar. 24, 2014), *available at* http://www.nytimes.com/2014/03/24/nyregion/beneath-cities-a-decaying-tangle-of-gas-pipes.html?hp&_r=0.

[27] Robert B. Jackson et al., *Natural Gas Pipeline Leaks Across Washington, D.C.*, 48 ENVIRON. SCI. TECHNOL. 2051 (Jan.16, 2014), *available at* http://pubs.acs.org/doi/abs/10.1021/es404474x.

[28] T. Howard, *University of Texas study underestimates national methane emissions at natural gas production sites due to instrument sensor failure*, ENERGY SCIENCE AND ENGINEERING doi: 10.1002/ese3.81 (2015).

Taken together, these studies provide overwhelming evidence that not only are oil and gas methane emissions large by EPA's estimates, but likely of such a magnitude that failing to address them will spell climate doom.

II. VOLUNTARY PROGRAMS DO NOT ACHIEVE ADEQUATE REDUCTIONS IN EMISSIONS

The proposed Methane Challenge is an extension of the EPA's Natural Gas STAR program, which has been in existence since 1993. Arguably the main benefit of these last 20 years has been the practical experiences gained through industry-agency collaboration that will be applicable to regulation. Although the goal of the program is laudable, the actual emission reductions have been underwhelming. Less than one percent of oil and gas operations have taken part in the program. With such low enrollment, the methane reductions that have been achieved over the last 20 years (1.2 trillion cubic feet)[29] have avoided only 5.75 MMT CO2eq.[30] For comparison, this 20-year achievement is about 3 percent of oil and gas methane emissions in year 2013 alone.

The proposed Methane Challenge does not address the fundamental obstacle of low enrollment. This is the nature of voluntary programs as opposed to regulatory requirements. The oil and gas industry has had 20 years to choose to make significant cuts to its methane emissions in partnership with the EPA. Despite the precatory language regarding EPA's perception of industry interest and aspirations to create a platform for "meaningful and transparent commitments,"[31] changing the structure of the program will not change the lack of commitment on the part of industry.

The EPA has been aware of the significant and concrete potential for methane mitigation from the oil and gas sector for nearly a decade. In 2006, the EPA published its report, *Global Mitigation of Non-CO_2 Greenhouse Gases*. The report conservatively estimated methane reduction potential of approximately 18 and 19 percent for oil and gas, respectively.[32] Over the intervening decade, information regarding low- and no-cost mitigation options has grown rapidly.[33] Moreover, the EPA recently updated its 2006 Non-CO_2 Mitigation report, finding that even greater cost-effective reductions in methane from oil and gas are now available, e.g., 27 percent reduction in 2030 at zero cost.[34] Thus, the EPA is armed with more than enough technical information to set meaningful emission guidelines for existing oil and gas sources of methane and in turn make a substantial dent in U.S. greenhouse gas emissions.

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[29] *See* http://www.epa.gov/gasstar/accomplishments/index.html.

[30] This assumes a methane GWP of 25 for comparison to data from EPA's US GHG Inventory.

[31] Methane Challenge, *supra* note 12 at 3.

[32] Assuming a low cost of carbon reductions ($15/ton CO_2eq). Much greater reductions are possible at higher cost.

[33] *See, e.g.*, Carbon Limits, *Quantifying Cost-effectiveness of Systematic Leak Detection and Repair Programs Using Infrared Cameras* (Mar. 2014), *available at* http://www.carbonlimits.no/PDF/Carbon_Limits_LDAR.pdf; ICF INTERNATIONAL, *Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries* (Mar. 2014); CLEAN AIR TASK FORCE, NATURAL RESOURCES DEFENSE COUNCIL, SIERRA CLUB, *Waste Not: Common Sense Ways to Reduce Methane Pollution from the Oil and Natural Gas Industry* (Jan. 2015), *available* at http://docs.nrdc.org/energy/files/ene_14111901b.pdf.

[34] U.S. EPA, *Global Mitigation of Non-CO2 Greenhouse Gases: 2010-2030 II-41* (Sept. 2013), *available at* http://www3.epa.gov/climatechange/Downloads/EPAactivities/MAC_Report_2013.pdf.

III. CONCLUSION

In summary, the issuance of NSPS for methane from oil and gas sources has triggered the requirement that EPA issue in a timely manner emission guidelines to reduce methane from existing sources. No form of voluntary program can fulfill this statutory obligation under the Clean Air Act. Furthermore, while there are substantial, feasible mitigation options for methane from oil and gas operations, no changes to the structure of the voluntary Methane Challenge Program can change the oil and gas industry's reluctance to make a significant shift in practices. Finally, at the same time that the EPA is working toward solutions for existing sources, we urge the EPA to rapidly finalize the methane and VOC NSPS for new oil and gas operations.

Thank you for the opportunity to provide input on the proposed Methane Challenge Program.

Sincerely,

/s/

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Measurements of methane emissions at natural gas production sites in the United States

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Edited by Susan L. Brantley, Pennsylvania State University, University Park, PA, and approved August 19, 2013 (received for review March 20, 2013)

Engineering estimates of methane emissions from natural gas production have led to varied projections of national emissions. This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States (150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 workovers). For well completion flowbacks, which clear fractured wells of liquid to allow gas production, methane emissions ranged from 0.01 Mg to 17 Mg (mean = 1.7 Mg; 95% confidence bounds of 0.67–3.3 Mg), compared with an average of 81 Mg per event in the 2011 EPA national emission inventory from April 2013. Emission factors for pneumatic pumps and controllers as well as equipment leaks were both comparable to and higher than estimates in the national inventory. Overall, if emission factors from this work for completion flowbacks, equipment leaks, and pneumatic pumps and controllers are assumed to be representative of national populations and are used to estimate national emissions, total annual emissions from these source categories are calculated to be 957 Gg of methane (with sampling and measurement uncertainties estimated at ±200 Gg). The estimate for comparable source categories in the EPA national inventory is ~1,200 Gg. Additional measurements of unloadings and workovers are needed to produce national emission estimates for these source categories. The 957 Gg in emissions for completion flowbacks, pneumatics, and equipment leaks, coupled with EPA national inventory estimates for other categories, leads to an estimated 2,300 Gg of methane emissions from natural gas production (0.42% of gross gas production).

greenhouse gas emissions | hydraulic fracturing

Methane is the primary component of natural gas and is also a greenhouse gas (GHG). In the US national inventories of GHG emissions for 2011, released by the Environmental Protection Agency (EPA) in April 2013 (1), 2,545 Gg of CH_4 emissions have been attributed to natural gas production activities. These published estimates of CH_4 emissions from the US natural gas industry are primarily based on engineering estimates along with average emission factors developed in the early 1990s (2, 3). During the past two decades, however, natural gas production processes have changed significantly, so the emission factors from the 1990s may not reflect current practices. This work presents direct measurements of methane emissions from multiple sources at onshore natural gas production sites incorporating operational practices that have been adopted or become more prevalent since the 1990s.

Horizontal drilling and hydraulic fracturing are among the practices that have become more widely used over the past two decades. During hydraulic fracturing, materials that typically consist of water, sand and, additives, are injected at high pressure into low-permeability formations. The injection of the hydraulic fracturing fluids creates channels for flow in the formations (often shale formations), allowing methane and other hydrocarbon gases and liquids in the formation to migrate to the production well. The well and formation is partially cleared of liquids in a process referred to as a completion flowback, after which the well is placed into production. Production of natural gas from shale formations (shale gas) accounts for 30% of US natural gas production, and this percentage is projected to grow to more than 50% by 2040 (4).

Multiple analyses of the environmental implications of gas production using hydraulic fracturing have been performed, including assessments of water contamination (5–8), criteria air pollutant and air toxics releases (9–11), and greenhouse gas emissions (11–18). Greenhouse gas emission analyses have generally been based on either engineering estimates of emissions or measurements made 100 m to a kilometer downwind of the well site. This work reports direct on-site measurements of methane emissions from natural gas production in shale gas production regions.

Methane emissions were measured directly at 190 natural gas production sites in the Gulf Coast, Midcontinent, Rocky Mountain, and Appalachian production regions of the United States. The sites included 150 production sites with 489 wells, all of which were hydraulically fractured. In addition to the 150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 well workovers were sampled; the sites were operated by nine different companies. The types of sources that were targeted for measurement account for approximately two-thirds of

Significance

This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States. The measurements indicate that well completion emissions are lower than previously estimated; the data also show emissions from pneumatic controllers and equipment leaks are higher than Environmental Protection Agency (EPA) national emission projections. Estimates of total emissions are similar to the most recent EPA national inventory of methane emissions from natural gas production. These measurements will help inform policymakers, researchers, and industry, providing information about some of the sources of methane emissions from the production of natural gas, and will better inform and advance national and international scientific and policy discussions with respect to natural gas development and use.

Author contributions: D.T.A. and M.H. designed research; D.T.A., V.M.T., J.T., D.W.S., M.H., A.H., and S.C.H. performed research; C.E.K., M.P.F., A.D.H., B.K.L., J.M., R.F.S., and J.H.S. analyzed data; and D.T.A. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1304880110/-/DCSupplemental.

methane emissions from all onshore and offshore natural gas production, as estimated in the 2011 national greenhouse gas emission inventory (1). A summary of the scope of the study, along with a rationale for the inclusion or exclusion of sources for direct measurement efforts, is provided in *SI Appendix*. Sampling was conducted from May 2012 through December 2012 at sites throughout the United States (see *SI Appendix* for a map and for the number of sampling sites in each region). All nine companies that participated in the study provided sites for sampling, and at least three companies provided sites in each of the regions (*SI Appendix*).

The data presented in this report represent hundreds of measurements of methane emissions from several types of onshore natural gas production activities; however, the sites sampled still represent a small fraction of the total number of sites nationwide (Table 1). This dataset is designed to be representative of the participating companies' activities and practices, but not necessarily all activities and practices. Multiple methods were used to minimize the potential for bias in the sample set, as described in *SI Appendix*.

Results

Emission measurements were performed for 27 well completion flowbacks, 9 liquids unloadings, 4 well workovers, and 150 production sites with 489 hydraulically fractured wells (Table 1 and *SI Appendix*). Data are summarized here for the well completion flowbacks, liquids unloading, and production site emissions. *SI Appendix* provides additional details. The data on well workovers, collected for workovers without hydraulic fracturing, are not presented because the data set was small and emission estimates for workovers without fracturing represent less than 0.1% of national emission estimates.

Well Completion Flowbacks. After a well is drilled, the well is "completed." Completion is the process of making a well ready for continuous production. Specifically, after drilling and fracturing, before natural gas production can begin, the well must be cleaned of sand and liquid of various types that had been injected into the well. The recovery of these liquids is referred to as a flowback, and gas, including methane, can be dissolved or entrained in the flowback liquids. Some of the methane in the liquids can be sent to sales or emission control devices, but some can be emitted.

Measurements were made of methane emissions during 27 completion flowback events. Emissions data for each of the 27 events is provided in *SI Appendix*. Five of the flowbacks were in the Appalachian region, seven in the Gulf Coast region, five in the Midcontinent region, and 10 in the Rocky Mountain region. The durations of the completions ranged from 5 to 339 h (2 wk). Measured methane emissions over an entire completion flowback event ranged from less than 0.01 Mg to more than 17 Mg, with an average value of 1.7 Mg and a 95% confidence interval of 0.67–3.3 Mg. Measurement and sampling uncertainty are included in the confidence interval; uncertainties due to a limited sample size dominate the overall uncertainty estimate. Methods for determining the confidence intervals are described in *SI Appendix*.

The completions with the lowest emissions were those in which the flowback from the well was sent immediately, at the start of the completion, to a separator, and all of the gases from the separator were sent to sales. The only emissions from these completions were from methane dissolved in liquids (mostly water) sent from the separator to a vented tank. The completion flowback with the highest total emissions, 17 Mg, was the longest in duration (339 h) and had initial flowback into a vented tank with very high methane concentrations. Some of the other relatively high emission completion flowbacks (~3 Mg to 6 Mg of methane) involved large amounts of flared gas (up to 130 Mg of methane to the flare, which was assumed to combust the methane at 98% efficiency, *SI Appendix*). Another completion with emissions of 4 Mg of methane was one in which all gases, for the entire event, were vented to the atmosphere. This type of venting for the entire duration of the completion was observed in 9 of the 27 completions. However, the nine completions of this type showed a wide range of emissions (4 Mg of methane for one completion and 0.5 Mg of methane for another completion of this type for an adjacent well).

These data provide extensive measurements on methane emissions from well completions that can be used in national emission estimates. Current national inventories of methane emissions have been assembled, based on simple engineering models of the completion process. In the most recent EPA national greenhouse gas emission inventory (2011 inventory, released April 2013) (1), 8,077 well completions with hydraulic fracturing are estimated to result in 654 Gg per year of emissions, for an average of 81 Mg of methane per completion flowback (compared with 1.7 Mg per flowback for the events reported here). To understand the reasons for the much lower emissions per event reported in this work, it is useful to define a potential emission for each flowback. The potential of a flowback to emit is defined here, and in the EPA national inventory (1), as the methane that would be emitted if all of the methane leaving the wellhead during the flowback were vented to the atmosphere. Potential emissions for the wells in this work ranged from 0.2 Mg to more than 1 Gg methane, with an average of 124 Mg. The average from the EPA national inventory is slightly higher at 151 Mg. Net emissions are calculated, in the EPA national inventory, by reducing potential emissions by estimates of methane captured or controlled because of regulatory or voluntary emission reductions. In the current national inventory, emission reductions are roughly one-half of potential emissions (*SI Appendix*). In this work, net or measured emissions for the total of all 27 completions are 98% less than potential emissions. This large difference between the net emissions measured in this work and the net emissions estimated in the national inventory is due to several factors. First, consistent with emerging regulatory requirements (21) and improved operating practices, 67% of the wells sent methane to sales or control

Table 1. Comparison of sample set size to emission source populations

Source	No. of events/locations sampled	Total no. of events/locations
Well completions	27	8,077*
Gas well unloading	9	35,828†
Well workovers	4	1782 (11,663)‡
Wells	489	446,745§

*Completions, with hydraulic fracturing reported in the 2011 National GHG Emission Inventory (1).
†Wells without plunger lift that have unloading events (the type of event sampled in this work) reported in the 2011 National GHG Emission Inventory (1).
‡Workover events with (and without) hydraulic fracturing reported in the 2011 National GHG Emission Inventory (1).
§Gas wells with and without hydraulic fracturing reported in the 2011 National GHG Emission Inventory (1); 513,000 on-shore natural gas wells are reported by the Energy Information Administration (20); see *SI Appendix*.

devices. Second, for those wells with methane capture or control, 99% of the potential emissions were captured or controlled. Finally, the wells with uncontrolled releases had much lower than average potential to emit. Of the nine wells in this work that had uncontrolled venting of methane, the average potential to emit was 0.83 Mg, which is 0.55% of the average potential to emit in the national inventory. The relative importance of these factors is discussed in *SI Appendix*.

Unloadings. Gas wells often produce liquid hydrocarbons and water along with natural gas. In most new wells, the velocity of natural gas up the production tubing of the well is sufficient to lift any produced water out of the well with the gas. As gas production declines, the velocity may no longer be sufficient to lift the liquids, which begin to accumulate in the wellbore and eventually restrict gas flow from the producing formation. Liquids accumulation therefore needs to be removed to allow the well to continue to produce gas at optimal rates.

There are multiple methods of unloading a gas well, some of which do not result in emissions. In this work, sampling was performed for unloadings in which an operator manually bypasses the well's separator. Unlike automated plunger lift methods, these manual unloading events could be scheduled, allowing the study team adequate time to install measurement equipment. As the flow to the separator, which typically operates at pressures of multiple atmospheres, is bypassed, flow is diverted to an atmospheric pressure tank. This diversion allows the well to flow to a lower pressure destination (the atmospheric pressure tank, rather than the pressurized separator). This lower pressure end point allows more gas to flow, increasing velocity in the production tubing and lifting the liquids out of the well. Gas is discharged from the tanks through the tank vent, unless the tanks have an emissions control system such as a combustor.

The nine unloading events reported in this work were varied in their characteristics. Methane emissions ranged from less than 0.02 Mg to 3.7 Mg. Some unloadings lasted 2 h (or more) and had relatively uninterrupted flow. Other unloadings were as short as 10–15 min with uninterrupted flow, and still others had intermittent flow for short periods and periods of no flow for much of the unloading period. Some of the wells sampled only unloaded once over the current life of the well, whereas others were unloaded monthly. The average emission per unloading event was 1.1 Mg of methane (95% confidence limits of 0.32–2.0 Mg). If the emissions per event for each well are multiplied by the event frequency (events per year) reported by the well operators, the average emission per well per year was 5.8 Mg (an average of 5.9 events per unloaded well per year). The sampled population reflected a wide range of emission rates, with a population of high emitting wells and a population of low emitting wells. When emissions are averaged per event, emissions from four of the nine events contribute more than 95% of the total emissions. *SI Appendix* provides more information about individual unloading events.

Because the characteristics of the unloading events sampled in this work are highly variable, and because the number of events sampled is small, extrapolating the results to larger populations should be done with caution. One source of data on larger populations of wells with unloadings, to which the population sampled in this work can be compared, is a survey reported by the American Petroleum Institute and America's Natural Gas Alliance (API/ANGA) (22). In this survey, more than 20 companies provided data and well characteristics for 40,000–60,000 wells (with the number in the sample depending on the type of emission event). These API/ANGA data were used by the EPA to arrive at 2011 national inventory emission estimates for 35,828 wells without plunger lift and 22,866 with plunger lift, which vent for unloading. Unloading emissions for the wells in the API/ANGA survey were estimated based on well characteristics such as well bore volume, well pressure, venting time, and gas production rate (3). For the unloading events without plunger lift, 100 of the 2,901 wells (3%) in the survey account for 50% of the estimated emissions. Ninety percent of the estimated emissions in the API/ANGA survey are due to one-half of the wells. Because a small population of wells (3%) accounts for one-half of the emissions, if this relatively small population of high emitting wells is not adequately sampled, it is not possible to accurately estimate national emissions. The wells sampled in this work unloaded relatively infrequently. In contrast, some wells in the API/ANGA survey, including some of the highest emitting wells, unload with a daily or weekly frequency. An average frequency of unloading for the wells in the API/ANGA survey is 32.57 events per year, compared with an average observed in this work of 5.9.

Because a small number of unloading events accounts for a large fraction of emissions in the API/ANGA survey (22), and because some of these wells had frequencies of unloading higher than any of the events observed in this work, the sample set of nine events reported in this work is not sufficient for accurately estimating emissions from unloading at a national scale. Nevertheless, the data reported here provide valuable insights for the design of future sampling campaigns.

One important result from the measurements reported here is that current EPA estimation methods overpredict measured emissions. If the emission estimation method (3) used in the API/ANGA survey is applied to the events sampled in this work, estimates are 5 times higher than measured emissions. Estimates of the emissions for the nine events are 5.2 Mg per event versus measured emissions of 1.1 Mg per event. Emissions were overestimated for every event. The percentage by which emissions are overestimated increases as emissions per event decrease (*SI Appendix*). Possible causes of the overestimate include the assumptions in the estimation method that the entire well bore volume is released in an unloading and that the gas flow during an unloading is continuous.

Overall, the implication of all of these issues is a large uncertainty bound in the national emissions from gas well unloading. If the per well annual emissions from this work are used, a national emission estimate based on counts of wells that undergo unloading is in reasonable agreement with emissions in the EPA national inventory (1). In contrast, another estimate of unloading emissions, based on the per event emissions observed in this work and an estimate of national unloading events (22), would lead to a national estimate five times the estimate based on well counts. This estimate is not supported by the available data, given that the national event count is dominated by high frequency unloading events and the wells observed here unloaded far less frequently with much higher emission estimates per event. A lower estimate of unloading emissions could be suggested based on national well counts, emission estimates, and the finding that emission estimation methods, used in many EPA inventory estimates, overestimate observations made in this work by a factor of 5. All of these methods, however, assume a single scalar value represents a wide range of unloadings; the data presented in this work and in the API/ANGA survey (22) suggest that refined emission estimation methods, taking into account well and unloading characteristics, will be required. Additional measurements of unloading emissions are needed, both to resolve the differences between estimates and measurements and to better characterize the population of wells with unloading emissions.

Finally, it is also clear from the data that properly accounting for unloading emissions will be important in reconciling emission inventories with regional ambient measurements. Average methane emission rates for a single unloading ranged from roughly 100 g/min to in excess of 30,000 g/min. These rates are much larger than emission rates for production sites (typically tens of grams of methane per minute per well) or from completions (typically a few hundred grams per event per minute). At these emission rates,

Table 2. National emission estimates for the natural gas production sector, based on this work and the 2011 national inventory

Category	2011 EPA GHG inventory net emissions,* Gg of methane/yr	Emission estimates from this report,† Gg of methane/yr	Comments
Sources with emissions measurements from this work used to generate national emission estimates			
Completion flowbacks from wells with hydraulic fracturing	654*	18‡ (5–27)§	Decrease in national emission estimate
Chemical pumps	34*	68 (35–100)§	Increase in national emission estimate
Pneumatic controllers	355*	580‡ (518–826)§	Increase in national emission estimate; if national emission factors derived from this work are used, this estimate becomes 790 Gg (*SI Appendix*)
Equipment leaks	172–211*,¶	291‡ (186–396)§	Increase in national emission estimate; this comparison is based on equivalent categories of equipment, not all equipment leaks¶ (*SI Appendix*)
Subtotal, national emissions, estimated based on this work	1215–1254†#	957 ± 200 #	Decrease of ~250 Gg for national emission estimate
Sources with limited measurements; national emissions not estimated			
Unloadings (nonplunger lift)	149* (EPA inventory)		Highly diverse events; small data set collected in this work; preliminary national emission estimates have a broad range of values (25–206 Gg; see text)
Workovers (without hydraulic fracturing)	0.3* (EPA inventory)		Measurements in this work included only one recompletion and three swabbing events (see text)
Other sources, not measured in this work			
Unloadings (plunger lift)	108* (EPA inventory)		No measurements made in this work
Workovers (with hydraulic fracturing)	143* (EPA inventory)		No measurements made in this work; equipment configurations are similar to completion flowbacks for wells with hydraulic fracturing; if emissions per event are comparable to completion flowbacks, current inventories may overestimate emissions
Other sources, not measured in this work	891–930*,¶ (EPA inventory)		Includes potential emissions of sources not measured less prorated regulatory and voluntary emission reductions*
Total methane, Gg	2,545	2,300	Decrease of ~250 Gg for estimate
Methane emissions,*,** % [percent of gross gas production]	0.47% [0.59%]	0.42% [0.53%]	Brackets: gross gas emitted/gross gas produced (assuming produced gas is 78.8% methane)

*Emissions from EPA national inventory are based on reported potential emissions less reductions; when reductions are reported for combined source categories, identical percentage reductions of potential emissions are assumed to apply across source categories (*SI Appendix*, section S5).

†Emission factors used to estimate national inventories are designed to be representative of the participating companies' activities and practices, but not necessarily all activities and practices.

‡National emissions based on a regionally weighted average (*SI Appendix*, section S5).

§Ranges are based on 95% confidence bounds of emission factors; activity factors are identical to those used in EPA inventory. Uncertainties in activity factors (e.g., device counts) are not included. Uncertainties associated with whether regional or national averaging is performed are included in the uncertainty estimate (*SI Appendix*, section S5.4).

¶Sampling in this work included compressors on well sites, but not all gathering compressors. Well site and gathering compressors are combined in the national inventory. Range reported for national inventory for equipment leaks and "other" sources reflect uncertainty in attributing compressor emissions from national inventory to a specific source category.

#Uncertainty bound assumes uncertainties for completion flowbacks, pneumatic pumps and controllers and leaks are independent, and consequently, the combined uncertainty is the square root of the sum of the squares of the individual uncertainties.

**US total gross gas production (oil and coal bed, gas, and shale, onshore and offshore): 547,000 Gg.

a single unloading event could, during the short period that it is occurring, result in emissions that are the equivalent of just a few wells in routine production to the equivalent of up to several thousand wells in routine production. Therefore, reconciliation between instantaneous ambient measurements and emission inventories will need to carefully represent the emissions from unloadings.

Well Sites in Routine Production. A well site contains one or more wellheads and may contain separators, pneumatic controllers, water tanks, hydrocarbon tanks (oil or condensate), and possibly other devices such as dehydrators, compressors, and flares. In this work, measurements were made from pneumatic controllers and pumps, because these devices release methane as part of their routine operation, and from equipment leaks detected by using an infrared camera (*SI Appendix*) at well sites.

Emissions for equipment on well sites, in routine production, that were targeted for measurements had much narrower uncertainty bounds than well completion flowbacks or well unloadings. Emissions from pneumatic chemical injection pumps measured in this work averaged 3.7 ± 1.6 g of methane per minute per pump, 9% lower than the EPA emission factor (*SI Appendix*, section S2). Intermittent and low bleed pneumatic devices measured in this work averaged 5.9 ± 2.4 and 1.7 ± 1.0 g of natural gas per device per minute, 29% and 270% higher than EPA emission factors, respectively (*SI Appendix*, section S2). No high bleed pneumatic devices were identified at the sampling sites, and the average emission rate for the population of pneumatic controllers sampled in this work was 3.36 ± 0.65 g of methane per min (3.8 ± 0.69 g of natural gas per min). Equipment leaks measured in this work averaged 1.23 ± 0.44 g of methane per minute per well, which can be compared with an

Table 3. Measurement methods used in the study

Source	Direct measurement methods	Mobile downwind sampling
Well completions	Measurements from flowback tanks made by using enclosures and temporary stacks with measurements of flow rate and composition	Downwind tracer ratio methods: Metered release of C_2H_2 and N_2O on site and downwind measurements of methane to C_2H_2 and methane to N_2O concentration ratios
Gas well unloading	Temporary stack with measurements of flow rate and composition	
Well workovers	Measurements from flowback tanks made by using enclosures and temporary stacks with measurements of flow rate and composition	
Production sites	Infrared (FLIR) camera surveys of sites and flow rate measurements using a HiFlow device	Metered release of C_2H_2 and N_2O on site and downwind measurements of methane to C_2H_2 and methane to N_2O concentration ratios

EPA estimate of potential emissions (no regulatory or voluntary emission reductions) of 1.37–1.67, derived from EPA's inventory for similar equipment types (wellheads, separators, heaters, meters/piping, and dehydrator fugitives), with the range reflecting whether small compressors are added to the comparison (*SI Appendix*, section S5). Comparing to net emissions is challenging because EPA does not assign emission reductions to specific equipment categories. Additional information is provided in *SI Appendix*.

There was significant geographical variability in the emissions rates from pneumatic pumps and controllers, but these regional differences were not as pronounced for equipment leaks. Emissions per pump from the Gulf Coast are statistically significantly different and roughly an order of magnitude higher than from pumps in the Midcontinent. Emissions per controller from the Gulf Coast are highest and are statistically significantly different from controller emissions in the Rocky Mountain and Appalachian regions. Emissions per controller in the Rocky Mountain region are lowest and an order of magnitude less than the national average (*SI Appendix*).

Implications for National Emission Estimates. If the average emissions reported in this work for well completion flowbacks, pneumatic devices, and equipment leaks are assumed to be representative of national populations and are applied to national counts of completions, pneumatic devices, and wells in EPA's national inventory, emissions from these source categories would be calculated as 957 Gg (with sampling and measurement uncertainties estimated at ±200 Gg), compared with 1,211–1,250 Gg methane per year in the 2011 EPA national inventory (1) for the same source categories. A large emissions decrease associated with completion flowbacks is partially offset by emission increases from pneumatic controllers and equipment leaks. Reasons for these differences are described in *SI Appendix*.

The estimated uncertainty in the national emission estimates based on this work is ∼20% (200 Gg). The sources of uncertainty include measurement uncertainty, uncertainty introduced by the selection of sites, and uncertainty due to choices in performing regional or national averaging of equipment counts and emission factors. These components of the quantified uncertainty are described in *SI Appendix*. The uncertainty estimate does not include factors such as uncertainty in national counts of wells or equipment and the issue of whether the companies that provided sampling sites are representative of the national population.

The 957 ± 200 Gg in emissions for completion flowbacks, pneumatics, and equipment leaks, coupled with national inventory estimates for other categories, leads to an estimated 2,300 Gg of methane emissions from natural gas production (0.42% of gross gas production). A summary is provided in Table 2, and details of the calculations are available in *SI Appendix*.

Total emissions estimated based on measurements in this work (2,300 Gg) are comparable with the most recent EPA national GHG inventory (2,545 Gg in the 2011 inventory, released in April 2013) (1). Table 2 also compares emissions in specific source categories, estimated based on the measurements made in this work, to EPA estimates of the same categories in the national inventory (1). For some emission categories, such as completion flowbacks and pneumatic controllers, conclusions can be drawn from the comparisons. Specifically, measured emissions from completion flowbacks are roughly 600 Gg lower than the completion flowback emissions in the current inventory; measured emissions from pneumatic controllers are 150–500 Gg higher than in the current inventory. For other emission categories, such as equipment leaks and pneumatic pumps, however, drawing conclusions is more difficult. For these source categories, the national inventory reports potential emissions for each category, but aggregates emission reductions, creating uncertainty in the net emissions in these categories (see *SI Appendix*, section S5.5 for more details).

It should also be noted that the national inventory has changed in recent years based on evolving regulations (21) and understanding of emission sources. In this work, comparisons are made to the most recent release of the inventory (2011 final version, released in April 2013) and back casts to previous years by using consistent calculation methodologies. Emissions were estimated as 2,545 Gg in 2011, compared with 2,948 Gg in 2009 and 2,724 Gg in 2010. The work presented here suggests practices such as combusting or capturing emissions from completion flowbacks, as required by New Source Performance Standards subpart OOOO and the revised National Emission Standards for Hazardous Air Pollutants subpart HH (21), are resulting in reduced methane emissions. Other source categories require more data to produce national emission estimates, and adjustments in the inventory may emerge as more emission measurements are performed. Emission estimates may be adjusted downward if workovers with hydraulic fracturing are found to have emissions per event that are similar to completion flowbacks and may be adjusted either upward or downward as more emissions data are collected for liquids unloading or pneumatic devices.

Finally, an emissions intensity of 0.42% is reported in Table 2. The intensity expresses a methane emission per unit of gross gas production. This intensity should be interpreted with caution, because it includes only production operations and implicitly attributes all methane emissions from natural gas wells to natural gas production, although natural gas wells produce substantial amounts of natural gas liquids and oil. The intensity is reported here because it facilitates comparisons with other analyses that have appeared in the literature (23).

Methods

Multiple independent and complementary techniques were used to measure methane emissions. The primary procedures involved direct measurements of CH_4 emissions at their source. A variety of different procedures were used for direct source measurements, depending on the type of source being sampled and the type of natural gas production equipment being used. Table 3 summarizes the direct source methods used in the study; detailed descriptions of the methods are provided in *SI Appendix*.

In addition to direct source measurements, tracer ratio measurements, designed to estimate the total methane emissions from a site, were made at 20% of the well completion flowbacks and 13% of the production sites. The tracer release method was developed in the 1990s to quantify methane emissions from a wide range of natural gas system components (24, 25). Sites for tracer releases were selected for their steady, moderate winds and downwind access. Measurements for sites without downwind access could not be made. Table 3 also summarizes these measurement methods, which are described in detail in *SI Appendix*. In brief, tracer compounds were released at a known rate on-site; downwind measurements of methane (minus background) and the tracer (minus background) were assumed to be equal to the ratio of emission rates, allowing methane emissions to be estimated. These measurements were performed for a subset of the sampling locations that had relatively open terrain and steady winds, producing well-defined emission plumes downwind of the sites. The tracer studies allowed for an independent measurement of emissions that were also measured by using direct source methods. For completion flowbacks, emission estimates based on the downwind measurements were generally within a factor of 2 of the direct source measurements, supporting the conclusion that emissions from completion flowbacks are roughly 97% below the most recent national estimates and that emissions from completion flowbacks without methane control or recovery equipment, observed in this work, are well below the average potential emissions in current national inventories (1). For the production sites, emissions estimated based on the downwind measurements were also comparable to total on-site measurements; however, because the total on-site emissions were determined by using a combination of measurements and estimation methods, it is difficult to use downwind measurements to confirm the direct source measurements. Tracer study results are summarized in *SI Appendix*.

ACKNOWLEDGMENTS. We thank the sponsors of this work for financial support, technical advice, and access to sites for sampling. The sponsors were Environmental Defense Fund (EDF), Anadarko Petroleum Corporation, BG Group plc, Chevron, Encana Oil & Gas (USA) Inc., Pioneer Natural Resources Company, SWEPI LP (Shell), Southwestern Energy, Talisman Energy USA, and XTO Energy, an ExxonMobil subsidiary. Funding for EDF's methane research series, including the University of Texas study, is provided for by Fiona and Stan Druckenmiller, Heising-Simons Foundation, Bill and Susan Oberndorf, Betsy and Sam Reeves, Robertson Foundation, Tom Steyer, Kat Taylor, and the Walton Family Foundation.

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Below 2°C or 1.5°C depends on rapid action from both Annex I and Non-Annex I countries

Climate Action Tracker

Policy Brief

4 June 2014

Revised 7 June 2014

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Summary: Next decade critical to keep warming below 2°C or 1.5°C

- The UNFCCC climate talks in June 2014 are aimed at increasing emissions reduction actions in the pre-2020 period, as well as substantially improving mitigation ambition for the post 2020 period in the new climate agreement to be concluded next year.
- In order to prevent dangerous climate change and limit warming to below 2°C or 1.5°C, both Annex I and Non-Annex I countries need to both significantly increase the level of current action to reduce emissions ahead of 2020 and commit to deeper cuts in emissions than currently pledged post 2020.
- In this update the Climate Action Tracker has conducted a new analysis of the IPCC AR5 emissions database to evaluate the required level of global and regional action for 2020, 2025 and 2030 to limit warming to below 2°C or 1.5°C with a likely (66%) and high (85%) probability. A likely pathway for limiting warming below 2°C still has a one in three chance of exceeding this level, and possibly higher when uncertainties in the climate sensitivity and carbon cycle not included in the climate models are considered. A higher probability set of emission pathways then gives much greater security that investments in limiting warming below 2°C will be successful. The high probability 2°C pathways in general also limit warming to 1.5°C or below by 2100.
- Limiting warming below 2°C with a high chance of success means that **total GHG emissions would need to be zero between 2060 and 2080, and likely negative thereafter. CO_2 emissions from fossil fuel combustion and industry would need to be zero between as early as 2045 and no later than 2065, and be negative thereafter.**
- Required emission reductions for Annex I and Non-Annex I groups depend on the economic and equity assumptions applied. For Annex I (developed) countries an equity approach based on capability to mitigate would require reductions of 25-55% below

1990 levels by 2025 and 35-55% below 1990[1] levels by 2030 for a likely 2°C pathway. Other equity approaches would require even deeper reductions.

- For Non-Annex I (developing countries) an equity approach based on capability to mitigate would require an emissions allocation limited to 0-95% above 1990 levels by 2025 for the likely 2° scenarios, and an emissions allocation limited to 5-90% above 1990[2] levels by 2030. Other equity approaches would allow higher emissions allocations. In 2010 Non-Annex I emissions were about 75-80% above 1990 levels, hence in overall terms during the 2020s these emissions under this equity approach would need to be, at their highest, close to present levels or, more likely, significantly below present levels.
- Rapid and deep emissions reductions are not only necessary to limit warming below 2° (or 1.5°C), but are feasible at a modest cost. However, the window of opportunity to limit warming below 2°C could be closed by end of the 2020s unless action is accelerated.
- The IPCC AR5 estimates that currently implemented policies put the world on track to a 3.7 to 4.8°C warming by 2100, confirming earlier projections carried out by the Climate Action Tracker.
- One of the main causes of the recent global increase in emissions growth is the post-2000 reversal of historic decarbonisation trends, driven in large part by the growth of coal combustion. In all of the studies assessed in the IPCC AR5 consistent with limiting warming below 2°C with a high probability **the energy sector needs to decarbonise rapidly and reduce to zero emissions as early as 2045 but no later than 2065.**
- One of the major challenges for Ministers at the UNFCCC meeting in Bonn is to take concrete steps to arrest and reverse this adverse trend in decarbonisation.

USA "Clean Power Plan" emissions reductions and decarbonisation rates far from those needed for 2°C

- In light of this need for decarbonisation of the industry and energy sectors, the CAT has also analysed the US Government's "Clean Power Plan" proposed rule leading to a 30% cut (from 2005 levels) in emissions from power plants.
- While the proposal is welcome, it is insufficient by itself to meet the USA pledge of a 17% reduction of all greenhouse gas emissions by 2020. In 2030, we project the US economy-wide emissions would be around 5% above 1990 levels (or 10 % below 2005 levels), far above levels required for a likely 2˚C pathway.
- The US "Clean Power Plan" implies an economy-wide decarbonisation rate of about 0.9% per annum over the next 15 years, significantly lower than the 1.4% p.a. achieved in the last decade. This is not as fast as is needed for a 2°C decarbonisation pathway.

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[1] 26-48% below 2010 levels

[2] 41% below to 8% above 2010 levels

Emissions levels compatible with 2°C and 1.5°C

The Climate Action Tracker has conducted a new analysis of the mitigation scenarios assessed by IPCC AR5 WGIII, to evaluate the global emissions pathways compatible with holding warming below 2°C and returning to below 1.5°C warming by 2100. The emissions pathways were selected on the basis that:

- These emission scenarios fall within historical limits up to 2010. This excludes some studies whose emissions diverge significantly below historic emissions before 2010.
- They limit warming to below 2°C with a likely (66%) or high (greater than 85%) probability. The latter pathways also return to, or below, 1.5°C by 2100.
- We differentiated between "overall least-cost" mitigation scenarios, which reach long-term targets by reducing emissions at any time over the 21st century to minimise costs, and those that involved a "deliberate" delay in mitigation action. We focussed on the former.

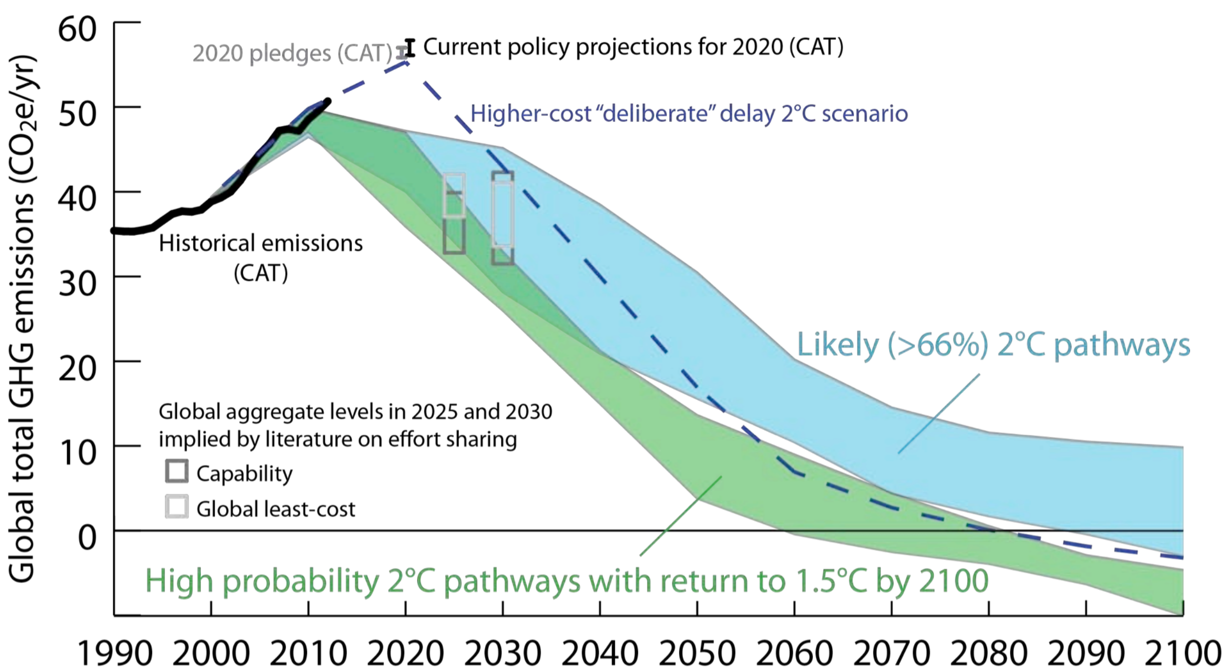

Figure 1: Timeline for global emissions (in Gt CO_2-equivalents per year) to peak and decline towards zero for 2°C and 1.5°C long-term temperature limits. The dashed line indicates the medium of the few scenarios from IPCC AR5 WGIII that reach emission levels in 2020 close to those implied by the Cancun pledges, while still reaching later-century deep reductions sufficient to hold warming below 2°C. Source: Climate Action Tracker calculations based on IPCC database (10-90% range of AR5 WGIII emissions scenarios that are not deliberately forced to reach 2020 emission levels comparable to those implied by the Cancun pledges and do hold warming below 2°C in >66% of climate-model runs) and scenarios that hold warming below 1.5°C by 2100 in >50% of climate-model runs.

	2020	2025	2030	2050	Zero emissions	2100
Stay below 2°C during 21st century with *likely* (more than 66%) probability						
Total GHG below 1990	25 to 10% above 1990	25% above to 5% below 1990	20% above to 25% below 1990	20 to 60% below 1990		75 to 105% below 1990
$GtCO_2e$/yr	40 to 47	35 to 46	28 to 45	16 to 31	2090 or after	-3 to 10
CO_2 emissions from fossil fuel and industry	26 to 35	21 to 34	16 to 33	3 to 19	2060 of after	-15 to 2
Stay below 2°C with at least 85% probability – return to below 1.5°C by 2100 with at least 50% probability						
Below 1990	25% above to 5% below	10% above to 15% below	10-30% below	65-90% below		110-125% below
$GtCO_2e$/yr	36 to 47	31 to 40	26 to 33	4 to 14	2060-2080	-10 to -5
CO2 emissions from fossil fuel and industry	21 to 31	17 to 26	13 to 20	-8 to 4	2045-2065	-17 to -9

Table 1: Global emissions pathway to 2°C and 1.5°C for 2020, 2025, 2030, 2050 and 2100 Source: Climate Action Tracker; calculations based on the scenarios assessed by IPCC Working Group 3 in AR5. Range represent 10-90% range for AR5 WGIII "no delay" emission scenarios, i.e. those for which the energy-economic models are not deliberately forced to reach 2020 emission levels comparable to those implied by the Cancun pledges. Likely 2°C scenarios hold warming below 2°C with over 66% probability over the whole of the 21st century. 1.5°C scenarios hold warming below 1.5°C by 2100 with over 50% probability and hold warming below 2°C with over 85% probability over the whole of the 21st century. Probabilities refer to the percentage of climate model runs within a large ensemble of runs, with varying sensitivity and carbon-cycle characteristics, that hold warming below 2 or 1.5°C.

The motivation to examine high probability 2°C pathways stems from that a likely pathway for limiting still has a one in three chance of exceeding 2°C. The chance of exceeding 2°C is possibly higher than this when uncertainties in the climate sensitivity and carbon cycle not included in the climate models are considered. A higher probability set of emission pathways would then give a much greater security that investments in limiting warming below 2°C will be successful. The high probability 2°C pathways in general also limit warming to 1.5oC or below by 2100.

As a consequence of these selection criteria, the detailed results differ from those presented in the IPCC AR5 WGIII Summary for Policy Makers. We confirm the broad findings of WGIII: **that limiting warming to 2°C implies halving global GHG emissions in 2010 (49 $GtCO_2eq$) by 2050 and reaching very low or even negative levels by 2100.**

However, for CO_2 emissions from the industry and energy sector, emissions must reach zero much sooner, from around 2045. In this report we have generally compared emissions to 1990 levels to enable easy cross-comparison with previous assessments. The emissions levels consistent with 2°C and 1.5°C pathways are displayed in Table 1 and Figure 1.

The lowest of the AR5 scenarios (RCP2.6) indicates global warming can be limited to close to 1.5°C above pre-industrial levels. Negative emissions play a larger role than in the 2°C scenarios. It is as likely as not that sustained globally negative emissions after 2050 will be required to achieve the reductions in atmospheric CO2 in RCP2.6 (AR5, WG1).

The global GHG emissions compatible with below 2°C or 1.5°C follow a steep declining pathway for the period 2020 through 2050. During the 2020s and early 2030s the 1.5°C emissions pathways overlap with the lower part of the 2°C emission ranges, before diverging:

- In 2020, global emissions should have peaked and dropped below 47 GtCO2 (25% above 1990 emissions; just below 2010 emissions) and safer, as low as 40 GtCO2: 10% above 1990 emissions levels and 15% below 2010 levels
- By 2025, emissions should have returned to 35-46 GtCO2eq (5% below to 25% above 1990 emission levels; 5-30% below 2010) for 2°C pathways and 31-40 GtCO2eq (10% above to 15% below 1990 emission levels; 15-35 below 2010) for 1.5°C pathways
- By 2030, emissions should have returned to 28-45 GtCO2eq (20% above to 25% below 1990 emissions levels; 5-40% below 2010) for 2°C pathways and 26-33 GtCO2eq (10-30% below 1990 emissions levels; 35-45% below 2010) for 1.5°C pathways.
- In 2050, emissions should be 16-31 GtCO2eq (20-60% below 1990 emissions levels; 35-65% below 2010) for 2°C pathways and 4-14 GtCO2eq (65-90% below 1990 emission levels; 70-90% below 2010) for 1.5°C pathways

Limiting warming below 2°C with a likely probability implies that total GHG emissions eventually have to decline towards zero by 2100 and CO_2 emissions from fossil fuel and industry would need to be zero as soon as the late 2050s. This contrasts with the high probability 2°C pathways where total GHG emissions reach zero between 2060 and 2080. In the case of CO_2 emissions from fossil fuel and industry the high probability require zero emissions about ten years earlier than in the likely pathways.

Bringing warming back to 1.5°C implies faster emission reductions and an earlier approach to zero GHG and CO_2 emissions: total GHG emissions would need to be zero between 2060 and 2080.

CO_2 emissions from fossil fuel and industry would need to be zero by the 2040s and no later than 2070, and negative thereafter.

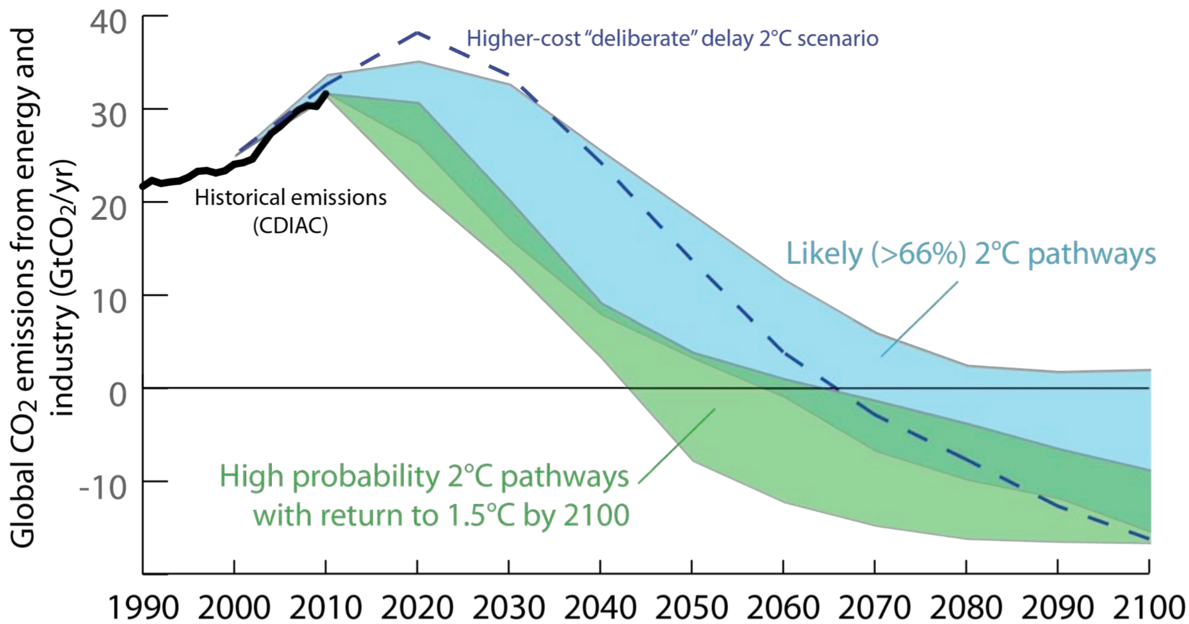

Figure 2: Total global CO_2 emissions from energy and industry 2005 – 2100 compatible with a 2°C pathway. Source: Own calculations based on IPCC database (10-90% range of AR5 WGIII emission scenarios that are not deliberately forced to reach 2020 emission levels comparable to those implied by the Cancun pledges and do hold warming below 2°C in >66% of climate-model runs) and scenarios that hold warming below 2°C in >66% and return to below 1.5°C by 2100 in >50% of climate-model runs.

These emissions reductions would ensure a high chance (>85%) of limiting warming below 2°C, significantly better than the "likely" 2°C pathway described above.

Comparing Figure 2 below with Figure 1 illustrates that for CO2 emissions, the picture looks quite different than is the case for all greenhouse gases.

A high probability 2°C pathway requires a full decarbonisation of the energy sector by as early as 2045, when CO_2 emissions from industry and energy use reach zero in the low emission scenarios.

For such low emission scenarios, IPCC WGIII notes that global CO2 emissions from the energy supply sector are projected to decline over the coming decades and are characterised by reductions of 90% or more below 2010 levels between 2040 and 2070. Emissions in many of these scenarios are projected to decline to below zero thereafter (IPCC AR5, WGIII, SPM).

The IPCC AR5 warns: "*Delays in mitigation through 2030 or beyond could substantially increase mitigation costs in the decades that follow and the second-half of the century*" (IPCC AR5, WGIII, SPM).

Delayed action also implies increased use of technologies that can provide 'negative emissions,' primarily bio-energy combined with carbon capture and storage (BECCS).

Mitigation scenarios without BECCS are found in the lower half of the emission ranges around 2020-2030 and at the upper end by the end of the 21st century.

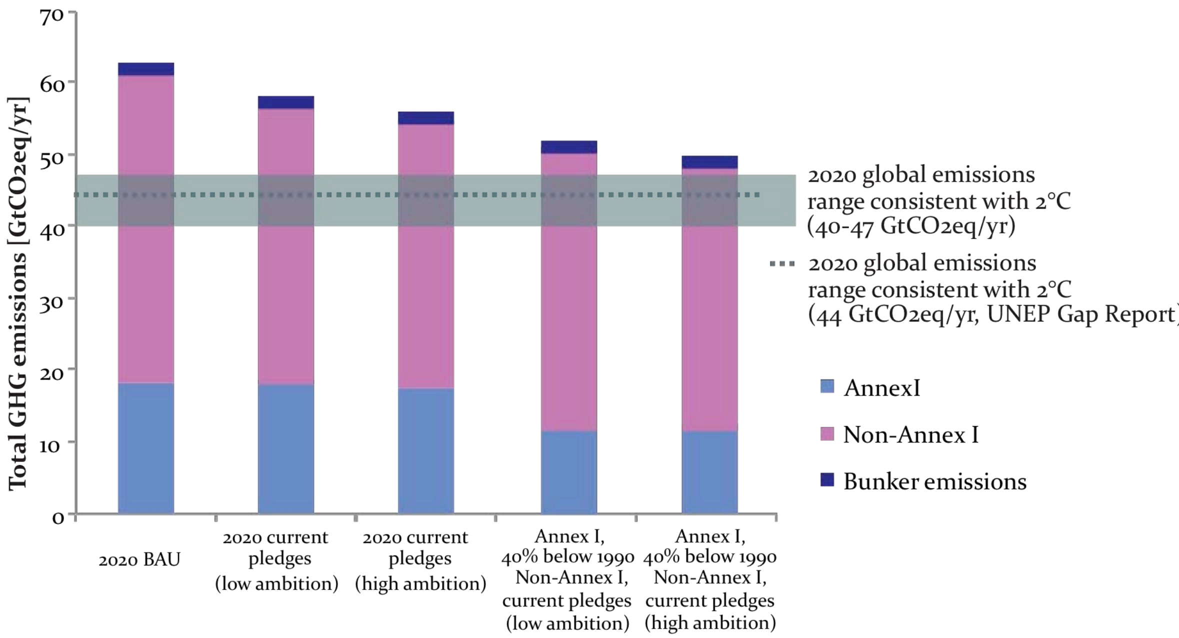

Figure 3: Effect of Annex I increasing mitigation efforts to 40% reduction below 1990 level in relation to 2020 global emissions level consistent 2 and 1.5°C. The emissions gap is the result of total global emissions (top of the bar) and the 44GtCO2eq level, depicted by the grey dotted line.

All Governments need to commit to deeper emissions reductions.

The results from the scientific research clearly show that international cooperation is a prerequisite for effective mitigation action. The endeavour to stay below 2°C will not be achieved if individual agents advance their own interests independently.

The numbers show that further action is needed by both Annex I and non-Annex I Governments to close the 2020 'emissions gap.'

Some parties to the UNFCCC have argued that if Annex I countries were to reduce emissions by 40%, this would be sufficient to close the so-called emissions gap in 2020. Figure 3 above shows the contribution of Annex I and Non Annex I Parties to 2020 levels of emissions. Even if Annex I Parties reduced emissions by 40% below 1990 levels, there would still be an emissions gap in 2020 that the major emitters in the Non-Annex I group would need to close through additional efforts .

Mitigation costs keeping warming below 2°C are modest

The costs of keeping warming levels below 2˚C by the end of this century are modest. Estimates of average global macro-economic costs over the century show that loss in total global consumption is limited compared to overall expected economic growth. It is important to note that these cost estimates do not take co-benefits of climate action into account.

Under a cost-effective approach, assuming a global and unique carbon price, macro-economic costs equal an average annual reduction of consumption of about 0.04-0.14 % per year.

Given that the models project a baseline increase of consumption over the 21st century of **1.6-3% per year**, this means that annual economic growth in 2030 would be 1.4%-3.0% instead of 1.6-3.0%.

In 2050, growth rates would be 1.5%-2.9% instead of 1.6-3% and, in 2100, the annual growth rate with mitigation action consistent with the 2C pathway is 1.5%-3.0% instead of 1.6-3.0% (IPCC AR5, WGIII, Chapter 6, p. 8)

This means that with mitigation action, GDP would grow by 43-107% in 2030 in relation to 2005, instead of 49-109% without mitigation action. In 2050, world GDP is projected to be 92-271% larger than in 2005 with implemented climate policy, against 104%-278% in the baseline scenario. In 2100, the economy is projected to grow by 302-1508% instead of 352-1558%, compared to 2005 levels. The differences in final global consumption of goods are marginal as displayed in Figure 4 below.

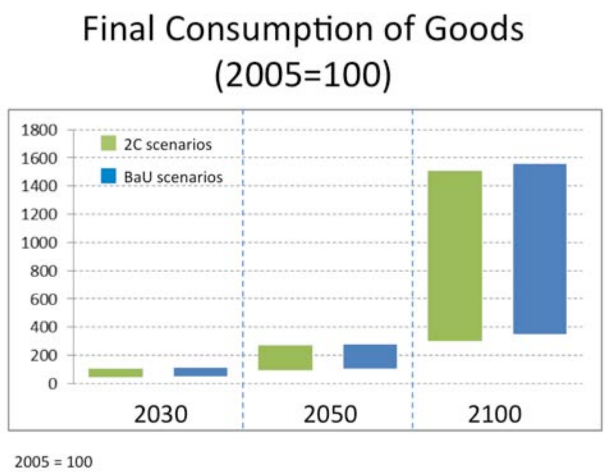

Figure 4: Final total global consumption of goods in 2030, 2050 and 2100, with and without mitigation action required to stay below 2°C. Source: Own elaboration based on IPCC numbers.

Regional distribution of emissions reductions on a below 2°C pathway

The overall emissions pathways to stay below 2°C in 2025 span a range of 35Gt – 46 $GtCO_2e$/yr, which reduces to 28-45 GtCO2e/yr by 2030. This translates into global emissions cuts of approximately 5% below 1990 to 25% above 1990 by 2025 and 25% below 1990 to 20% above 1990 by 2030.[3] It should be noted the feasible emissions pathways cannot be at the top of both the 2025 and 2030 ranges. The task now is to share this fixed global emissions level amongst all countries.

This condition could be met, for example, if all individual Governments were to reduce their emissions by the same percentage, say, 30% below today's level in 2030.

This is highly unlikely since the basic principle of the United Nations Framework Convention on Climate Change is that "Parties should protect the climate system […] on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities."

This means that, depending on each government's responsibility and capability, countries' emissions cuts would diverge from the global average.

[3] 5-30% below 2010 by 2025 and 5-40% below 2010 by 2030

Option	Annex I			Non-Annex I			
	Total	OECD90	EIT	**Total**	LAM	MAF	ASIA
	Relative to 2010						
Global least cost	**-33% to -40%**	-30% to -35%	-39% to -53%	**3% to -32%**	-23% to -75%	21% to -22%	2% to -26%
Average	**-28% to -73%**	-32% to -79%	-20% to -59%	**15% to -28%**	-12% to -54%	-10% to 26%	17% to -28%
Equal cumulative per capita	**-75% to -85%**	-76% to -84%	-72% to -85%	**4% to -12%**	-15% to -71%	n.a.	12% to -13%
Capability	**-20% to -50%**	-19% to -52%	-23% to -44%	**10% to -42%**	-16% to -66%	-9% to 47%	3% to -48%
	Relative to 1990						
Global least cost	**-39% to -46%**	-26% to -31%	-60% to -69%	**21% to 81%**	-11% to -71%	62% to 152%	37% to 90%
Average	**-35% to -76%**	-27% to -78%	-47% to -72%	**28% to 104%**	1% to -47%	89% to 164%	34% to 119%
Equal cumulative per capita	**-77% to -86%**	-74% to -83%	-82% to -90%	**55% to 83%**	-3% to -67%	n.a.	63% to 109%
Capability	**-27% to -54%**	-14% to -49%	-48% to -63%	**2% to 94%**	-3% to -61%	91% to 207%	-3% to 93%

Table 2: 2025 Regional distribution of emission reductions for illustrative cases (relative difference to 1990 and 2010 emissions in 2025) staying within atmospheric GHG concentrations keeping temperature increase below 2°C above preindustrial levels. The same exercise could be done for 1.5°C, however data for sharing efforts under these scenarios are less available. Source: Own analysis based on supplemental data from Höhne et al. 2013

If some governments manage to reduce more than 30%, others can reduce less or even increase their emissions. Developed countries currently emit two thirds of the total greenhouse gas emissions of all developing countries. As a rule of thumb, three percentage points additional reduction to 30% by all developed countries would give room for two percentage points less reduction below 30% for all developing countries, if the same global total is to be reached.

One way to differentiate between country reductions would be to assume they would need to happen where they are the cheapest. Global models provide such scenarios where total global costs are minimised. Results for such a case depend on the model used and the assumptions on costs. Illustrative results of such scenarios are provided in Table 2 and Table 3 as Option "global least cost."

Reductions for developing countries as a whole would be less stringent than a 30% flat rate, because these calculations take into account consumption growth in the developing world. For Latin America, however, it would be more than 30%,

Option	Annex I			Non-Annex I			
	Total	OECD90	EIT	**Total**	LAM	MAF	ASIA
				Relative to 2010			
Global least cost	**-33% to -41%**	-30% to -35%	-39% to -57%	**2% to -32%**	-25% to -75%	21% to -22%	2% to -27%
Average	**-36% to -65%**	-39% to -69%	-28% to -54%	**-28% to 11%**	-18% to -51%	-7% to 38%	7% to -31%
Equal cumulative per capita	**-81% to -85%**	-82% to -85%	-80% to -85%	**1% to -12%**	-35% to -75%	n.a.	10% to -15%
Capability	**-26% to -48%**	-28% to -49%	-23% to -47%	**8% to -41%**	-15% to -58%	-7% to 48%	-1% to -49%
				Relative to 1990			
Global least cost	**-39% to -47%**	-26% to -31%	-60% to -71%	**20% to 80%**	-14% to -71%	62% to 152%	37% to 90%
Average	**-42% to -68%**	-35% to -67%	-52% to -69%	**26% to 95%**	-6% to -44%	93% to 189%	29% to 100%
Equal cumulative per capita	**-83% to -86%**	-81% to -84%	-86% to -90%	**56% to 78%**	-25% to -71%	n.a.	58% to 105%
Capability	**-33% to -53%**	-23% to -46%	-48% to -65%	**4% to 90%**	-2% to -52%	94% to 210%	-4% to 85%

Table 3: 2030 Regional distribution of emission reductions for illustrative cases (relative difference to 1990 and 2010 emissions in 2030) staying within atmospheric GHG concentrations keeping temperature increase below 2°C above preindustrial levels. As there is no data for MAF, we use the same reduction as in the second option for this region when adding up the total non-Annex I. The same exercise could be done for 1.5°C, however data for sharing efforts under these scenarios are less available.
Source: Own elaboration based on data from Höhne et al. 2013

because some models assume there is a large potential to reduce emissions from deforestation at relatively low costs.

A second way to look at it is to distribute differentiated reductions across countries based on their responsibility and/or capability, building on the Convention principles.

Below we show several options for how emission reductions can be distributed among different groups of countries or regions. We draw upon the summary of these studies in the IPCC AR5,[4] which is based on Höhne et al. 2013.[5] They find a large variation across different options, reflecting that there are many ways to share emission reductions.

Taking a broad average over all possible ways of sharing the reductions based on the principles, emission reduction targets for OECD1990 countries would be roughly half of current emissions by 2030.

Targets for Economies in Transition (EIT) would be approximately two

[4] IPCC AR5, working group III, Figure 6.28 and 6.29, www.mitigation2014.org

[5] Niklas Höhne, Michel den Elzen & Donovan Escalante (2014) Regional GHG reduction targets based on effort sharing: a comparison of studies, Climate Policy, 14:1, 122-147, DOI:10.1080/14693062.2014.849452

thirds of current levels. Emissions reduction targets in Asia would be similar to current levels; for the Middle East and Africa (MAF), slightly above the 2010 level and, in Latin America (LAM), well below the 2010 level (Option "Average"). Compared to the "global least cost" option, developing countries as a group would have to reduce less: their mitigation potential is larger than their responsibility and capability.

To cover the extremes of the spectrum, we also show the results for two categories of approaches to share reductions. One extreme approach is "equal cumulative per capita emissions", i.e. equal carbon budgets for countries. In this case, developed countries would have to reduce significantly more, because they have already used most of their per capita carbon budget in the past.

Another extreme approach is sharing emissions reductions according to capability, defined as equal mitigation costs per GDP. In this case, developed countries would have to reduce a lot less, but still more than the 30% we started from.

When the regions are added up in groups of Annex I and non-Annex I countries, Annex I countries will need to reduce emissions beyond the 30% average under all options. Some approaches suggest substantial additional reductions (Table 3).

A related question is where international financial flows should support mitigation actions. Trading of emission allowances may be necessary as expected developed country emission reductions go beyond mitigation potentials.

Changing the negative trend: reversal of recarbonisation is both critical - and possible

From 2000-2010, the energy sector saw a reversal of the decarbonisation trend that took place over the preceding 30 years (1970 – 2000).

This is a critical observation when considering the fact that global CO2 emissions from energy and industry will have to decrease to zero around 2060 to keep warming below 2°C as shown in Figure 2 above.

The IPCC's interpretation of this development is that economic growth and population continue to be the most important drivers of the increase in CO2 emissions from fossil fuel combustion.

While it is true that population and GDP are responsible for the largest absolute changes in decadal CO2 emissions, both these parameters cannot be "improved" like carbon intensity and energy intensity can.

On the one hand, population is an exogenous driver to the models that calculate the emission scenarios. On the other hand, the goal of these models is to maximise consumption of final goods per capita, which is directly linked to GDP growth.

Therefore reducing GDP growth in order to meet a climate target is an option of last resort for these models. The only parameters that can actually be changed are therefore carbon intensity and energy intensity. Achieving the 2°C targets hence requires substantial efforts in these two areas.

Carbon intensity

Figure 5 illustrates how carbon intensity has increased over the past ten years. The figure shows historical development of carbon intensity from 1970 to 2010. It also draws the line for the continued trend from 1970 – 2000 to 2010, to show the significant deviation from the previous trend.

CAT's assessment finds that about **80% of the accelerated increase in CO2 emissions in the period 2000 – 2010 is due to a reversal of the historical decarbonisation trend.**[6]

carbon intensity i.e. the amount of carbon emissions to energy use.

Figure 6 describes what values are required for carbon intensity from now until 2050 in order to stay below the 2°C pathway with 66% probability. It becomes clear that carbon intensity rates will have to decrease rapidly in the coming decades: increasing to 3% annually by 2030 and close to this level through the 2040s, before gradually reducing to 1.6% annually in the 2050s.

The energy sector is decarbonised at the point when global carbon intensity, i.e. total CO_2 emissions from energy and industry related to global energy consumption, approach zero.[7]

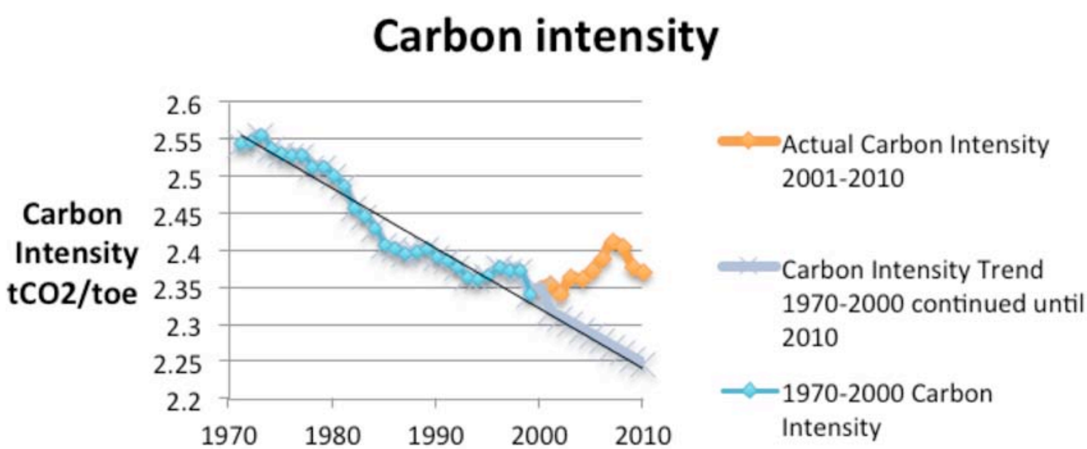

Figure 5: Carbon intensity over the period 1970-2010, actual and corrected to fit the historical trend from 1970-2000. Source: Own calculation based on IEA numbers.

Increasing emissions reductions in the energy sector means reducing the

[6] These 80% are the share of additional increase in emissions from 2000 – 2010 compared to the emissions trend from 1970 – 2000 that can be explained by the reversal of in carbon intensity. 83% of this additional increase, i.e. the increase above the trend from 1970-2000, is explained by carbon intensity, not population growth or GDP.

[7] With the Kaya identity, a decomposition method aimed at analysing emission scenarios for CO_2 emissions from energy and industry, we can investigate what the required pathways for energy intensity and carbon intensity should be in order to stay below 2°C (and 1.5°C). GDP and population are here considered as external drivers for reasons explained above.

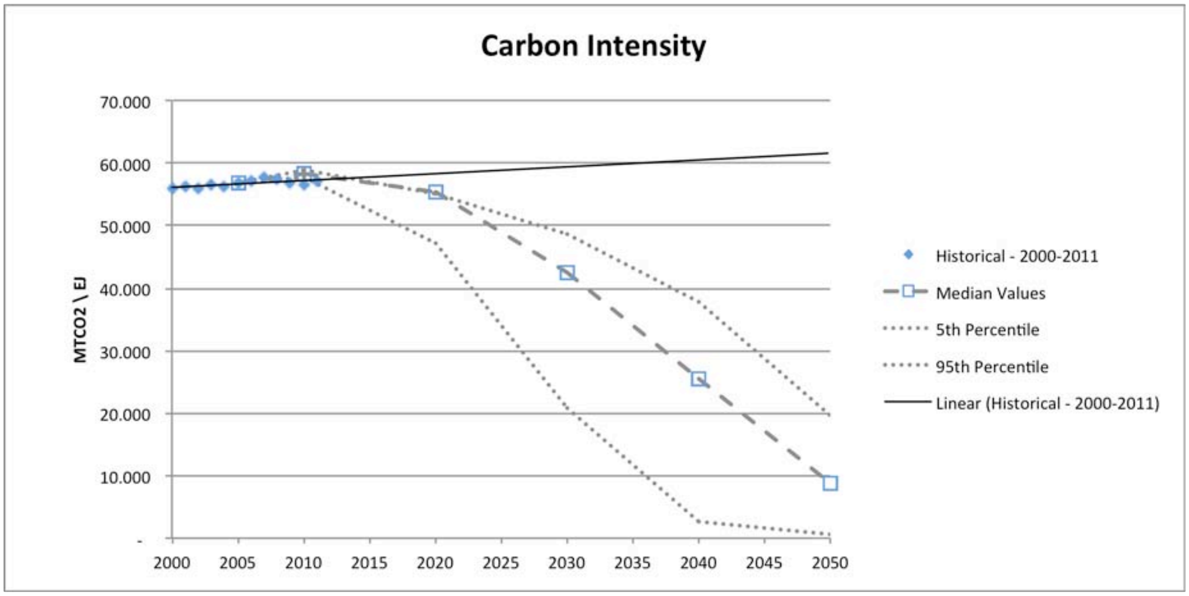

Figure 6: Carbon intensity 2000 – 2050, historical and projected. The solid line shows the trend for 2000-2010 if continued up to 2050. The dotted line shows carbon intensity compatible with 2°C. Source: Own estimates based on IEA

Rapid shifts are possible

Examples from the past show that transformative processes can move faster than initially expected.

Increase in renewable energy: Costs of renewable energy have declined dramatically over the last years and much faster than previously expected. One exceptional example is the decline of costs for solar photovoltaic. Some renewable energy technologies have achieved market competitiveness.

In 2012, renewables made up **just over half of total net additions to electric generating capacity** from all sources in 2012[8]. This could be the start of a new positive trend paving the way to a full decarbonisation of the energy sector.

A low-carbon world requires 100% of net additions from carbon-neutral technologies and phase-out of fossil fuel-based power plants. This transition has been much faster than expected. The International Energy Agency has constantly underestimated the growth of renewable energy: since 2006, every version of the World Energy Outlook has had to increase its renewable capacity projections to reflect real developments.

Efficient lighting: the transition to very efficient lighting was also faster than predicted: 55 countries have agreed to phase out inefficient lighting by 2016 under the initiative En.lighten and are implementing concrete actions to meet this target.[9]

The IPCC expects very efficient LEDs to become the most widely-used light source in the future.[10] Some global lighting technology providers have switched entirely to very efficient LEDs.

[8] http://www.ipcc-wg3.de/assessment-reports/fifth-assessment-report

[9] http://www.enlighten-initiative.org

[10] http://www.ipcc-wg3.de/assessment-reports/fifth-assessment-report

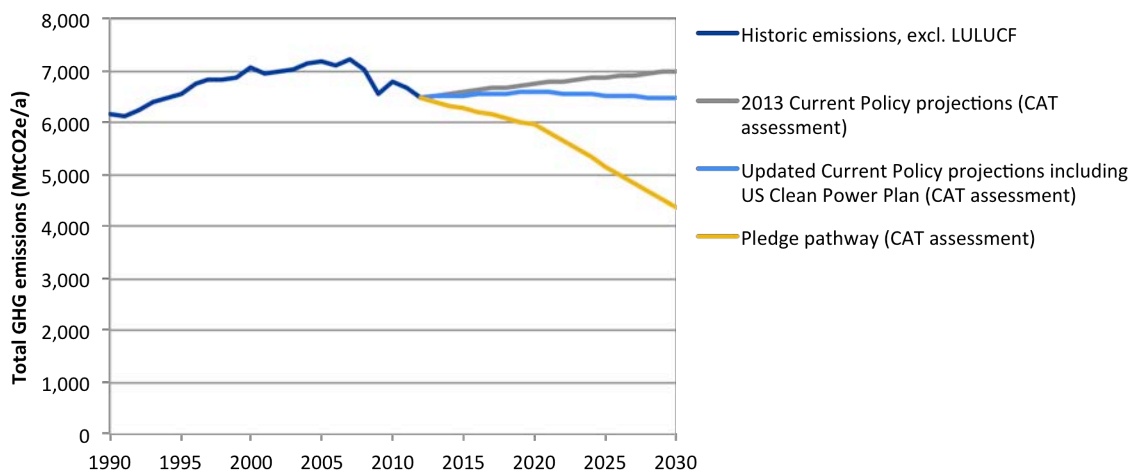

Figure 7: GHG emissions of the USA under different scenarios. Source: Own calculations and CAT update 2013.

Car standards/electro mobility: Various countries have now put in place or intend to instigate – increased efficiency or emissions standards for cars. Important examples are the US, the EU, Japan and China.

The EU has the globally strongest standard – and is overachieving it. The Global Fuel Economy Initiative, founded in 2009, promotes the improvement of the energy efficiency of vehicles globally to 50% of current energy intensity.[11] An electric car is now in the palette of every large car manufacturer, unthinkable a few years ago. They expect this technology to be the future.

US action on existing power plants an important but, taken alone, is insufficient to meet its pledge

The US Environmental Protection Agency (EPA) announced on 2 June 2014 a new regulation that will **reduce GHG emissions from the electricity sector by 30% below 2005 levels by 2030**.

This is the first time US authorities are regulating CO2 emissions from the electricity sector on a federal level. Until now, comprehensive policies that reduce GHG emissions from power plants have only been implemented at the state level.

However, the new rule is insufficient to meet the US pledge of a 17% reduction from 2005 emissions[12] of all greenhouse gas emissions by 2020 (equivalent to about 4% below 1990 levels) and is inconsistent with the long-term target of 83% below 2005 levels by 2050 (equivalent to about 80% below 1990 levels by 2050)(Figure 7).

[11] http://www.globalfueleconomy.org

[12] US 2005 emissions were 16% above 1990 levels.

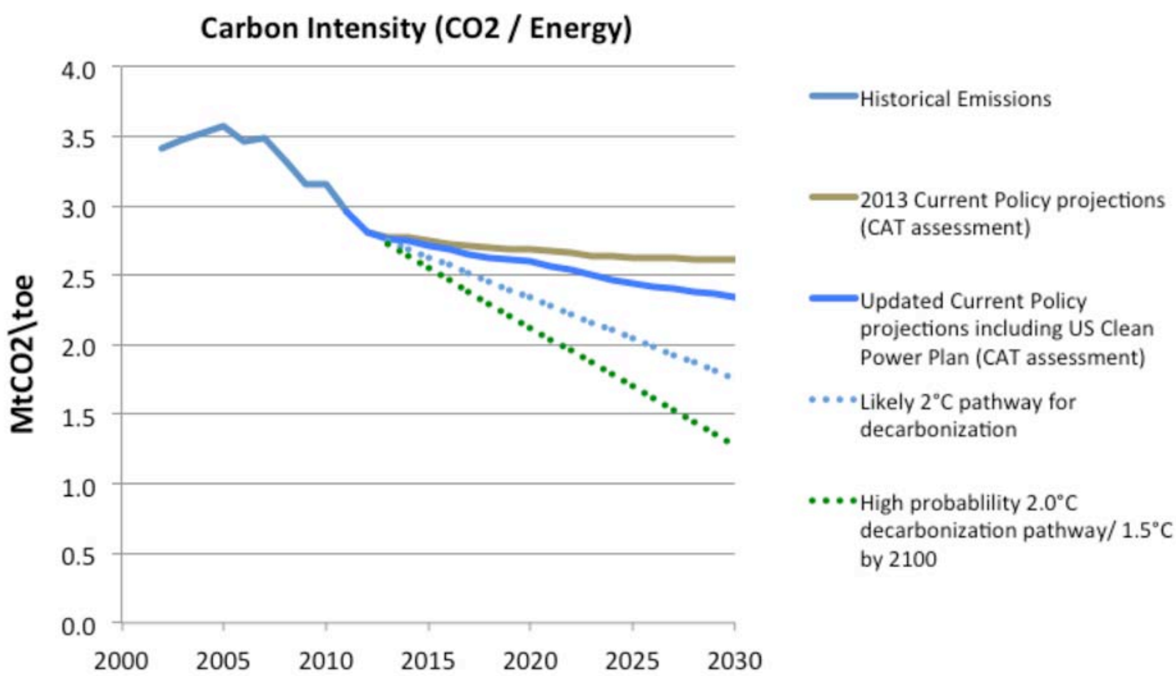

Figure 8: Carbon intensity for the USA historically and under different scenario projections, including the estimated effects of the recently announced Clean Power Plan Proposed Rule.

Based on the CAT assessment, US 2030 economy-wide emissions would be around 5% **above** 1990 levels (or 10 % below 2005 levels). These levels are far above those required for a 2°C pathway. The CAT has calculated from the IPCC AR5 scenarios that reductions for Annex I countries in 2025 and 2030 should be 25-55% and 35-65% **below** 1990 levels respectively for an equity scenario based on relative capability to mitigate.

The EPA's Clean Power Plan addresses emissions from the electricity sector only, which is a major contributor to the USA's total GHG emissions.

In 2012, around one third of the USA's total emissions of 6488 MtCO2eq originated from the power sector.[13]

The new proposed regulation for emissions of electric power plants in the USA will bring GHG emissions down by around 200 MtCO2e/a in 2020 compared to trends without this regulation.

This will help the USA to implement its pledge, but will not be sufficient to close the full gap of around 700 MtCO2e between recent trends and the pledge from earlier assessments[14] of the Climate Action Tracker.

Under the Copenhagen Accord, the USA has announced a long-term target of reducing total GHG emissions: 83% below 2005 in 2050. This target would be just within the range of the USA's emissions

[13] In several analyses of the EPA plan a share of 38% was used. This figure arises when including carbon removals from forestry into the US total emissions.

[14] http://climateactiontracker.org/publications/publication/154/Analysis-of-current-greenhouse-gas-emission-trends.html

compatible with 2°C.[15] In order to be on track to meet their long-term target, the US GHG emissions in 2030 would have to be about 39% below 2005 levels (equivalent to 29% below 1990 levels).

Linearly extrapolating the proposed target for emissions from the electricity sector (30% below 2005 in 2030) into the future would mean that emissions reach minus 54% in 2050 and zero by 2090. This would be too late to reach the long-term pledge of the USA of -83% of all greenhouse gas emissions by 2050.

We calculate a reduction below BAU of approximately 0.5 GtCO2e in 2030 and a decrease of 726MtCO2e/a from 2491MtCO2e/a in 2005. Assuming a linear decrease from today onwards, this would mean emissions of 1950 MtCO2e/a in 2020, in comparison to 2120 MtCO_2e/a in the most recent projections of the USA.[16]

The **Clean Power Plan** is part of President Obama's Climate Action Plan and covers the complete electricity sector, suggesting measures in the areas of efficiency on the supply and demand side, renewable energy, and other low-carbon technologies. It will provide options for states to meet the reduction goals in a "flexible manner."[17]

Clean Power Plan decarbonisation rates far from those needed for 2°C

Over the past ten years, there has been a substantial decline in CO_2 emissions in the US energy sector.

The decline corresponds to a 15% decrease in carbon intensity from 2002 to 2012 (about 1.4% per annum improvement), primarily as a result of a fuel switch from coal to gas.

The new policy implies an economy-wide decarbonisation rate of about 0.9% per annum, significantly lower than that achieved in the last decade.

This is not as fast as is needed for a 2°C decarbonisation pathway, and **could therefore mean an actual deterioration of the current decarbonisation rate,** illustrated by the 'historical emissions' in figure 8. The CAT team has calculated the required global carbon intensity pathways for the period 2020 – 2100 consistent with a 2°C pathway.

15 According to Höhne et al. (2013) 'North America's' fair share for 2050 is at minimum an 80% reduction relative to 2010. The USA's 83% reduction below 2005 pledge is equivalent to an 82% reduction below 2010 levels. The 2050 pledge is therefore just within the range of effort-sharing proposals. If all regions only meet the top end of the range, we will not reach the 2 degree goal.

16 http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf

17 http://www2.epa.gov/sites/production/files/2014-05/documents/20140602fs-overview.pdf

Background on the Climate Action Tracker

The "Climate Action Tracker", www.climateactiontracker.org, is a science-based assessment by Ecofys, Climate Analytics and the Potsdam Institute for Climate Impact Research (PIK) that provides regularly updated information on countries' reduction proposals.

The Climate Action Tracker[18] reflects the latest status of the progress being made at international climate negotiations. The team that performed the analyses followed peer-reviewed scientific methods (see publications in Nature and other journals)[19] and significantly contributed to the UNEP Emissions Gap Report[20].

The Climate Action Tracker enables the public to track the emission commitments and actions of countries. The website provides an up-to-date assessment of individual country pledges about greenhouse gas emission reductions. It also plots the consequences for the global climate of commitments and actions made ahead of and during the Copenhagen Climate Summit.

The Climate Action Tracker shows that much greater transparency is needed when it comes to targets and actions proposed by countries. In the case of developed countries, accounting for forests and land-use change significantly degrades the overall stringency of the targets. For developing countries, climate plans often lack calculations of the resulting impact on emissions.

Contacts

Dr. Niklas Höhne (n.hoehne@ecofys.com) - Director of Energy and Climate Policy at Ecofys and lead author at the IPCC developed, together with Dr. Michel den Elzen from MNP, the table in the IPCC report that is the basis for the reduction range of -25% to -40% below 1990 levels by 2020 that is currently being discussed for Annex I countries.

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[18] www.climateactiontracker.org

[19] e.g. http://www.nature.com/nature/journal/v464/n7292/full/4641126a.html and http://iopscience.iop.org/1748-9326/5/3/034013/fulltext

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CLIMATE ANALYTICS is a non-profit organization based in Potsdam, Germany. It has been established to synthesize climate science and policy research that is relevant for international climate policy negotiations. It aims to provide scientific, policy and analytical support for Small Island States (SIDS) and the least developed country group (LDCs) negotiators, as well as non-governmental organisations and other stakeholders in the 'post-2012' negotiations. Furthermore, it assists in building in-house capacity within SIDS and LDCs.

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Energy Science & Engineering

Open Access

RESEARCH ARTICLE

University of Texas study underestimates national methane emissions at natural gas production sites due to instrument sensor failure

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Keywords
Greenhouse gases, methane, natural gas

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Funding Information
This paper used data that are publicly available and did not rely on external funding.

Received: 25 November 2014; Revised: 13 May 2015; Accepted: 23 June 2015

***Energy Science and Engineering* 2015; 3(5):443–455**

doi: 10.1002/ese3.81

Abstract

The University of Texas reported on a campaign to measure methane (CH_4) emissions from United States natural gas (NG) production sites as part of an improved national inventory. Unfortunately, their study appears to have systematically underestimated emissions. They used the Bacharach Hi-Flow® Sampler (BHFS) which in previous studies has been shown to exhibit sensor failures leading to underreporting of NG emissions. The data reported by the University of Texas study suggest their measurements exhibit this sensor failure, as shown by the paucity of high-emitting observations when the wellhead gas composition was less than 91% CH_4, where sensor failures are most likely; during follow-up testing, the BHFS used in that study indeed exhibited sensor failure consistent with under-reporting of these high emitters. Tracer ratio measurements made by the University of Texas at a subset of sites with low CH_4 content further indicate that the BHFS measurements at these sites were too low by factors of three to five. Over 98% of the CH_4 inventory calculated from their own data and 41% of their compiled national inventory may be affected by this measurement failure. Their data also indicate that this sensor failure could occur at NG compositions as high as 97% CH_4, possibly affecting other BHFS measurement programs throughout the entire NG supply chain, including at transmission sites where the BHFS is used to report greenhouse gas emissions to the United States Environmental Protection Agency Greenhouse Gas Reporting Program (USEPA GHGRP, U.S. 40 CFR Part 98, Subpart W). The presence of such an obvious problem in this high profile, landmark study highlights the need for increased quality assurance in all greenhouse gas measurement programs.

Introduction

The climatic benefits of switching from coal to natural gas (NG) depend on the magnitude of fugitive emissions of methane (CH_4) from NG production, processing, transmission, and distribution [12, 13, 27]. This is of particular concern as the United States increasingly exploits NG from shale formations: a sudden increase in CH_4 emissions due to increased NG production could trigger climate "tipping points" due to the high short-term global warming potential of CH_4 (86× carbon dioxide on a 20-year time scale) [19]. The United States Environmental Protection Agency (USEPA) estimates CH_4 emissions from the NG supply chain by scaling up individual ground-level measurements, mostly collected by reporting from industry [26]. However, some recent studies have questioned whether these "bottom-up" inventories are too low, since airborne measurements indicate that CH_4 emissions from NG production regions are higher than the inventories indicate [5, 14, 17, 20, 21].

In order to help determine the climate consequences of expanded NG production and use, and to address the apparent discrepancy in top-down and bottom-up measurements, the University of Texas (UT) at Austin and the

Environmental Defense Fund launched a large campaign to measure CH_4 emissions at NG production sites in the United States [1]. This study used both existing EPA GHG inventory data and new measurements to compile a new national inventory of CH_4 emissions from production sites. Forty-one percent of this new inventory was based on measurements made by [1], which included measurements of emissions from well completion flowbacks as well as measurements of emissions from chemical injection pumps, pneumatic devices, equipment leaks, and tanks at 150 NG production sites around the United States already in routine operation (measurements from tanks were not used for inventory purposes). However, the measurements of emissions at well production sites already in operation (which comprised 98% of the new inventory developed by [1]) were made using the Bacharach Hi-Flow Sampler (BHFS; Bacharach, Inc., New Kensington, PA) and recent work has shown that the BHFS can underreport individual emissions measurements by two orders of magnitude [10]. This anomaly occurs due to sensor transition failure that can prevent the sampler from properly measuring NG emission rates greater than ~0.4 standard cubic feet per minute (scfm; 1 scfm = 1.70 $m^3\ h^{-1}$ or 19.2 g min^{-1} for pure CH_4 at 60°F [15.6°C] and 1 atm; these are the standard temperature and pressure used by the U.S. NG industry). Although this failure is not well understood, it does not seem to occur when measuring pure CH_4 streams, but has been observed in four different samplers when measuring NG streams with CH_4 contents ranging from 66% to 95%. The sampler's firmware version and elapsed time since last calibration may also influence the occurrence of this problem [10, 18].

This paper presents an analysis of the UT [1] emissions measurements that were made with the BHFS, and shows that high emitters (>0.4 scfm [0.7 $m^3\ h^{-1}$]) were reported very rarely at sites with a low CH_4 content in the wellhead gas (<91%), consistent with sensor transition failure. It also details testing of the exact BHFS instrument used in that study and shows the occurrence of this sensor failure at an NG production site with a wellhead composition of 91% CH_4 (the highest CH_4 concentration site available during testing). Finally, the downwind tracer ratio measurements made by [1] at a subset of their test sites are reexamined and indicate that the BHFS measurements made at sites with low wellhead CH_4 concentrations were too low by factors of three to five.

Evidence of BHFS Sensor Transition Failure in the UT Dataset

The Allen et al. [1] UT dataset is unique due to the large number of BHFS measurements made across a wide geographic range, the variety of emissions sources (equipment leaks, pneumatic devices, chemical injection pumps, and tanks) and the wide range of NG compositions (67.4–98.4% CH_4) that were sampled. As such, the UT study provides an important opportunity to evaluate the occurrence of sensor transition failure in the BHFS as well as the impact of this issue on emission rates and emissions factors based on measurements in other segments of the NG supply chain.

The BHFS uses a high flow rate of air and a loose enclosure to completely capture the NG-emitting from a source, with the emission rate calculated from the total flow rate of air and the resulting sample NG concentration, after the background NG concentration is subtracted. The sampler uses a catalytic oxidation sensor to measure sample concentrations from 0% to 5% NG in air, but must transition to a thermal conductivity sensor in order to accurately measure sample concentrations higher than 5%. It is the failure of the sampler to transition to the higher range that has been previously observed by Howard et al. [10] and which can prevent the sampler from correctly measuring emission rates larger than 0.3–0.5 scfm (0.5–0.9 $m^3\ h^{-1}$) (corresponding to sampler flow rates of 6–10 scfm [10–17 $m^3\ h^{-1}$]). Figure 1 summarizes data

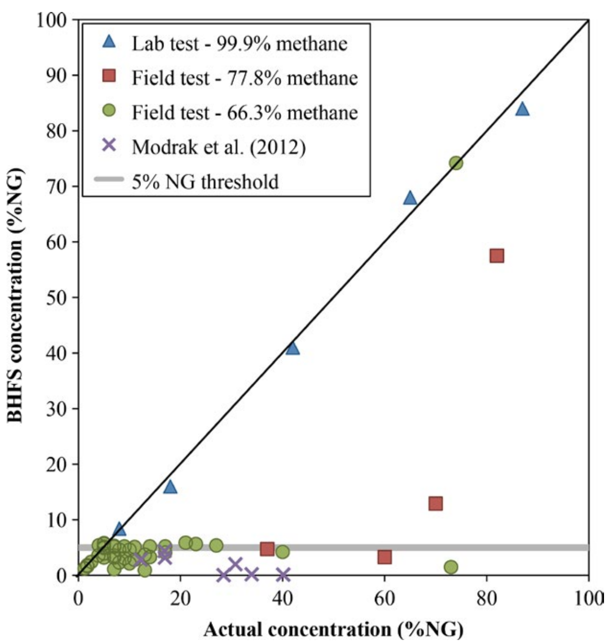

Figure 1. Occurrence of sensor transition failure in BHFS instruments with natural gas of varying CH_4 content from field and lab testing and from emission measurement studies (data from [10, 18]). NG concentrations in the BHFS sampling system measured by the BHFS internal sensor are compared to independent measurements of the sample NG concentrations. The 5% NG sample concentration threshold is the approximate concentration above which sensors should transition from catalytic oxidation to thermal conductivity. BHFS, Bacharach Hi-Flow Sampler; NG, natural gas.

showing the occurrence of sensor transition failure in several BHFS instruments during both field and laboratory testing as well as an example of the failure that occurred during an emission measurement study [10, 18].

Figure 2 presents the BHFS emission measurements from [1] as a function of percent CH_4 in wellhead gas at each site. Figure 2 also shows a line corresponding to emission rates of 0.3–0.5 scfm (0.5–0.9 $m^3 h^{-1}$), which represents the range of emission rates that would require transition from the catalytic oxidation sensor to the thermal conductivity sensor at sample flows ranging from 6 to 10 scfm (10–17 $m^3 h^{-1}$).

As seen in Figure 2, there are very few measurements in the thermal conductivity sensor range (above ~0.4 scfm [0.7 $m^3 h^{-1}$]) at sites where the wellhead gas composition of CH_4 is less than 91%, and this is true across all source categories. Raw data for sample flow and concentration from the BHFS were not provided in [1] supplemental information, so for this analysis, an average BHFS sample flow rate of 8 scfm (14 $m^3 h^{-1}$) has been assumed, which is the lower of the two sampling flows specified by the Bacharach operating manual [4]. At this sample flow rate, an emission source of 0.4 scfm (0.7 $m^3 h^{-1}$) corresponds with a sample concentration of 5% NG in air, above which point the sampler would need to transition to the thermal conductivity sensor to allow for accurate measurements. For sites with CH_4 concentrations less than 91%, only four out of 259 measurements (1.5%) exceeded 0.4 scfm (0.7 $m^3 h^{-1}$), while for sites with CH_4 concentrations greater than 91%, 68 out of 510 measurements (13.3%) exceeded 0.4 scfm (0.7 $m^3 h^{-1}$). Consequently, there were almost nine times fewer measurements in the thermal conductivity range at sites with wellhead gas compositions of <91% CH_4 (Fig. 2). If the sample flow rate were 6 scfm (10 $m^3 h^{-1}$) (due to a flow restriction or reduced battery power), the threshold for transition to the thermal conductivity range would be 0.3 scfm (0.5 $m^3 h^{-1}$); this would still mean that there were almost seven times fewer measurements in the thermal conductivity range at sites with wellhead gas compositions of <91% CH_4 than at sites with >91% CH_4. Although it is well known that a small percentage of NG emission sources account for most of the total emissions from any given population [9, 15, 25], it is unlikely that almost all the significant emitters at NG production sites would occur only at sites with well head gas compositions >91% CH_4. It is also unlikely that the emission rates of all of the source categories surveyed by [1], which had diverse emission mechanisms such as equipment leaks, pneumatic controllers, chemical injection pumps, and tanks, would all have a ceiling of ~0.4 scfm (0.7 $m^3 h^{-1}$) at sites with lower wellhead gas CH_4 concentrations. Consequently, the low occurrence of high emitters at sites with lower wellhead gas CH_4 concentrations in [1] indicates that sensor transition failure occurred at sites with CH_4 content <91% and is consistent with the BHFS sensor failure found by Howard et al. [10].

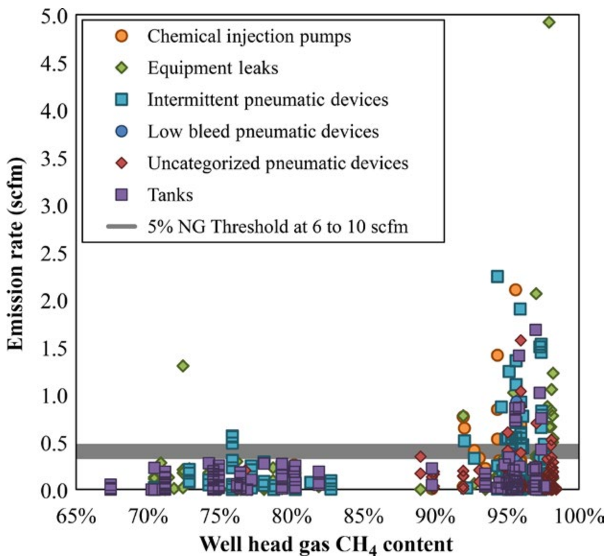

Figure 2. Emission rates of various sources measured by BHFS at NG production sites versus CH_4 concentration of the wellhead gas (data from [1]). The solid line indicates the maximum emission rate that could be measured by the catalytic oxidation sensor only (i.e., in the case of sensor transition failure). For sites with a NG composition greater than 91% CH_4, 13.3% of the measurements are in the TCD sensor range, assuming a sampler flow rate of 8 cubic feet per minute. For sites with less than 91% CH_4, only 1.5% of the measurements are in the TCD range. BHFS, Bacharach Hi-Flow Sampler; NG, natural gas; TCD, thermal conductivity detector.

Alternative Theories for the Emission Rate Pattern

Other possible causes of the emission rate pattern in the UT BHFS measurements were considered, including: regional operating differences at production sites; lighter gas densities resulting in higher emission rates; and improved detection of emissions by auditory, visual, and olfactory (AVO, e.g., [24]) methods at sites with heavier hydrocarbon concentrations.

Regional operating differences

Allen et al. [1] point out that air pollution regulations in Colorado which required installation of low bleed pneumatic devices in ozone nonattainment areas after 2009 might have led to lower emission rates in the Rocky Mountain region, which also had the lowest average concentration of CH_4 in the wellhead gas. However, if the

Rocky Mountain region is removed from the analysis, the occurrence of emitters >0.4 scfm (0.7 m^3 h^{-1}) at sites with wellhead gas <91% CH_4 was still only four out of 129 measurements (3.1%), while for sites with CH_4 concentrations greater than 91%, there remain 68 out of 510 measurements (13.3%) that exceeded 0.4 scfm (0.7 m^3 h^{-1}) (there were no Rocky Mountain sites with CH_4 >91%). Consequently, even if the Rocky Mountain region is removed from consideration, the occurrence of emitters >0.4 scfm (0.7 m^3 h^{-1}) was almost four times less at sites with less than 91% CH_4 than at sites with greater than 91% CH_4, so air quality regulations in Colorado do not appear to be the cause of the emission rate trend shown in Figure 2.

Beyond air pollution regulations, other unknown regional operating practices unrelated to CH_4 concentration might coincidentally cause the apparent relationship of site CH_4 concentrations with the occurrence of high emitters. However, as shown in Figure 3, the increase in leaks >0.4 scfm (0.7 m^3 h^{-1}) directly correlates with the increase in the average regional CH_4 concentration. Because there are four regions and two variables (site CH_4 concentration and the percent of leaks >0.4 scfm [0.7 m^3 h^{-1}]), the likelihood that regional operating characteristics would coincidentally cause the increase in occurrence of leaks >0.4 scfm (0.7 m^3 h^{-1}) to mirror the increasing regional site CH_4 concentration is only one in 24 (four factorial), or ~4%.

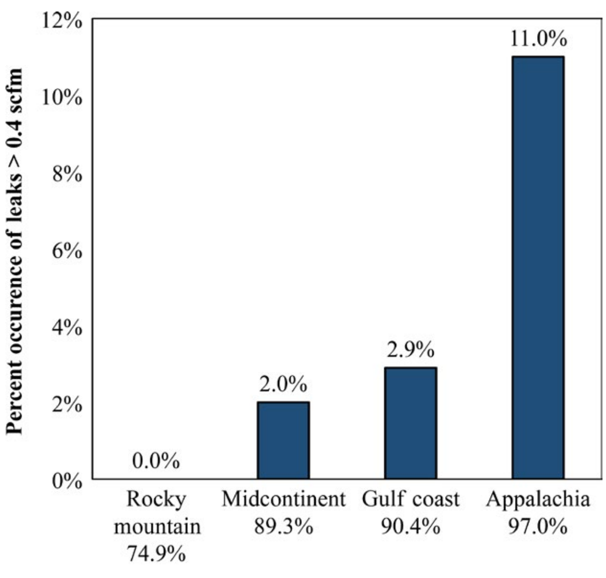

Figure 3. Occurrence of equipment leaks >0.4 scfm in each region of the [1] equipment leak data set. The odds of the occurrence of leaks >0.4 scfm being positively correlated with site CH_4 concentration are one in 24, which makes it unlikely this trend is due to regional operating effects.

Other known operating characteristics of the regions, such as average site pressure and average site age, are not related to the occurrence of equipment leaks >0.4 scfm (0.7 m^3 h^{-1}): average site pressures show no correlation, and average site age is negatively correlated with the occurrence of equipment leaks >0.4 scfm (0.7 m^3 h^{-1}).

Another argument against regional differences comes from the air quality study conducted by the City of Fort Worth ([6]; or the Ft. Worth study). Ft. Worth is part of the Mid-Continent region defined by [1], where the occurrence of equipment leaks only (as opposed to all BHFS measurement categories) >0.4 scfm (0.7 m^3 h^{-1}) observed by [1] was 2.0% of the total equipment leaks in that region. However, equipment leaks >0.4 scfm (0.7 m^3 h^{-1}) were 9.9% of the equipment leaks measured in the Ft. Worth study. This was determined using the Ft. Worth study categories of valves and connectors; their remaining category of "other", which included pneumatic control devices, had an even higher occurrence of sources >0.4 scfm (0.7 m^3 h^{-1}) of 27.0%. Previous work [10] has shown that although sensor transition failure likely occurred in the Ft. Worth study, these incidents were limited compared to those in [1]. Consequently, the much lower occurrence of leaks >0.4 scfm (0.7 m^3 h^{-1}) in the Mid-Continent region in [1] compared to the Ft. Worth study indicates that sensor transition failure was responsible for the low occurrence of emitters <0.4 scfm (0.7 m^3 h^{-1}) as opposed to regional differences.

Gas density

Wellhead gas with a lower CH_4 and a greater heavier hydrocarbon content will be denser than gas with higher CH_4 content. Since gas flow through an opening is inversely related to the square root of the gas density, streams with lower CH_4 content would have a lower flow rate if all other conditions were the same. However, this would cause at most a 20% decrease for the lowest CH_4/highest heavier hydrocarbon streams compared to the highest CH_4/lowest heavier hydrocarbon streams observed in the UT study. This would also result in a gradual increase in emissions as CH_4 content increased, as opposed to the dramatic increase in emissions observed over a very narrow range of CH_4 concentrations (Fig. 2).

AVO detection

AVO methods might improve for gas streams with a greater proportion of heavier hydrocarbons, since those streams would have greater odor and might leave more visible residue near a leak. However, Figure 4 presents the occurrence of emitters >0.4 scfm (0.7 m^3 h^{-1}) as a function of site CH_4 concentrations in the Appalachia

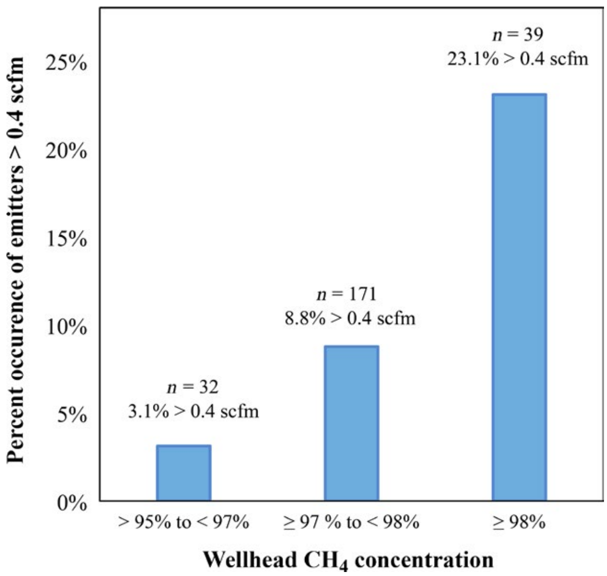

Figure 4. Occurrence of emitters >0.4 scfm as a function of site wellhead gas composition in [1] for the Appalachia region. An emission rate of greater than 0.4 scfm would require the transition from catalytic oxidation sensor to the thermal conductivity sensor for an average sample flow rate of 8 scfm. The dramatic increase in emitters >0.4 scfm over a narrow concentration range argues against the possibility that auditory, visual, and olfactory leak detection is the cause of the emission rate pattern seen in the [1] data set.

region alone. This region had the highest average CH_4 concentration in wellhead gas of any of the regions sampled in [1]. As seen in Figure 4, even over a very narrow range of site CH_4 concentrations (from 95% to >98% CH_4), there is a dramatic increase in emitters >0.4 scfm (0.7 m^3 h^{-1}) with increasing CH_4 concentration. It is unlikely that AVO methods would become so much more efficient over such a narrow range of high CH_4 concentrations where the gas streams are likely odorless and would leave little residue. This dramatic increase in high emitters at sites with high CH_4 concentrations within the Appalachia region alone also argues against the previously discussed regional operating differences hypothesis in general, since this trend is within a single region. Additionally, although the Rocky Mountain region surveyed by UT [1] had the lowest average site CH_4 concentration (74.9%) and heaviest hydrocarbon content, it actually had the highest number of equipment leaks (of any size) per well of all the regions, and there were 25% more leaks per well in that region than in the Appalachia region, which had the highest average site CH_4 concentration (97.0%) and therefore the lowest heavier hydrocarbon content. If AVO methods were more effective due to the presence of heavier hydrocarbons, it seems unlikely the region with the heaviest hydrocarbon concentrations would have the highest rate of overall leak occurrences.

Field Testing of the UT BHFS

Because the trend in the [1] data was consistent with sensor transition failure in the BHFS and no other explanation seemed plausible, I partnered with UT to test the sampler used by [1]. During that field program, the UT sampler had a version of firmware earlier than version 3.03, and older firmware versions have been shown to exhibit sensor transition failure [10]. However, the possible effect of the sampler's firmware version on the sensor failure was not known before this testing of the UT sampler, and at the time of my testing its firmware had been upgraded to a custom version (3.04).

As previously explained, the BHFS uses a catalytic oxidation sensor to measure sample stream concentrations from 0% to ~5% NG, and a thermal conductivity sensor for concentrations from ~5% to 100% NG. The catalytic oxidation sensor is typically calibrated with 2.5% CH_4 in air and the thermal conductivity sensor is calibrated with 100% CH_4 [4]. The manufacturer recommends sensor calibration every 30 days, a process which adjusts the response of the instrument. The calibration may also be checked ("bump-tested") periodically by the user, which does not adjust the instrument response. It is important to note that the description of the BHFS sensor operation in the supplemental information of [1] is incorrect, as they state that:

> [A] portion of the sample is drawn from the manifold and directed to a combustibles sensor that measures the sample's methane concentration in the range of 0.05–100% gas by volume. The combustibles sensor consists of a catalytic oxidizer, designed to convert all sampled hydrocarbons to CO_2 and water. A thermal conductivity sensor is then used to determine CO_2 concentration.

However, the BHFS manual [4] clearly states that the catalytic oxidation sensor is used to measure concentrations from 0% to 5% CH_4 and the thermal conductivity sensor from 5% to 100% CH_4. This is a critical distinction because understanding that the BHFS uses a different sensor for each range and that it must transition from the catalytic oxidation sensor to the thermal conductivity sensor in order to conduct accurate measurements is critical to understanding the problem of sensor transition failure.

I initially conducted field testing of the UT sampler in conjunction with the UT team at a NG production site with a wellhead gas CH_4 concentration of 90.8%. NG composition analysis (via gas chromatograph-flame ionization detector) of wellhead gas at this site was conducted by the host company just prior to the sampler testing. The tests were conducted by metering known flow rates of NG into the BHFS inlets through a rotameter (King Instrument Company, Garden Grove, CA; 0–10 scfm air scale). The sample concentration indicated by the internal BHFS sensor was recorded and compared to an external gas concentration monitor used to measure the actual NG concentration at the sampler exhaust (Bascom-Turner Gas Sentry CGA 201, Norwood, MA). The Gas Sentry unit was calibrated with 2.5% and 100% CH_4 prior to the testing; exhaust concentrations measured using this unit agreed with concentrations calculated using the sampler flow rate and amount of NG metered into the inlet to within an average of ±6%.

This field testing was conducted in March of 2014 and is described by [10]; the UT sampler is identified therein as BHFS No. 3. At the time of this testing, the UT BHFS had firmware Version 3.04 (September 2013); this sampler had been calibrated 2 weeks prior to the field test and had been used for emission measurements at production sites since that time. The response of the sensors was checked ("bump-tested") by the UT field team but not calibrated prior to the start of testing. This was apparently consistent with the UT field program methodology: the sampler had been used for measurements with only sensor bump tests, but without the actual calibration unless the sensors failed the bump tests (as was acceptable according to the manufacturer's guidelines) during their ongoing field measurement program and was provided to me for these measurements "ready for testing".

Although the UT sampler's internal sensors initially measured the sample concentration correctly, after ~20 min of testing the sampler's sensors failed to transition from the catalytic oxidation scale (<5% NG) to the thermal conductivity scale (>5% NG), resulting in sample concentration measurements that were 11–57 times lower than the actual sample concentration (Fig. 5). Because sample concentration is directly used to calculate emission measurements made by the sampler, this would result in emission measurements that are too low. After this sensor transition failure occurred, the UT BHFS was calibrated (not simply "bump-tested") and thereafter did not exhibit any further sensor transition failures even during a second day of testing at sites with wellhead CH_4 concentrations as low as 77%. Two other BHFS that were not part of the UT program were also tested using the same procedure; these instruments had the most updated firmware commercially available (Version 3.03) and were put through an actual calibration sequence by the instrument distributor's representative prior to any testing. Neither of these instruments exhibited sensor transition failure at any of the sites. These results combined with the sensor transition failure previously observed in instruments with earlier versions of firmware suggest that the combination of updated firmware and frequent actual calibrations might reduce sensor failure, although this has not been proved conclusively [10, 11].

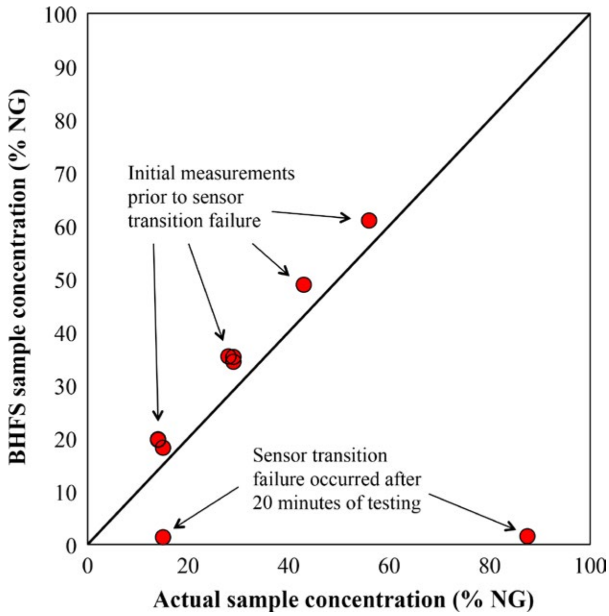

Figure 5. Performance of the BHFS used during the [1] study with NG composed of 90.8% CH_4; instrument firmware had been upgraded to version 3.04 after that study but before this testing; calibration was 2 weeks old. Sensor transition failure set in after ~20 min of testing; this failure was eliminated once the BHFS was put through a calibration sequence (as opposed to just a response test). BHFS, Bacharach Hi-Flow Sampler; NG, natural gas.

The UT recently published a follow-up study of pneumatic device emissions [2]. As part of this work, Allen et al. [2] conducted laboratory testing of the UT BHFS by making controlled releases of both 100% CH_4 and a test gas of 70.5% CH_4 mixed with heavier hydrocarbons into the UT BHFS and did not report any sensor transition failures during these tests, but during this laboratory testing the sampler (with the updated firmware version 3.04) was calibrated (not 'bump-tested") immediately prior to any testing. Consequently, the absence of sensor failure during their laboratory testing is consistent with the results observed during the March 2014 field tests, where calibrating the instrument eliminated the sensor failure.

Allen et al. [3] have suggested that the protocol during their field campaign was to check the calibration of the UT BHFS anytime it was turned on and that not following this protocol led to the sensor transition failure observed during this testing. However, in this instance, the sensor failure occurred both prior to and after the instrument was restarted. Additionally, the UT team observing the testing process did not suggest a calibration check when the instrument was turned back on for further testing. It was only after the sensor failure was observed that they checked and calibrated the instrument, so it does not appear that their protocol was to check the instrument calibration anytime it was turned on.

In summary, because the firmware for the UT sampler was updated prior to this testing (and therefore not the same as the version used during the UT field campaign [1]), and updated firmware may be a factor in reducing sensor failure, it is not expected that these test results are representative of how frequently sensor transition failure might have occurred during the UT study [1]. However, these results do clearly demonstrate that sensor transition failure could occur while using the UT BHFS.

Comparison With Other Pneumatic Device Studies

Two other recent studies have measured emission rates from pneumatic devices by installing meters into the supply gas lines of the devices, as opposed to measuring emissions using the BHFS as was done by Allen et al. [1]. Prasino [22] used the meter installation technique to study emissions from pneumatic controllers in British Columbia, and the UT follow-up study [2] installed meters to measure emission rates from pneumatics in the four regions surveyed in the previous UT study [1].

Unfortunately, it is not possible to compare the pneumatic device emission factors from [1] to those from either the Prasino study, or from [2], because even though [1] sought to randomly sample pneumatic devices, the result was clearly an emitter data set (measurements focused on pneumatic devices that were emitting), while the Prasino data set was made with a random selection of devices and [2] made comprehensive measurements of all devices that could be measured safely at each site. This difference can be demonstrated by comparing the percentage of emitting intermittent pneumatic devices occurring in [1] to that in [2]. In [1], 95.3% (123 out of 129 intermittent devices) were greater than zero, with the smallest nonzero emitter equal to 0.12 scfh (0.0034 m^3 h^{-1}). In [2], only 57.5% (184 out of 320 intermittent devices) were greater than zero. This percentage of nonzero measurements drops further if the lowest nonzero emitter (0.12 scfh; 0.0034 m^3 h^{-1}) observed by [1] is used as a threshold, in which case only 21.3% (68 out of 320) would be considered emitters. Since this threshold of 0.12 scfh (0.0034 m^3 h^{-1}) is 25 times lower than the typical minimum range of the Fox FT2A meters by [2], the reported emitters below this threshold are most likely instrument noise caused by the meter's thermal elements inducing convection currents [7].

Consequently, although the intent of [1] was to survey randomly selected devices, their approach actually resulted in a data set comprised almost exclusively of emitting devices; this possibility is acknowledged by [2]. Therefore, average emissions and emission factors for pneumatic devices calculated from [1] cannot be compared to those calculated from data collected by random or comprehensive sampling, such as presented in [22] or [2], because the emitter data set removes almost all the zero emitters and would result in much higher average emissions.

However, both [1] and [2] provide the CH_4 composition of the wellhead gas at the sites surveyed. This allows a comparison of emission rate patterns as a function of CH_4 concentration between devices measured by the BHFS [1] and by installed meters [2]. If the scarcity of high emitters measured by BHFS at sites with lower CH_4 concentrations in the initial UT study [1] was not an artifact caused by sensor transition failure, then the same concentration pattern should be present whether measured by the BHFS or by installed meters.

For this analysis, I removed the Rocky Mountain region to eliminate any bias from current or impending regulations that might have affected emission rates. Additionally, I focused on emissions from intermittent pneumatics because that provides the most complete data set from the two studies. Finally, as noted previously, the pneumatic device measurements from [1] apparently focused on emitting devices, whereas the devices surveyed in [2] were sampled as comprehensively as possible so the occurrences of high emitters in each study cannot be directly compared. Consequently, it is the ratio of the occurrences of high emitters at low CH_4 sites compared to high CH_4 sites within each study that must be compared.

As seen in Table 1, when measured by [1] via BHFS, the occurrence of emitters >0.4 scfm (0.7 m^3 h^{-1}) (on a percentage basis) at sites with wellhead gas compositions <91% CH_4 is almost a factor of five less than at sites with CH_4 >91%, consistent with BHFS sensor failure. Conversely, when measured via installed meters [2], the occurrence of emitters >0.4 scfm (0.7 m^3 h^{-1}) at sites with wellhead gas compositions <91% CH_4 is almost a factor of three higher than at sites with >91% CH_4, indicating a complete reversal in this trend. This stark difference between BHFS measurements and installed meter measurements corroborates that the scarcity of high emitters at sites with lower wellhead gas CH_4 content present in [1] was an artifact due to sensor failure in the BHFS.

Focused Analysis of the UT Study Equipment Leaks

In order to better understand the threshold of wellhead gas CH_4 concentrations at which sensor transition failure might occur, I conducted further analysis focused only on the equipment leak measurements in [1]. Equipment leaks were targeted because they are expected to be short term, steady state measurements, whereas emissions

Table 1. Occurrence of intermittent pneumatic device high emitters as a function of wellhead gas composition, measured by Bacharach Hi-Flow Sampler (BHFS) and installed meters (Rocky Mountain region excluded).

	No. of devices measured	No. of devices with emissions >0.4 scfm	% of devices with emissions >0.4 scfm
Allen et al. [1] (Measured by BHFS sampler)			
Wellhead gas composition >91% CH_4	85	28	32.9
Wellhead gas composition <91% CH_4	44	3	6.8
Ratio of frequency of high emitters at sites with wellhead gas compositions <91% CH_4 to sites with wellhead gas compositions >91% CH_4			0.21
Allen et al. [2] (Measured by installed meters)			
Wellhead gas composition >91% CH_4	106	3	2.8
Wellhead gas composition <91% CH_4	97	8	8.2
Ratio of frequency of high emitters at sites with wellhead gas compositions <91% CH_4 to sites with wellhead gas compositions >91% CH_4			2.9

reported from pneumatic devices and chemical injection pumps are likely to be an average of several measurements, and emissions from tanks may have an NG composition different from the reported wellhead composition.

Figure 6 presents the occurrence of equipment leaks in [1] that are >0.4 scfm (0.7 m^3 h^{-1}) as a function of site CH_4 concentrations. At sites with gas compositions of >97% CH_4, 11.7% of the leaks were >0.4 scfm (0.7 m^3 h^{-1}). At sites with wellhead compositions between 90% and 97% CH_4, only 2.7% of the leaks were >0.4 scfm (0.7 m^3 h^{-1}), and this occurrence dropped to less than 1% at sites with wellhead gas compositions of <90% CH_4, indicating that the sampler's ability to measure leaks >0.4 scfm (0.7 m^3 h^{-1}) declined dramatically with decreasing concentrations of CH_4 in the wellhead gas (Fig. 6). This analysis indicates the BHFS may underreport emitters >0.4 scfm (0.7 m^3 h^{-1}) even when making measurements of NG streams with CH_4 content up to 97%, and provides a valuable refinement of the possible CH_4 concentration threshold where sensor failure may occur, since the highest CH_4 wellhead content available for direct field testing of the BHFS was only 91.8%.

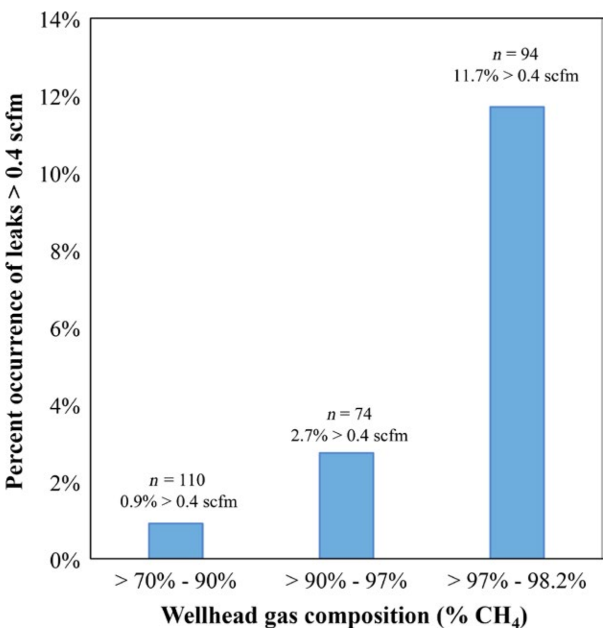

Figure 6. Occurrence of equipment leaks >0.4 scfm as a function of site well head gas CH_4 content in the [1] study. Leaks >0.4 scfm would require the transition from catalytic oxidation sensor to the thermal conductivity sensor for an average sample flow rate of 8 scfm. The large increase in the occurrence of leaks >0.4 scfm at sites with CH_4 content >97% indicates sensor transition failure below that threshold.

Comparison of the UT Study Downwind Tracer Ratio Measurements to On-Site Measurements

Allen et al. [1] also made emission measurements using a downwind tracer ratio method at 19 sites for comparison to their on-site measurements. Their emissions from on-site measurements were calculated by using direct measurements of equipment leaks and pneumatic devices that were made by the UT team combined with estimates of emissions from any sources at the well pad that were not measured. These unmeasured sources included all tanks and compressors (compressors were a small source in comparison to all other sources) as well as any pneumatics that was not directly measured during the site survey. For CH_4 emissions from tanks and compressors, the authors used "standard emissions estimation methods" [1]. For pneumatic devices that were not surveyed, they applied their own emission factors based on the measurements of pneumatic devices collected during the UT study.

The tracer ratio measurements were made by releasing a tracer gas at a known rate to simulate the emissions from the site being measured. Simultaneous downwind measurements were then made of the concentrations of both the tracer gas and CH_4, and then the emission rate of CH_4 was calculated after correcting for background CH_4 and tracer concentrations. The tracer ratio method allows for the calculation of CH_4 emissions from the entire production site by accounting for the dilution of CH_4 as it is transported into the atmosphere from the source to the receptor.

In summarizing their tracer ratio measurements, [1] state: "For the production sites, emissions estimated based on the downwind measurements were also comparable to total on-site measurements; however, because the total on-site emissions were determined by using a combination of measurements and estimation methods, it is difficult to use downwind measurements to confirm the direct source measurements." However, upon further examination, I found that the downwind tracer measurements do in fact indicate the occurrence of sensor transition failure in their BHFS measurements.

Table 2 summarizes the characteristics of the sites surveyed by [1] using both the BHFS and the tracer ratio method. As described above, the on-site total is a combination of the measurements made by BHFS and estimates for any sources not actually measured by the UT team. I calculated the ratio of actual BHFS measurements to the total reported on-site emissions (estimated and measured) using the supplemental information provided by [1]. Actual measured emissions ranged from 1% to 79% of the total reported on-site emissions and the on-site total emissions range from 13% to 3500% of the downwind tracer ratio measurements (Table 2).

Table 3 compares the tracer ratio measurements to the on-site emissions, categorized by CH_4 content in the wellhead gas and by the fraction of actual BHFS measurements that comprise the on-site emissions. As shown in Table 3, when comparing all sites without separating them into these categories, the total of the tracer ratio measurements does agree closely to the on-site emissions, as [1] concluded. However, four of the sites had wellhead gas compositions of ≥97% CH_4, at which the BHFS would be expected to make accurate measurements. The remaining 15 sites had wellhead gas compositions of <82% CH_4, at which sensor transition failure might occur and the BHFS would underreport emissions measurements.

Once the sites are categorized by these wellhead gas compositions, a deficit between the on-site emissions and the tracer ratio measurements appears in sites with lower CH_4 concentrations, and this deficit becomes more

Table 2. Sites surveyed by Allen et al. [1] using both Bacharach Hi-Flow Sampler (BHFS) and downwind tracer methods.

Tracer site name[1]	BHFS site name[1]	Wellhead gas CH_4 concentration (%)	On-site total[2] (BHFS measurements and estimates) (scfm CH_4)	BHFS measure-ments/on-site total[3]	Leaks measured by BHFS/on-site total[3]	Tracer ratio emission rate (scfm CH_4)	On-site total/ tracer ratio emission rate
MC-1	MC-1	70.9	1.89	0.12	0.12	2.32	0.815
MC-2	MC-14	78.1	0.99	0.34	0.01	2.00	0.495
MC-3	MC-20	77.2	1.63	0.45	0.18	2.95	0.552
MC-4	MC-5	74.2	2.31	0.19	0.14	3.36	0.687
MC-5	MC-16	79.3	1.85	0.56	0.18	4.16	0.445
RM-1	RM-7	81.9	0.22	0.11	0.09	0.584	0.368
RM-2	RM-8	74.5	4.43	0.02	0.02	1.70	2.60
RM-3	RM-1	76.4	0.13	0.67	0.69	0.442	0.303
RM-4	RM-3	74.9	0.11	0.21	0.00	0.839	0.137
RM-5	RM-2	74.5	0.09	0.35	0.33	0.240	0.392
RM-6	RM-5	74.5	0.74	0.41	0.42	0.421	1.75
RM-7	RM-14	74.5	0.27	0.26	0.26	0.368	0.736
RM-8	RM-19	76.2	0.29	0.82	0.79	1.08	0.266
RM-9	RM-12	74.5	0.38	0.05	0.05	0.864	0.436
RM-10	RM-4	76.2	2.86	0.01	0.00	0.080	35.7
AP-2	AP-23	97.6	1.28	0.68	0.35	0.270	4.74
AP-3	AP-43	97.0	4.75	0.62	0.59	4.12	1.15
AP-4	AP-37	97.0	1.36	0.44	0.42	0.709	1.92
AP-5	AP-18	97.0	0.39	0.74	0.69	0.288	1.37

[1]MC, Midcontinent; RM, Rocky Mountain; AP, Appalachia. Different site numbers were used to identify the same sites in the [1] supplemental information depending on whether BHFS or tracer ratio measurements were under discussion.
[2]On-site totals were calculated by [1] by combining measurements made by the BHFS with estimates of any sources not measured; these estimates were made using mathematical models for tanks as well as emission factors for compressors and any pneumatic controllers not directly measured.
[3]Calculated by this author from [1] supplemental information.

pronounced as the amount of the on-site emissions actually measured by the BHFS becomes a larger fraction of the total on-site emissions (measured and estimated). As seen in Table 3, for the high CH_4 sites where the sampler should function properly, the on-site measurements and estimates exceed the tracer measurements, but approach a ratio of one (complete agreement) as the amount of actual measurements increases. For the two sites with wellhead gas compositions ≥97% where the measured equipment leaks (which should produce steady emissions as compared to pneumatic devices which might be intermittent) averaged 64% of the total on-site measurements and estimates, the on-site total still exceeds the tracer measurements but are within 17% (Table 3). However, for the sites with wellhead gas CH_4 concentrations <82%, there is a clear trend of increasing deficit of the on-site emissions compared to the tracer ratio measurements as the actual BHFS measurements become a larger part of the on-site total. For instance, for the nine sites with at least 20% of on-site emissions from BHFS measurements (for an average of 45% of the total on-site emissions measured by the BHFS), the on-site emissions are only 49% of the tracer measurements (Table 3). For the two sites that had greater than 67% of on-site emissions data actually measured by the BHFS (for an average of 75% of on-site emissions data measured by the BHFS), the on-site emissions are only 28% of the tracer measurements (Table 3).

Comparing the on-site data to the downwind tracer measurements provides two valuable insights. First, there were six sites in the Rocky Mountain region for which at least 20% of the on-site emissions were measured by the BHFS (for an average of 45% actual BHFS measurements) (Table 2). For these six sites, the on-site emissions average 48% of the tracer data. For the two sites in this region with at least 67% of on-site emissions from actual BHFS measurements (and with BHFS measurements averaging 75% of the total on-site data), the on-site emissions were only 28% of the tracer measurements (Table 2). This provides clear evidence that the sampler actually did fail in the Rocky Mountain region, as opposed to any possible regional differences (discussed previously) that might have created an emission pattern of no high emitters at sites with lower CH_4 concentrations in the wellhead gas.

Additionally, the tracer measurements provide a method to estimate the magnitude of errors introduced in the data collected by [1] due to BHFS sensor transition failure. For all of the sites with wellhead gas compositions ≥97% CH_4 (where the sampler should operate correctly), the emission rates determined by on-site measurements exceeded those determined by the downwind tracer ratio measurements. Assuming that the tracer method accurately measured the total emissions from the sites surveyed (e.g., [8, 15, 16]), I concluded that the methods used in [1] overestimated the on-site sources that were not directly measured. Therefore, I calculated the error in BHFS measurements at sites with low CH_4 wellhead gas composition by assuming the tracer ratio measurements are correct. I have also assumed for this analysis that the estimates of any on-site sources made by [1] are also correct, even though the tracer data indicate they may be too high, because this is conservative in the sense that correcting for this overestimate would increase the BHFS error calculated below. Given these assumptions, subtracting the on-site estimated emissions from the tracer ratio emissions gives the expected measurement total that should have been reported from the BHFS measurements. Comparing this expected measurement total to the actual

Table 3. Comparison of on-site measurements to tracer ratio measurements made by Allen et al. [1] categorized by wellhead gas CH_4 concentration.

Site category (number of sites in parentheses)	Average percentage of on-site emissions reported by BHFS	Total on-site emissions (reported by BHFS and estimated) (scfm CH_4)	Total emissions measured by tracer (scfm CH_4)	Ratio of on-site emissions to emissions measured by tracer
All sites (19)	37	26.0	26.8	0.97
Sites where BHFS measurements are expected to be accurate (wellhead gas composition ≥97% CH_4)				
All sites (4)	62	7.78	5.39	1.44
Sites with >50% BHFS measurements (3)	68	6.42	4.68	1.37
Sites with >50% equipment leaks (2)	64 (equipment leaks/on-site total)	5.14	4.41	1.17
Sites where BHFS measurements are expected to underreport high emitters (wellhead gas composition <82% CH_4)				
All sites (15)	28	18.2	21.4	0.85
Sites with ≥5% BHFS measurements (13)	35	10.9	19.6	0.56
Sites with ≥20% BHFS measurements (9)	45	6.10	12.5	0.49
Sites with >50% BHFS measurements (3)	69	2.27	5.68	0.40
Sites with >67% BHFS measurements (2)	75	0.42	1.52	0.28

BHFS, Bacharach Hi-Flow Sampler.

measurement total reported by the BHFS provides an estimate of the error in BHFS measurements made by Allen et al. [1].

Table 4 presents the results of this analysis, and shows that for the 13 sites with wellhead gas compositions <82% CH_4 and with at least 5% actual BHFS measurements (with an average of 35% of emission sources measured by BHFS; bottom half of Table 3), the actual measurement total of the BHFS is less than one-third of the expected total, and this appears consistent as sites with greater fractions of actual BHFS measurements are examined. For these sites, the emission rates for equipment leaks and pneumatics devices presented by [1] are approximately equal, so it is not possible to assign a larger error to one category or another. Additionally, the errors introduced by the sensor failure would be expected to vary from site to site depending on how many emitters were present with emission rates exceeding the sensor transition threshold ceiling. Nevertheless, for these 13 sites, the BHFS underreported emissions for equipment leaks and pneumatic devices on average by more than a factor of 3 (Table 4).

Although the magnitude of error due to BHFS sensor failure is not known for all the sites in [1], the tracer ratio measurements make clear that the BHFS measurements for sites with lower CH_4 content in the wellhead gas could be at least a factor of three too low. More precise estimates of errors in [1] are not possible because of the nature of the sensor failure. Unlike a simple calibration error, for which it might be possible to correct, when sensor transition failure occurs, it is not possible to know for any particular measurement if the failure has occurred, and if it has, what the resulting error was, since the reported emission rates could range from 20% to two orders of magnitude too low.

Implications

Sensor transition failure is clearly apparent in the BHFS measurements made in the UT study by Allen et al. [1], as evidenced by the rare occurrence of high emitters at sites with lower CH_4 (<91%) content in the wellhead gas. The occurrence of this sensor transition failure was corroborated by field tests of the UT BHFS during which it exhibited this sensor failure, as well as by tracer ratio measurements made by [1] at a subset of sites with lower wellhead gas CH_4 concentrations. At this subset of sites, the tracer ratio measurements indicate that the BHFS measurements were too low by at least a factor of three. Because BHFS measurements were the basis of 98% of the inventory developed by [1] using their own measurements (and 41% of their total compiled inventory), the inventory clearly underestimates CH_4 emissions from production sites. However, the extent of this error is difficult to estimate because the underreporting of emission rates due to BHFS sensor transition failure at any given site would vary depending on sampler performance and on how many high emitters were present at that site. Estimating this error is further complicated by the fact that the data set collected for pneumatic devices by [1] was an emitter data set; this might offset the effect of underreported high emitters in their pneumatic device emission factors. Finally, although real differences may exist in regional emission rates, the UT data set [1] should not be used to characterize them because the occurrence of sensor failure clearly varied between regions due to variations in wellhead CH_4 compositions, which may mask any actual regional differences that existed.

Although the performance of the BHFS may vary between instruments or with sensor age or calibration vintage, this analysis of the [1] data set shows that measurements made using a BHFS for NG streams with CH_4 content

Table 4. Estimation of underreporting in Allen et al. [1] BHFS measurements of CH_4 emission rates at sites with low CH_4 well head gas composition (<82%), using downwind tracer measurements (from Table 3).

Minimum percentage of on-site emissions reported by BHFS	Average percentage of on-site emissions reported by BHFS	No. of sites	Total emissions measured by tracer (scfm CH_4)	On-site emissions estimated by UT (excludes BHFS measurements) (scfm CH_4)	Expected BHFS measurement total (tracer – on-site estimates) (scfm CH_4)	Emissions reported by BHFS (scfm CH_4)	Ratio of reported BHFS to expected BHFS
≥5	35	13	19.63	7.09	12.54	3.81	0.30
≥20	45	9	12.50	3.34	9.16	2.76	0.30
>50	69	3	5.68	0.71	4.97	1.56	0.31
>67	75	2	1.52	0.11	1.42	0.31	0.22

BHFS, Bacharach Hi-Flow Sampler; UT, University of Texas.

up to 97% could lead to severe underreporting of NG leaks. That this failure can occur at such high CH_4 concentrations, which are close to the higher end of those found in transmission and distribution systems, indicates that past measurements in all segments of the NG supply chain could have been affected by this problem. Because the BHFS sensor transition failure phenomenon is not fully understood, it is not known how much this error may have affected past measurements of CH_4 emission rates. Two factors preclude this: first, the performance of any individual BHFS may vary, and second, once sensor transition failure occurs, there is no way to determine the magnitude of the measurement error in the absence of an independent flux or concentration measurement.

If BHFS sensor transition failure has occurred during industry monitoring at transmission, storage, and processing compressor stations where the BHFS is approved for leak measurements mandated by the USEPA Subpart W Greenhouse Gas Reporting Program (GHGRP) [23], then these errors could be larger than those observed at production sites. Leaks at transmission, storage, and processing compressor stations commonly exceed 0.4 scfm (0.7 m^3 h^{-1}) (the approximate threshold for BHFS sensor transition failure) and in some cases may range from 10 to over 100 scfm. Because the largest 10% of leaks typically account for 60–85% of the total leak rate at a given facility [9, 25], sensor transition failure in the BHFS could bias CH_4 emission inventories compiled by the USEPA GHGRP substantially low since the most significant leaks could be underreported. Additionally, leak measurements using the BHFS may be used to guide repair decisions at NG facilities, and underreporting of leaks could compromise safety if large leaks remain unrepaired as a result.

Finally, it is important to note that the BHFS sensor failure in the UT study [1] went undetected in spite of the clear artifact that it created in the emission rate trend as a function of wellhead gas CH_4 content and even though the authors' own secondary measurements made by the downwind tracer ratio technique confirmed the BHFS sensor failure. That such an obvious problem could escape notice in this high profile, landmark study highlights the need for increased vigilance in all aspects of quality assurance for all CH_4 emission rate measurement programs.

Acknowledgments

The author thanks Dave Allen (University of Texas at Austin) for making the UT BHFS available for field testing, and Adam Pacsi (University of Texas at Austin), Matt Harrison and Dave Maxwell (URS Corporation), and Tom Ferrara (Conestoga Rovers & Associates) for their assistance with the field testing of the BHFS. This paper was substantially improved by the comments of three anonymous reviewers.

Conflict of Interest

The author is the developer of high flow sampling technology (US Patent RE37, 403) and holds a license to use it for any purpose; however, he does not sell high flow samplers nor was he involved in the development of the Bacharach Hi-Flow Sampler.

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World Energy Outlook 2014

EXECUTIVE SUMMARY

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

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An energy system under stress

The global energy system is in danger of falling short of the hopes and expectations placed upon it. Turmoil in parts of the Middle East – which remains the only large source of low-cost oil – has rarely been greater since the oil shocks in the 1970s. Conflict between Russia and Ukraine has reignited concerns about gas security. Nuclear power, which for some countries plays a strategic role in energy security (and which is examined in depth in this edition of the *World Energy Outlook* [*WEO-2014*]), faces an uncertain future. Electricity remains inaccessible to many people, including two out of every three people in sub-Saharan Africa (the regional focus in *WEO-2014*). The point of departure for the climate negotiations, due to reach a climax in 2015, is not encouraging: a continued rise in global greenhouse-gas emissions and stifling air pollution in many of the world's fast-growing cities.

Advances in technology and efficiency give some reasons for optimism, but sustained political efforts will be essential to change energy trends for the better. Signs of stress would be much more serious, were it not for improvements in efficiency and continuous efforts to innovate and reduce the cost of emerging energy technologies, such as solar photovoltaics (PV). But global energy trends are not easily changed and worries over the security and sustainability of energy supply will not resolve themselves. Actions from well-informed policy-makers, industry and other stakeholders are needed. *WEO-2014*, with projections and analysis extended to 2040 for the first time, provides insights that can help to ensure that the energy system is changed by design, rather than just by events.

Energy: the answer to – and the cause of – some urgent problems

Global energy demand is set to grow by 37% by 2040 in our central scenario, but the development path for a growing world population and economy is less energy-intensive than it used to be. In our central scenario, growth in global demand slows markedly, from above 2% per year over the last two decades to 1% per year after 2025; this is a result both of price and policy effects, and a structural shift in the global economy towards services and lighter industrial sectors. The global distribution of energy demand changes more dramatically, with energy use essentially flat in much of Europe, Japan, Korea and North America, and rising consumption concentrated in the rest of Asia (60% of the global total), Africa, the Middle East and Latin America. A landmark is reached in the early 2030s, when China becomes the largest oil-consuming country, crossing paths with the United States, where oil use falls back to levels not seen for decades. But, by this time, it is India, Southeast Asia, the Middle East and sub-Saharan Africa that take over as the engines of global energy demand growth.

By 2040, the world's energy supply mix divides into four almost-equal parts: oil, gas, coal and low-carbon sources. Resources are not a constraint over this period, but each of these four pillars faces a distinct set of challenges. Policy choices and market developments that bring the share of fossil fuels in primary energy demand down to just under three-quarters in 2040 are not enough to stem the rise in energy-related carbon dioxide (CO_2) emissions, which grow by one-fifth. This puts the world on a path consistent with a long-term global average temperature increase of 3.6 °C. The Intergovernmental Panel on Climate Change estimates that in order to limit this temperature increase to 2 °C – the internationally agreed goal to avert the most severe and widespread implications of climate change – the world cannot emit more than around 1 000 gigatonnes of CO_2 from 2014 onwards. This entire budget will be used up by 2040 in our central scenario. Since emissions are not going to drop suddenly to zero once this point is reached, it is clear that the 2 °C objective requires urgent action to steer the energy system on to a safer path. This will be the focus of a *WEO* Special Report, to be released in mid-2015 in advance of the critical UN climate talks in Paris.

Energy security concerns on the rise

The short-term picture of a well-supplied oil market should not disguise the challenges that lie ahead as reliance grows on a relatively small number of producers. Regional oil demand trends are quite distinct: for each barrel of oil no longer used in OECD countries, two barrels more are used in the non-OECD. Increased oil use for transport and petrochemicals drives demand higher, from 90 million barrels per day (mb/d) in 2013 to 104 mb/d in 2040, although high prices and new policy measures gradually constrain the pace of overall consumption growth, bringing it towards a plateau. Investment of some $900 billion per year in upstream oil and gas development is needed by the 2030s to meet projected demand, but there are many uncertainties over whether this investment will be forthcoming in time – especially once United States tight oil output levels off in the early 2020s and its total production eventually starts to fall back. The complexity and capital-intensity of developing Brazilian deepwater fields, the difficulty of replicating the US tight oil experience at scale outside North America, unresolved questions over the outlook for growth in Canadian oil sands output, the sanctions that restrict Russian access to technologies and capital markets and – above all – the political and security challenges in Iraq could all contribute to a shortfall in investment below the levels required. The situation in the Middle East is a major concern given steadily increasing reliance on this region for oil production growth, especially for Asian countries that are set to import two out of every three barrels of crude traded internationally by 2040.

Demand for natural gas grows by more than half, the fastest rate among the fossil fuels, and increasingly flexible global trade in liquefied natural gas (LNG) offers some protection against the risk of supply disruptions. The main regions that push global gas demand higher are China and the Middle East, but gas also becomes the leading fuel in the OECD energy mix by around 2030, helped by new regulations in the United States limiting power sector emissions. In contrast to oil, gas production increases almost everywhere (Europe is the main exception) and unconventional gas accounts for almost 60% of global supply growth. The key uncertainty – outside North America – is whether gas can be made available at prices that are attractive to consumers while still offering incentives for the necessary large capital-intensive investments in gas supply; this is an issue of domestic regulation in many of the emerging non-OECD markets, notably in India and across the Middle East, as well as a concern in international trade. Import needs are set to rise across much of Asia as well as in Europe, but concerns about the security of future gas supply are allayed in part by a growing cast of international gas suppliers, a near-tripling of global liquefaction sites and a rising share of LNG that can be re-directed in response to the short-term needs of increasingly interconnected regional markets.

While coal is abundant and its supply secure, its future use is constrained by measures to tackle pollution and reduce CO_2 emissions. Global coal demand grows by 15% to 2040, but almost two-thirds of the increase occurs over the next ten years. Chinese coal demand plateaus at just over 50% of global consumption, before falling back after 2030. Demand declines in the OECD, including the United States, where coal use for electricity generation plunges by more than one-third. India overtakes the United States as the world's second-biggest coal consumer before 2020, and soon after surpasses China as the largest importer. Current low coal prices have put pressure on producers worldwide to cut costs, but the shedding of high-cost capacity and demand growth are expected to support an increase in price sufficient to attract new investment. China, India, Indonesia and Australia alone account for over 70% of global coal output by 2040, underscoring Asia's importance in coal markets. Adoption of high-efficiency coal-fired generation technologies, and of carbon capture and storage in the longer term, can be a prudent strategy to ensure a smooth transition to a low carbon power system, while reducing the risk that capacity is idled before recovering its investment costs.

Prices and policies have to be right to get more efficiency into the mix

Energy efficiency is a critical tool to relieve pressure on energy supply and it can also mitigate in part the competitive impacts of price disparities between regions. A renewed policy focus on efficiency is taking hold in many countries and the transport sector is in the front line. With more than three-quarters of global car sales now subject to efficiency standards, oil transport demand is expected to rise by only one-quarter despite the number of cars and trucks on the world's roads more than doubling by 2040. New efficiency efforts have the effect of suppressing total oil demand growth by an estimated 23 mb/d in 2040 – more than current oil production of Saudi Arabia and Russia combined – and measures mainly in power generation and industry hold the growth in gas demand back by 940 billion cubic metres, more than current gas output in North America. Aside from reducing energy-import bills and environmental impacts, efficiency measures can also help in part to address the concern, felt in some import-dependent regions, that relatively high prices for natural gas and electricity put their energy-intensive industries at a competitive disadvantage. But regional energy price disparities are set to persist and North America, in particular, remains a relatively low-cost region through to 2040: the average amount spent on a unit of energy in the United States is expected even to fall below that of China in the 2020s.

Fossil-fuel subsidies totalled $550 billion in 2013 – more than four-times those to renewable energy – and are holding back investment in efficiency and renewables. In the Middle East, nearly 2 mb/d of crude oil and oil products are used to generate electricity when, in the absence of subsidies, the main renewable energy technologies would be competitive with oil-fired power plants. In Saudi Arabia, the additional upfront cost of a car twice as fuel-efficient as the current average would, at present, take about 16 years to recover through lower spending on fuel: this payback period would shrink to 3 years if gasoline were not subsidised. Reforming energy subsidies is not easy and there is no single formula for success. However, as our case studies of Egypt, Indonesia and Nigeria show, clarity over the objectives and timetable for reform, careful assessment of the effects and how they can (if necessary) be mitigated, and thorough consultation and good communication at all stages of the process are essential.

Power sector is leading the transformation of global energy

Electricity is the fastest-growing final form of energy, yet the power sector contributes more than any other to the reduction in the share of fossil fuels in the global energy mix. In total, some 7 200 gigawatts (GW) of capacity needs to be built to keep pace with increasing electricity demand while also replacing existing power plants due to retire by 2040 (around 40% of the current fleet). The strong growth of renewables in many countries raises their share in global power generation to one-third by 2040. Adequate price signals will be needed to ensure timely investments in the new thermal generation capacity, which is necessary, alongside investment in renewables, to maintain the reliability of electricity supply. This will require reforms to market design or electricity pricing in some cases. The shift towards more capital-intensive technologies and high fossil fuel prices lead to increasing average electricity supply costs and end-user prices in most countries in the world. However, end-use efficiency gains help reduce the proportion of household income spent on electricity.

Renewable energy technologies, a critical element of the low-carbon pillar of global energy supply, are rapidly gaining ground, helped by global subsidies amounting to $120 billion in 2013. With rapid cost reductions and continued support, renewables account for almost half of the increase in total electricity generation to 2040, while use of biofuels more than triples to 4.6 mb/d and the use of renewables for heat more than doubles. The share of renewables in power generation increases most in OECD countries, reaching 37%, and their growth is equivalent to the entire net increase in OECD electricity supply. However, generation from renewables grows more than twice as much in non-OECD countries, led by China, India, Latin America and Africa. Globally, wind power accounts for the largest share of growth in renewables-based generation (34%), followed by hydropower (30%) and solar technologies (18%). As the share of wind and solar PV in the world's power mix quadruples, their integration both from a technical and market perspective becomes more challenging, with wind reaching 20% of total electricity generation in the European Union and solar PV accounting for 37% of summer peak demand in Japan.

A complex set of elements in decision-making on nuclear power

Policies concerning nuclear power will remain an essential feature of national energy strategies, even in countries which are committed to phasing out the technology and that must provide for alternatives. Global nuclear power capacity increases by almost 60% in our central scenario, from 392 GW in 2013 to over 620 GW in 2040. However, its share of global electricity generation, which peaked almost two decades ago, rises by just one percentage point to 12%. This pattern of growth reflects the challenges facing all types of new thermal generation capacity in competitive power markets and the specific suite of other economic, technical and political challenges that nuclear power has to overcome. Growth is concentrated in markets where electricity is supplied at regulated prices, utilities have state backing or governments act to facilitate private investment. Of the growth in nuclear generation to 2040, China accounts for 45% while India, Korea and Russia collectively make up a further 30%. Generation increases by 16% in the United States, rebounds in Japan (although not to the levels prior to the accident at Fukushima Daiichi) and falls by 10% in the European Union.

Despite the challenges it currently faces, nuclear power has specific characteristics that underpin the commitment of some countries to maintain it as a future option. Nuclear plants can contribute to the reliability of the power system where they increase the diversity of power generation technologies in the system. For countries that import energy, it can reduce their dependence on foreign supplies and limit their exposure to fuel price movements in international markets. In a Low Nuclear Case – in which global capacity drops by 7% compared with today – indicators of energy security tend to deteriorate in countries that utilise nuclear power. For example, the share of energy demand met from domestic sources is reduced in Japan (by 13 percentage points), Korea (by six) and the European Union (by four) relative to our central scenario.

Nuclear power is one of the few options available at scale to reduce carbon-dioxide emissions while providing or displacing other forms of baseload generation. It has avoided the release of an estimated 56 gigatonnes of CO_2 since 1971, or almost two years of total global emissions at current rates. Annual emissions avoided in 2040 due to nuclear power (as a share of projected emissions at that time) reach almost 50% in Korea, 12% in Japan, 10% in the United States, 9% in the European Union and 8% in China. The average cost of avoiding emissions through new nuclear capacity depends on the mix and the costs of the fuels it displaces, and therefore ranges from very low levels to over $80/tonne.

Almost 200 reactors (of the 434 operational at the end of 2013) are retired in the period to 2040, with the vast majority in Europe, the United States, Russia and Japan; the challenge to replace the shortfall in generation is especially acute in Europe. Utilities need to start planning either to develop alternative capacity or to continue operating existing plants years in advance of nuclear plants reaching the end of their current licence periods. To facilitate this process, governments need to provide clarity on their approach to licence extensions and details of the regulatory steps involved well ahead of possible plant closures. We estimate the cost of decommissioning nuclear plants that are retired in the period to 2040 at more than $100 billion. Considerable uncertainties remain about these costs, reflecting the relatively limited experience to date in dismantling and decontaminating reactors and restoring sites for other uses. Regulators and utilities need to continue to ensure adequate funds are set aside to cover these future expenses.

Public concerns about nuclear power must be heard and addressed. Recent experience has shown how public views on nuclear power can quickly shift and play a determining role in its future in some markets. Safety is the dominant concern, particularly in relation to operating reactors, managing radioactive waste and preventing the proliferation of nuclear weapons. Confidence in the competence and independence of regulatory oversight is essential, especially as nuclear power spreads: in our central scenario, the number of economies operating reactors rises from 31 to 36 as newcomers outnumber those that phase out nuclear power. The cumulative total of spent nuclear fuel doubles to more than 700 thousand tonnes over the projection period, but, to date, no country has opened a permanent disposal facility to isolate the most long-lived and highly radioactive waste produced by commercial reactors. All countries that have ever produced radioactive waste should have an obligation to develop a solution for permanent disposal.

Power to shape the future in sub-Saharan Africa

Those who have no access to modern energy suffer from the most extreme form of energy insecurity. An estimated 620 million people in sub-Saharan Africa do not have access to electricity, and for those that do have it, supply is often insufficient, unreliable and among the most costly in the world. Around 730 million people in the region rely on solid biomass for cooking, which – when used indoors with inefficient cookstoves – causes air pollution that results in nearly 600 000 premature deaths in Africa each year. Sub-Saharan Africa accounts for 13% of the global population, but only 4% of global energy demand (more than half of which is solid biomass). The region is rich in energy resources, but they are largely undeveloped. Almost 30% of global oil and gas discoveries made over the last five years were in the region, and it is also endowed with huge renewable energy resources, especially solar and hydro, as well as wind and geothermal.

The sub-Saharan energy system is set to expand rapidly but, even so, many of the existing energy challenges will be only partly overcome. By 2040, the region's economy quadruples in size, the population nearly doubles and energy demand grows by around 80%. Power generation capacity quadruples and almost half of the growth in generation comes from renewables, which also increasingly provide the source of power for mini- and off-grid systems in rural areas. Overall, nearly one billion people gain access to electricity, but more than half a billion still remain without it in 2040. Output from Nigeria, Angola and a host of smaller producers means that sub-Saharan Africa remains an important centre of global oil supply – although an increasing share of output is consumed within the region. The region emerges also as an important player in gas, as development of the major east coast discoveries off Mozambique and Tanzania accompanies increased production in Nigeria and elsewhere.

Sub-Saharan Africa's energy sector can do more to support inclusive growth. In an "African Century Case", three actions in the energy sector – if accompanied by more general governance reforms – boost the sub-Saharan economy by a further 30% in 2040, delivering an extra decade's worth of growth in per-capita incomes:

- An upgraded power sector: additional investment that reduces power outages by half and achieves universal electricity access in urban areas.
- Deeper regional co-operation: expanding markets and unlocking a greater share of the continent's hydropower potential.
- Better management of energy resources and revenues: more efficiency and transparency in financing essential improvements to Africa's infrastructure.

A modern and integrated energy system allows for more efficient use of resources and brings energy to a greater share of the poorest parts of sub-Saharan Africa. Concerted action to improve the functioning of the energy sector is essential if the 21st is to become an African century.

IEA PUBLICATIONS, 9 rue de la Fédération, 75739 Paris Cedex 15
Printed in France by CORLET, November 2014
Cover design: IEA, photo credits: © GraphicObsession

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World **Energy** Outlook 2014

- Does growth in North American oil supply herald a new era of abundance – or does turmoil in parts of the Middle East cloud the horizon?
- Does the expansion of LNG trade offer the prospect of greater security in global gas supply?
- How much can energy efficiency close the competitiveness gap caused by differences in regional energy prices?
- What considerations should shape decision-making in countries using, pursuing or phasing out nuclear power?
- How can sub-Saharan Africa's energy sector help to unlock a better life for its citizens?
- How close is the world to using up the available carbon budget, which cannot be exceeded if global warming is to be contained?

Answers to these questions and a host of others are to be found in the pages of *WEO-2014*, based on new projections which are extended, for the first time, to 2040. The energy prospects of sub-Saharan Africa are analysed comprehensively and the state and prospects of nuclear energy examined in depth, all as part of a systematic analysis of developments in global energy across all fuels and nations.

For more information, please visit: **www.worldenergyoutlook.org**

SPM

Summary for Policymakers

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This Summary for Policymakers should be cited as:
IPCC, 2013: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

A. Introduction

The Working Group I contribution to the IPCC's Fifth Assessment Report (AR5) considers new evidence of climate change based on many independent scientific analyses from observations of the climate system, paleoclimate archives, theoretical studies of climate processes and simulations using climate models. It builds upon the Working Group I contribution to the IPCC's Fourth Assessment Report (AR4), and incorporates subsequent new findings of research. As a component of the fifth assessment cycle, the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) is an important basis for information on changing weather and climate extremes.

This Summary for Policymakers (SPM) follows the structure of the Working Group I report. The narrative is supported by a series of overarching highlighted conclusions which, taken together, provide a concise summary. Main sections are introduced with a brief paragraph in italics which outlines the methodological basis of the assessment.

The degree of certainty in key findings in this assessment is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from *very low* to *very high*) and, when possible, probabilistically with a quantified likelihood (from *exceptionally unlikely* to *virtually certain*). Confidence in the validity of a finding is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement[1]. Probabilistic estimates of quantified measures of uncertainty in a finding are based on statistical analysis of observations or model results, or both, and expert judgment[2]. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers. (See Chapter 1 and Box TS.1 for more details about the specific language the IPCC uses to communicate uncertainty).

The basis for substantive paragraphs in this Summary for Policymakers can be found in the chapter sections of the underlying report and in the Technical Summary. These references are given in curly brackets.

B. Observed Changes in the Climate System

Observations of the climate system are based on direct measurements and remote sensing from satellites and other platforms. Global-scale observations from the instrumental era began in the mid-19th century for temperature and other variables, with more comprehensive and diverse sets of observations available for the period 1950 onwards. Paleoclimate reconstructions extend some records back hundreds to millions of years. Together, they provide a comprehensive view of the variability and long-term changes in the atmosphere, the ocean, the cryosphere, and the land surface.

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased (see Figures SPM.1, SPM.2, SPM.3 and SPM.4). {2.2, 2.4, 3.2, 3.7, 4.2–4.7, 5.2, 5.3, 5.5–5.6, 6.2, 13.2}

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1 In this Summary for Policymakers, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see Chapter 1 and Box TS.1 for more details).

2 In this Summary for Policymakers, the following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely: 95–100%, more likely than not >50–100%, and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Chapter 1 and Box TS.1 for more details).

B.1 Atmosphere

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (see Figure SPM.1). In the Northern Hemisphere, 1983–2012 was *likely* the warmest 30-year period of the last 1400 years (*medium confidence*). {2.4, 5.3}

- The globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C[3], over the period 1880 to 2012, when multiple independently produced datasets exist. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85] °C, based on the single longest dataset available[4] (see Figure SPM.1). {2.4}

- For the longest period when calculation of regional trends is sufficiently complete (1901 to 2012), almost the entire globe has experienced surface warming (see Figure SPM.1). {2.4}

- In addition to robust multi-decadal warming, global mean surface temperature exhibits substantial decadal and interannual variability (see Figure SPM.1). Due to natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over the past 15 years (1998–2012; 0.05 [–0.05 to 0.15] °C per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] °C per decade)[5]. {2.4}

- Continental-scale surface temperature reconstructions show, with *high confidence*, multi-decadal periods during the Medieval Climate Anomaly (year 950 to 1250) that were in some regions as warm as in the late 20th century. These regional warm periods did not occur as coherently across regions as the warming in the late 20th century (*high confidence*). {5.5}

- It is *virtually certain* that globally the troposphere has warmed since the mid-20th century. More complete observations allow greater confidence in estimates of tropospheric temperature changes in the extratropical Northern Hemisphere than elsewhere. There is *medium confidence* in the rate of warming and its vertical structure in the Northern Hemisphere extra-tropical troposphere and *low confidence* elsewhere. {2.4}

- *Confidence* in precipitation change averaged over global land areas since 1901 is *low* prior to 1951 and *medium* afterwards. Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudes area-averaged long-term positive or negative trends have *low confidence* (see Figure SPM.2). {TS TFE.1, Figure 2; 2.5}

- Changes in many extreme weather and climate events have been observed since about 1950 (see Table SPM.1 for details). It is *very likely* that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale[6]. It is *likely* that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has *likely* increased in North America and Europe. In other continents, *confidence* in changes in heavy precipitation events is at most *medium*. {2.6}

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[3] In the WGI contribution to the AR5, uncertainty is quantified using 90% uncertainty intervals unless otherwise stated. The 90% uncertainty interval, reported in square brackets, is expected to have a 90% likelihood of covering the value that is being estimated. Uncertainty intervals are not necessarily symmetric about the corresponding best estimate. A best estimate of that value is also given where available.

[4] Both methods presented in this bullet were also used in AR4. The first calculates the difference using a best fit linear trend of all points between 1880 and 2012. The second calculates the difference between averages for the two periods 1850–1900 and 2003–2012. Therefore, the resulting values and their 90% uncertainty intervals are not directly comparable. {2.4}

[5] Trends for 15-year periods starting in 1995, 1996, and 1997 are 0.13 [0.02 to 0.24] °C per decade, 0.14 [0.03 to 0.24] °C per decade, and, 0.07 [–0.02 to 0.18] °C per decade, respectively.

[6] See the Glossary for the definition of these terms: cold days/cold nights, warm days/warm nights, heat waves.

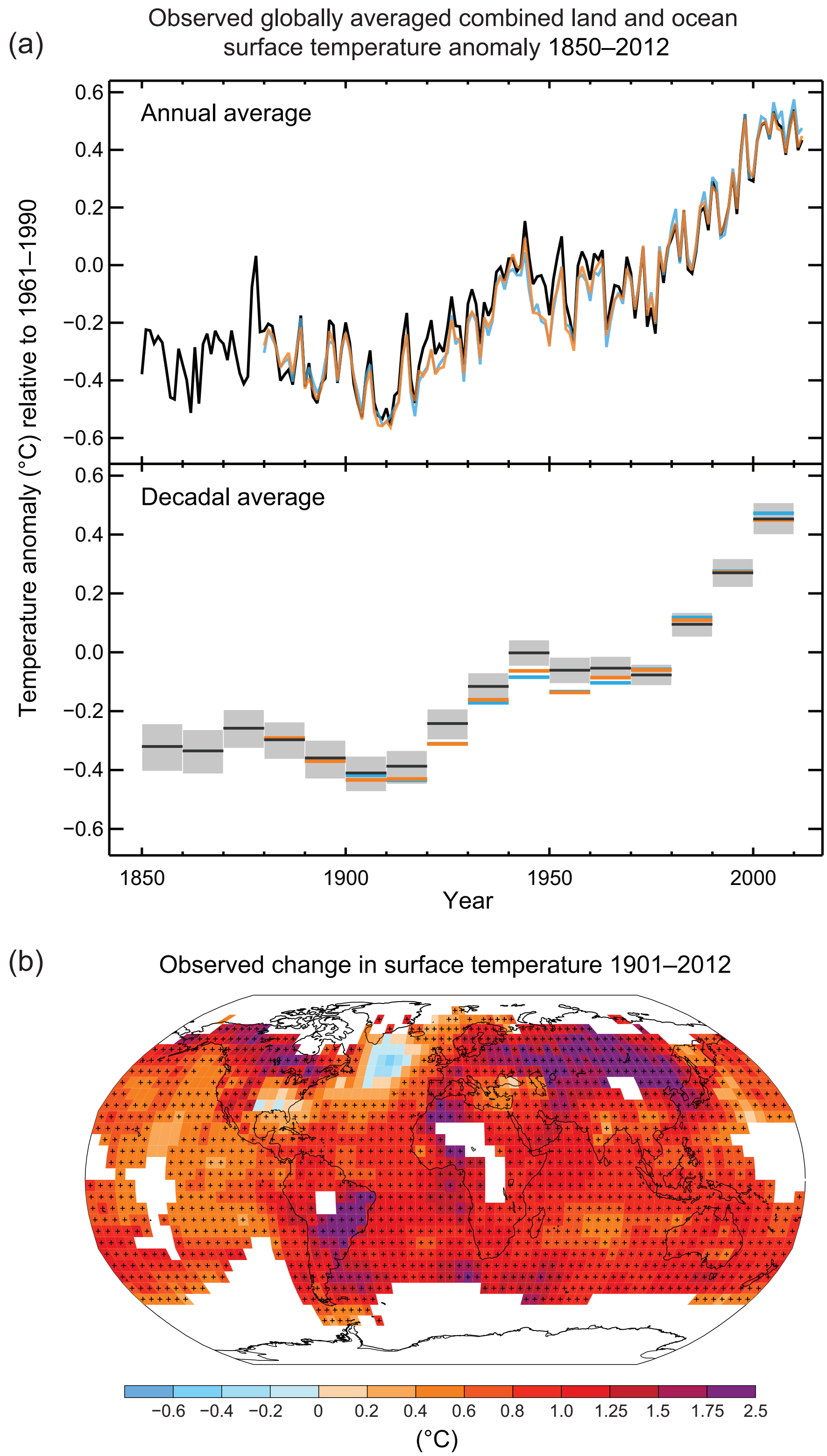

Figure SPM.1 | (a) Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three data sets. Top panel: annual mean values. Bottom panel: decadal mean values including the estimate of uncertainty for one dataset (black). Anomalies are relative to the mean of 1961–1990. (b) Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset (orange line in panel a). Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign. For a listing of the datasets and further technical details see the Technical Summary Supplementary Material. {Figures 2.19–2.21; Figure TS.2}

Table SPM.1 | Extreme weather and climate events: Global-scale assessment of recent observed changes, human contribution to the changes, and projected further changes for the early (2016–2035) and late (2081–2100) 21st century. Bold indicates where the AR5 (black) provides a revised* global-scale assessment from the SREX (blue) or AR4 (red). Projections for early 21st century were not provided in previous assessment reports. Projections in the AR5 are relative to the reference period of 1986–2005, and use the new Representative Concentration Pathway (RCP) scenarios (see Box SPM.1) unless otherwise specified. See the Glossary for definitions of extreme weather and climate events.

Phenomenon and direction of trend	Assessment that changes occurred (typically since 1950 unless otherwise indicated)	Assessment of a human contribution to observed changes	Likelihood of further changes: Early 21st century	Likelihood of further changes: Late 21st century
Warmer and/or fewer cold days and nights over most land areas	*Very likely* {2.6}	***Very likely*** {10.6}	*Likely* {11.3}	*Virtually certain* {12.4}
	Very likely *Very likely*	*Likely* *Likely*		*Virtually certain* *Virtually certain*
Warmer and/or more frequent hot days and nights over most land areas	*Very likely* {2.6}	***Very likely*** {10.6}	*Likely* {11.3}	*Virtually certain* {12.4}
	Very likely *Very likely*	*Likely* *Likely* (nights only)		*Virtually certain* *Virtually certain*
Warm spells/heat waves. Frequency and/or duration increases over most land areas	***Medium confidence*** on a global scale *Likely* in large parts of Europe, Asia and Australia {2.6}	***Likely***[a] {10.6}	Not formally assessed[b] {11.3}	*Very likely* {12.4}
	Medium confidence in many (but not all) regions *Likely*	Not formally assessed *More likely than not*		*Very likely* *Very likely*
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation	*Likely* more land areas with increases than decreases[c] {2.6}	***Medium confidence*** {7.6, 10.6}	*Likely* over many land areas {11.3}	***Very likely*** over most of the mid-latitude land masses and over wet tropical regions {12.4}
	Likely more land areas with increases than decreases *Likely* over most land areas	*Medium confidence* *More likely than not*		*Likely* over many areas *Very likely* over most land areas
Increases in intensity and/or duration of drought	***Low confidence*** on a global scale *Likely* changes in some regions[d] {2.6}	***Low confidence*** {10.6}	*Low confidence*[g] {11.3}	***Likely** (medium confidence)* on a regional to global scale[h] {12.4}
	Medium confidence in some regions *Likely* in many regions, since 1970[e]	*Medium confidence*[f] *More likely than not*		*Medium confidence* in some regions *Likely*[e]
Increases in intense tropical cyclone activity	***Low confidence*** in long term (centennial) changes *Virtually certain* in North Atlantic since 1970 {2.6}	***Low confidence***[i] {10.6}	*Low confidence* {11.3}	***More likely than not*** in the Western North Pacific and North Atlantic[j] {14.6}
	Low confidence *Likely* in some regions, since 1970	*Low confidence* *More likely than not*		*More likely than not* in some basins *Likely*
Increased incidence and/or magnitude of extreme high sea level	*Likely* (since 1970) {3.7}	***Likely***[k] {3.7}	*Likely*[l] {13.7}	***Very likely***[l] {13.7}
	Likely (late 20th century) *Likely*	*Likely*[k] *More likely than not*[k]		*Very likely*[m] *Likely*

* The direct comparison of assessment findings between reports is difficult. For some climate variables, different aspects have been assessed, and the revised guidance note on uncertainties has been used for the SREX and AR5. The availability of new information, improved scientific understanding, continued analyses of data and models, and specific differences in methodologies applied in the assessed studies, all contribute to revised assessment findings.

Notes:

[a] Attribution is based on available case studies. It is *likely* that human influence has more than doubled the probability of occurrence of some observed heat waves in some locations.

[b] Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells.

[c] In most continents, *confidence* in trends is not higher than *medium* except in North America and Europe where there have been *likely* increases in either the frequency or intensity of heavy precipitation with some seasonal and/or regional variation. It is *very likely* that there have been increases in central North America.

[d] The frequency and intensity of drought has *likely* increased in the Mediterranean and West Africa, and *likely* decreased in central North America and north-west Australia.

[e] AR4 assessed the area affected by drought.

[f] SREX assessed *medium confidence* that anthropogenic influence had contributed to some changes in the drought patterns observed in the second half of the 20th century, based on its attributed impact on precipitation and temperature changes. SREX assessed *low confidence* in the attribution of changes in droughts at the level of single regions.

[g] There is *low confidence* in projected changes in soil moisture.

[h] Regional to global-scale projected decreases in soil moisture and increased agricultural drought are *likely (medium confidence)* in presently dry regions by the end of this century under the RCP8.5 scenario. Soil moisture drying in the Mediterranean, Southwest US and southern African regions is consistent with projected changes in Hadley circulation and increased surface temperatures, so there is *high confidence* in *likely* surface drying in these regions by the end of this century under the RCP8.5 scenario.

[i] There is *medium confidence* that a reduction in aerosol forcing over the North Atlantic has contributed at least in part to the observed increase in tropical cyclone activity since the 1970s in this region.

[j] Based on expert judgment and assessment of projections which use an SRES A1B (or similar) scenario.

[k] Attribution is based on the close relationship between observed changes in extreme and mean sea level.

[l] There is *high confidence* that this increase in extreme high sea level will primarily be the result of an increase in mean sea level. There is *low confidence* in region-specific projections of storminess and associated storm surges.

[m] SREX assessed it to be *very likely* that mean sea level rise will contribute to future upward trends in extreme coastal high water levels.

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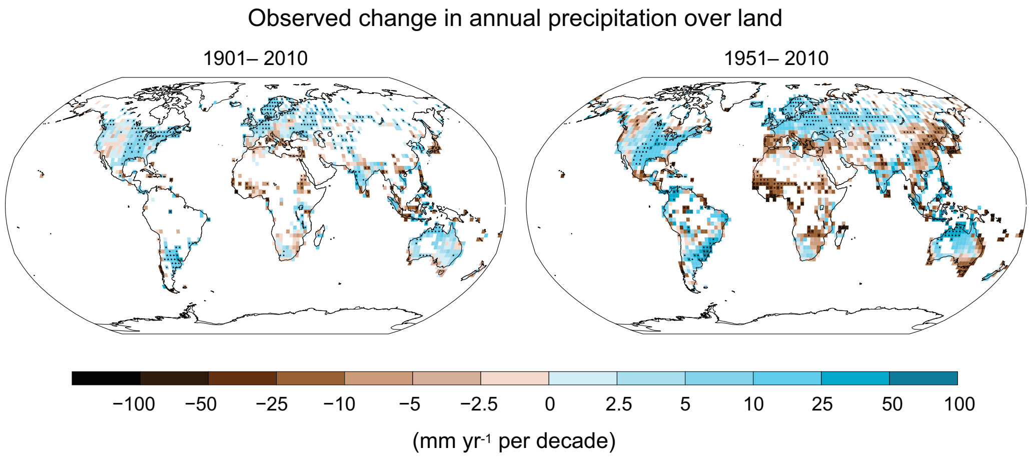

Figure SPM.2 | Maps of observed precipitation change from 1901 to 2010 and from 1951 to 2010 (trends in annual accumulation calculated using the same criteria as in Figure SPM.1) from one data set. For further technical details see the Technical Summary Supplementary Material. {TS TFE.1, Figure 2; Figure 2.29}

B.2 Ocean

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*). It is *virtually certain* that the upper ocean (0–700 m) warmed from 1971 to 2010 (see Figure SPM.3), and it *likely* warmed between the 1870s and 1971. {3.2, Box 3.1}

- On a global scale, the ocean warming is largest near the surface, and the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010. Since AR4, instrumental biases in upper-ocean temperature records have been identified and reduced, enhancing confidence in the assessment of change. {3.2}

- It is *likely* that the ocean warmed between 700 and 2000 m from 1957 to 2009. Sufficient observations are available for the period 1992 to 2005 for a global assessment of temperature change below 2000 m. There were *likely* no significant observed temperature trends between 2000 and 3000 m for this period. It is *likely* that the ocean warmed from 3000 m to the bottom for this period, with the largest warming observed in the Southern Ocean. {3.2}

- More than 60% of the net energy increase in the climate system is stored in the upper ocean (0–700 m) during the relatively well-sampled 40-year period from 1971 to 2010, and about 30% is stored in the ocean below 700 m. The increase in upper ocean heat content during this time period estimated from a linear trend is *likely* 17 [15 to 19] × 10^{22} J [7] (see Figure SPM.3). {3.2, Box 3.1}

- It is *about as likely as not* that ocean heat content from 0–700 m increased more slowly during 2003 to 2010 than during 1993 to 2002 (see Figure SPM.3). Ocean heat uptake from 700–2000 m, where interannual variability is smaller, *likely* continued unabated from 1993 to 2009. {3.2, Box 9.2}

- It is *very likely* that regions of high salinity where evaporation dominates have become more saline, while regions of low salinity where precipitation dominates have become fresher since the 1950s. These regional trends in ocean salinity provide indirect evidence that evaporation and precipitation over the oceans have changed (*medium confidence*). {2.5, 3.3, 3.5}

- There is no observational evidence of a trend in the Atlantic Meridional Overturning Circulation (AMOC), based on the decade-long record of the complete AMOC and longer records of individual AMOC components. {3.6}

[7] A constant supply of heat through the ocean surface at the rate of 1 W m^{-2} for 1 year would increase the ocean heat content by 1.1 × 10^{22} J.

B.3 Cryosphere

Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (*high confidence*) (see Figure SPM.3). {4.2–4.7}

- The average rate of ice loss[8] from glaciers around the world, excluding glaciers on the periphery of the ice sheets[9], was *very likely* 226 [91 to 361] Gt yr^{-1} over the period 1971 to 2009, and *very likely* 275 [140 to 410] Gt yr^{-1} over the period 1993 to 2009[10]. {4.3}

- The average rate of ice loss from the Greenland ice sheet has *very likely* substantially increased from 34 [–6 to 74] Gt yr^{-1} over the period 1992 to 2001 to 215 [157 to 274] Gt yr^{-1} over the period 2002 to 2011. {4.4}

- The average rate of ice loss from the Antarctic ice sheet has *likely* increased from 30 [–37 to 97] Gt yr^{-1} over the period 1992–2001 to 147 [72 to 221] Gt yr^{-1} over the period 2002 to 2011. There is *very high confidence* that these losses are mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica. {4.4}

- The annual mean Arctic sea ice extent decreased over the period 1979 to 2012 with a rate that was *very likely* in the range 3.5 to 4.1% per decade (range of 0.45 to 0.51 million km^2 per decade), and *very likely* in the range 9.4 to 13.6% per decade (range of 0.73 to 1.07 million km^2 per decade) for the summer sea ice minimum (perennial sea ice). The average decrease in decadal mean extent of Arctic sea ice has been most rapid in summer (*high confidence*); the spatial extent has decreased in every season, and in every successive decade since 1979 (*high confidence*) (see Figure SPM.3). There is *medium confidence* from reconstructions that over the past three decades, Arctic summer sea ice retreat was unprecedented and sea surface temperatures were anomalously high in at least the last 1,450 years. {4.2, 5.5}

- It is *very likely* that the annual mean Antarctic sea ice extent increased at a rate in the range of 1.2 to 1.8% per decade (range of 0.13 to 0.20 million km^2 per decade) between 1979 and 2012. There is *high confidence* that there are strong regional differences in this annual rate, with extent increasing in some regions and decreasing in others. {4.2}

- There is *very high confidence* that the extent of Northern Hemisphere snow cover has decreased since the mid-20th century (see Figure SPM.3). Northern Hemisphere snow cover extent decreased 1.6 [0.8 to 2.4] % per decade for March and April, and 11.7 [8.8 to 14.6] % per decade for June, over the 1967 to 2012 period. During this period, snow cover extent in the Northern Hemisphere did not show a statistically significant increase in any month. {4.5}

- There is *high confidence* that permafrost temperatures have increased in most regions since the early 1980s. Observed warming was up to 3°C in parts of Northern Alaska (early 1980s to mid-2000s) and up to 2°C in parts of the Russian European North (1971 to 2010). In the latter region, a considerable reduction in permafrost thickness and areal extent has been observed over the period 1975 to 2005 (*medium confidence*). {4.7}

- Multiple lines of evidence support very substantial Arctic warming since the mid-20th century. {Box 5.1, 10.3}

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8 All references to 'ice loss' or 'mass loss' refer to net ice loss, i.e., accumulation minus melt and iceberg calving.

9 For methodological reasons, this assessment of ice loss from the Antarctic and Greenland ice sheets includes change in the glaciers on the periphery. These peripheral glaciers are thus excluded from the values given for glaciers.

10 100 Gt yr^{-1} of ice loss is equivalent to about 0.28 mm yr^{-1} of global mean sea level rise.

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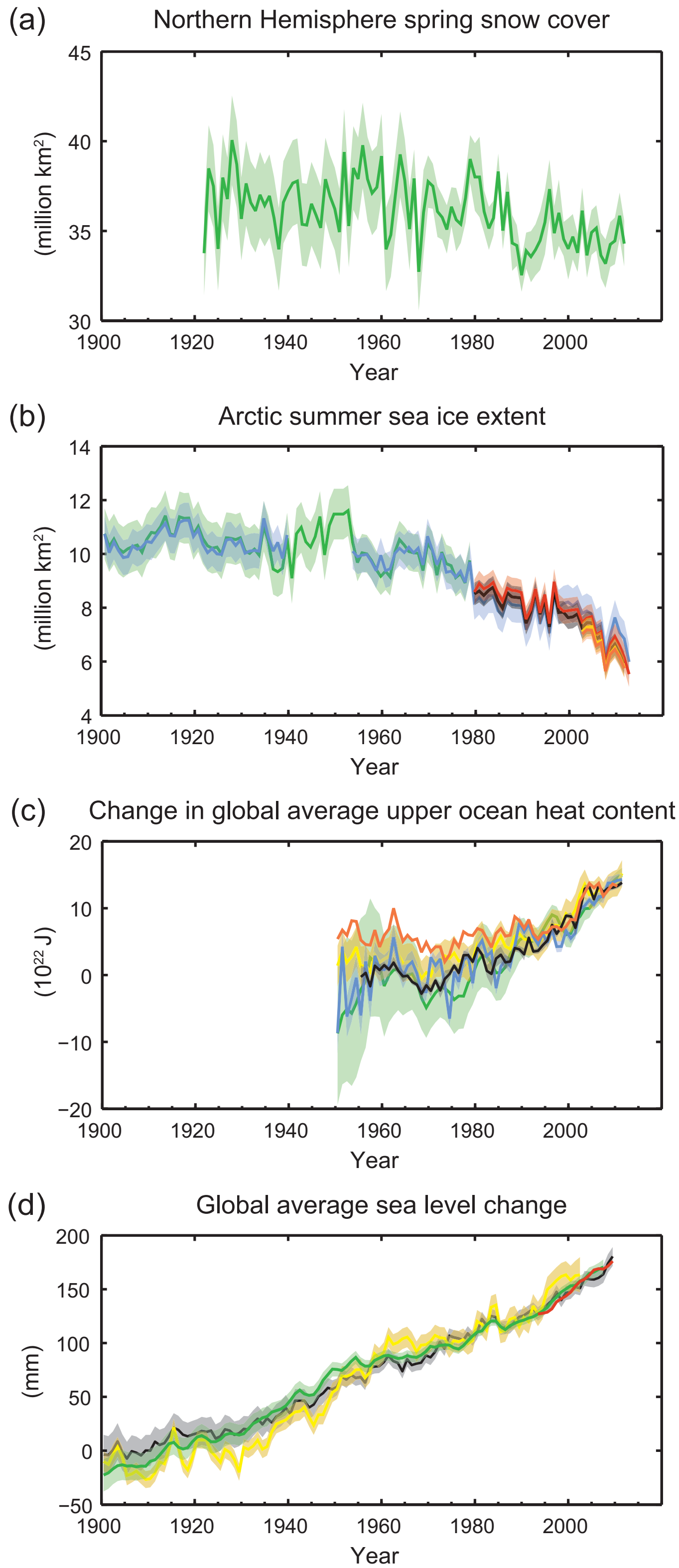

Figure SPM.3 | Multiple observed indicators of a changing global climate: (a) Extent of Northern Hemisphere March-April (spring) average snow cover; (b) extent of Arctic July-August-September (summer) average sea ice; (c) change in global mean upper ocean (0–700 m) heat content aligned to 2006–2010, and relative to the mean of all datasets for 1970; (d) global mean sea level relative to the 1900–1905 mean of the longest running dataset, and with all datasets aligned to have the same value in 1993, the first year of satellite altimetry data. All time-series (coloured lines indicating different data sets) show annual values, and where assessed, uncertainties are indicated by coloured shading. See Technical Summary Supplementary Material for a listing of the datasets. {Figures 3.2, 3.13, 4.19, and 4.3; FAQ 2.1, Figure 2; Figure TS.1}

B.4 Sea Level

The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). Over the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m (see Figure SPM.3). {3.7, 5.6, 13.2}

- Proxy and instrumental sea level data indicate a transition in the late 19th to the early 20th century from relatively low mean rates of rise over the previous two millennia to higher rates of rise (*high confidence*). It is *likely* that the rate of global mean sea level rise has continued to increase since the early 20th century. {3.7, 5.6, 13.2}

- It is *very likely* that the mean rate of global averaged sea level rise was 1.7 [1.5 to 1.9] mm yr^{-1} between 1901 and 2010, 2.0 [1.7 to 2.3] mm yr^{-1} between 1971 and 2010, and 3.2 [2.8 to 3.6] mm yr^{-1} between 1993 and 2010. Tide-gauge and satellite altimeter data are consistent regarding the higher rate of the latter period. It is *likely* that similarly high rates occurred between 1920 and 1950. {3.7}

- Since the early 1970s, glacier mass loss and ocean thermal expansion from warming together explain about 75% of the observed global mean sea level rise (*high confidence*). Over the period 1993 to 2010, global mean sea level rise is, with *high confidence*, consistent with the sum of the observed contributions from ocean thermal expansion due to warming (1.1 [0.8 to 1.4] mm yr^{-1}), from changes in glaciers (0.76 [0.39 to 1.13] mm yr^{-1}), Greenland ice sheet (0.33 [0.25 to 0.41] mm yr^{-1}), Antarctic ice sheet (0.27 [0.16 to 0.38] mm yr^{-1}), and land water storage (0.38 [0.26 to 0.49] mm yr^{-1}). The sum of these contributions is 2.8 [2.3 to 3.4] mm yr^{-1}. {13.3}

- There is *very high confidence* that maximum global mean sea level during the last interglacial period (129,000 to 116,000 years ago) was, for several thousand years, at least 5 m higher than present, and *high confidence* that it did not exceed 10 m above present. During the last interglacial period, the Greenland ice sheet *very likely* contributed between 1.4 and 4.3 m to the higher global mean sea level, implying with *medium confidence* an additional contribution from the Antarctic ice sheet. This change in sea level occurred in the context of different orbital forcing and with high-latitude surface temperature, averaged over several thousand years, at least 2°C warmer than present (*high confidence*). {5.3, 5.6}

B.5 Carbon and Other Biogeochemical Cycles

The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification (see Figure SPM.4). {2.2, 3.8, 5.2, 6.2, 6.3}

- The atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have all increased since 1750 due to human activity. In 2011 the concentrations of these greenhouse gases were 391 ppm[11], 1803 ppb, and 324 ppb, and exceeded the pre-industrial levels by about 40%, 150%, and 20%, respectively. {2.2, 5.2, 6.1, 6.2}

- Concentrations of CO_2, CH_4, and N_2O now substantially exceed the highest concentrations recorded in ice cores during the past 800,000 years. The mean rates of increase in atmospheric concentrations over the past century are, with *very high confidence*, unprecedented in the last 22,000 years. {5.2, 6.1, 6.2}

[11] ppm (parts per million) or ppb (parts per billion, 1 billion = 1,000 million) is the ratio of the number of gas molecules to the total number of molecules of dry air. For example, 300 ppm means 300 molecules of a gas per million molecules of dry air.

- Annual CO_2 emissions from fossil fuel combustion and cement production were 8.3 [7.6 to 9.0] GtC[12] yr^{-1} averaged over 2002–2011 (*high confidence*) and were 9.5 [8.7 to 10.3] GtC yr^{-1} in 2011, 54% above the 1990 level. Annual net CO_2 emissions from anthropogenic land use change were 0.9 [0.1 to 1.7] GtC yr^{-1} on average during 2002 to 2011 (*medium confidence*). {6.3}

- From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC. {6.3}

- Of these cumulative anthropogenic CO_2 emissions, 240 [230 to 250] GtC have accumulated in the atmosphere, 155 [125 to 185] GtC have been taken up by the ocean and 160 [70 to 250] GtC have accumulated in natural terrestrial ecosystems (i.e., the cumulative residual land sink). {Figure TS.4, 3.8, 6.3}

- Ocean acidification is quantified by decreases in pH[13]. The pH of ocean surface water has decreased by 0.1 since the beginning of the industrial era (*high confidence*), corresponding to a 26% increase in hydrogen ion concentration (see Figure SPM.4). {3.8, Box 3.2}

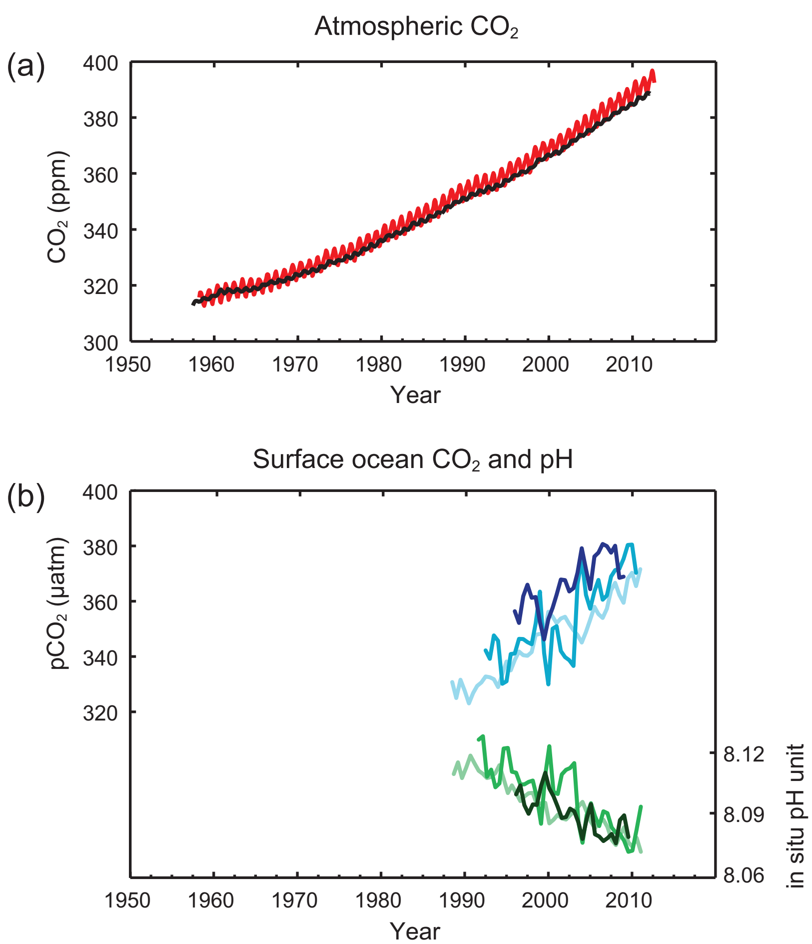

Figure SPM.4 | Multiple observed indicators of a changing global carbon cycle: (a) atmospheric concentrations of carbon dioxide (CO_2) from Mauna Loa (19°32'N, 155°34'W – red) and South Pole (89°59'S, 24°48'W – black) since 1958; (b) partial pressure of dissolved CO_2 at the ocean surface (blue curves) and in situ pH (green curves), a measure of the acidity of ocean water. Measurements are from three stations from the Atlantic (29°10'N, 15°30'W – dark blue/dark green; 31°40'N, 64°10'W – blue/green) and the Pacific Oceans (22°45'N, 158°00'W – light blue/light green). Full details of the datasets shown here are provided in the underlying report and the Technical Summary Supplementary Material. {Figures 2.1 and 3.18; Figure TS.5}

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[12] 1 Gigatonne of carbon = 1 GtC = 10^{15} grams of carbon. This corresponds to 3.667 $GtCO_2$.

[13] pH is a measure of acidity using a logarithmic scale: a pH decrease of 1 unit corresponds to a 10-fold increase in hydrogen ion concentration, or acidity.

C. Drivers of Climate Change

Natural and anthropogenic substances and processes that alter the Earth's energy budget are drivers of climate change. Radiative forcing[14] (RF) quantifies the change in energy fluxes caused by changes in these drivers for 2011 relative to 1750, unless otherwise indicated. Positive RF leads to surface warming, negative RF leads to surface cooling. RF is estimated based on in-situ and remote observations, properties of greenhouse gases and aerosols, and calculations using numerical models representing observed processes. Some emitted compounds affect the atmospheric concentration of other substances. The RF can be reported based on the concentration changes of each substance[15]. Alternatively, the emission-based RF of a compound can be reported, which provides a more direct link to human activities. It includes contributions from all substances affected by that emission. The total anthropogenic RF of the two approaches are identical when considering all drivers. Though both approaches are used in this Summary for Policymakers, emission-based RFs are emphasized.

Total radiative forcing is positive, and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO_2 since 1750 (see Figure SPM.5). {3.2, Box 3.1, 8.3, 8.5}

- The total anthropogenic RF for 2011 relative to 1750 is 2.29 [1.13 to 3.33] W m^{-2} (see Figure SPM.5), and it has increased more rapidly since 1970 than during prior decades. The total anthropogenic RF best estimate for 2011 is 43% higher than that reported in AR4 for the year 2005. This is caused by a combination of continued growth in most greenhouse gas concentrations and improved estimates of RF by aerosols indicating a weaker net cooling effect (negative RF). {8.5}

- The RF from emissions of well-mixed greenhouse gases (CO_2, CH_4, N_2O, and Halocarbons) for 2011 relative to 1750 is 3.00 [2.22 to 3.78] W m^{-2} (see Figure SPM.5). The RF from changes in concentrations in these gases is 2.83 [2.26 to 3.40] W m^{-2}. {8.5}

- Emissions of CO_2 alone have caused an RF of 1.68 [1.33 to 2.03] W m^{-2} (see Figure SPM.5). Including emissions of other carbon-containing gases, which also contributed to the increase in CO_2 concentrations, the RF of CO_2 is 1.82 [1.46 to 2.18] W m^{-2}. {8.3, 8.5}

- Emissions of CH_4 alone have caused an RF of 0.97 [0.74 to 1.20] W m^{-2} (see Figure SPM.5). This is much larger than the concentration-based estimate of 0.48 [0.38 to 0.58] W m^{-2} (unchanged from AR4). This difference in estimates is caused by concentration changes in ozone and stratospheric water vapour due to CH_4 emissions and other emissions indirectly affecting CH_4. {8.3, 8.5}

- Emissions of stratospheric ozone-depleting halocarbons have caused a net positive RF of 0.18 [0.01 to 0.35] W m^{-2} (see Figure SPM.5). Their own positive RF has outweighed the negative RF from the ozone depletion that they have induced. The positive RF from all halocarbons is similar to the value in AR4, with a reduced RF from CFCs but increases from many of their substitutes. {8.3, 8.5}

- Emissions of short-lived gases contribute to the total anthropogenic RF. Emissions of carbon monoxide (CO) are *virtually certain* to have induced a positive RF, while emissions of nitrogen oxides (NO_x) are *likely* to have induced a net negative RF (see Figure SPM.5). {8.3, 8.5}

- The RF of the total aerosol effect in the atmosphere, which includes cloud adjustments due to aerosols, is –0.9 [–1.9 to –0.1] W m^{-2} (*medium confidence*), and results from a negative forcing from most aerosols and a positive contribution

[14] The strength of drivers is quantified as Radiative Forcing (RF) in units watts per square metre (W m^{-2}) as in previous IPCC assessments. RF is the change in energy flux caused by a driver, and is calculated at the tropopause or at the top of the atmosphere. In the traditional RF concept employed in previous IPCC reports all surface and tropospheric conditions are kept fixed. In calculations of RF for well-mixed greenhouse gases and aerosols in this report, physical variables, except for the ocean and sea ice, are allowed to respond to perturbations with rapid adjustments. The resulting forcing is called Effective Radiative Forcing (ERF) in the underlying report. This change reflects the scientific progress from previous assessments and results in a better indication of the eventual temperature response for these drivers. For all drivers other than well-mixed greenhouse gases and aerosols, rapid adjustments are less well characterized and assumed to be small, and thus the traditional RF is used. {8.1}

[15] This approach was used to report RF in the AR4 Summary for Policymakers.

from black carbon absorption of solar radiation. There is *high confidence* that aerosols and their interactions with clouds have offset a substantial portion of global mean forcing from well-mixed greenhouse gases. They continue to contribute the largest uncertainty to the total RF estimate. {7.5, 8.3, 8.5}

- The forcing from stratospheric volcanic aerosols can have a large impact on the climate for some years after volcanic eruptions. Several small eruptions have caused an RF of –0.11 [–0.15 to –0.08] W m^{-2} for the years 2008 to 2011, which is approximately twice as strong as during the years 1999 to 2002. {8.4}

- The RF due to changes in solar irradiance is estimated as 0.05 [0.00 to 0.10] W m^{-2} (see Figure SPM.5). Satellite observations of total solar irradiance changes from 1978 to 2011 indicate that the last solar minimum was lower than the previous two. This results in an RF of –0.04 [–0.08 to 0.00] W m^{-2} between the most recent minimum in 2008 and the 1986 minimum. {8.4}

- The total natural RF from solar irradiance changes and stratospheric volcanic aerosols made only a small contribution to the net radiative forcing throughout the last century, except for brief periods after large volcanic eruptions. {8.5}

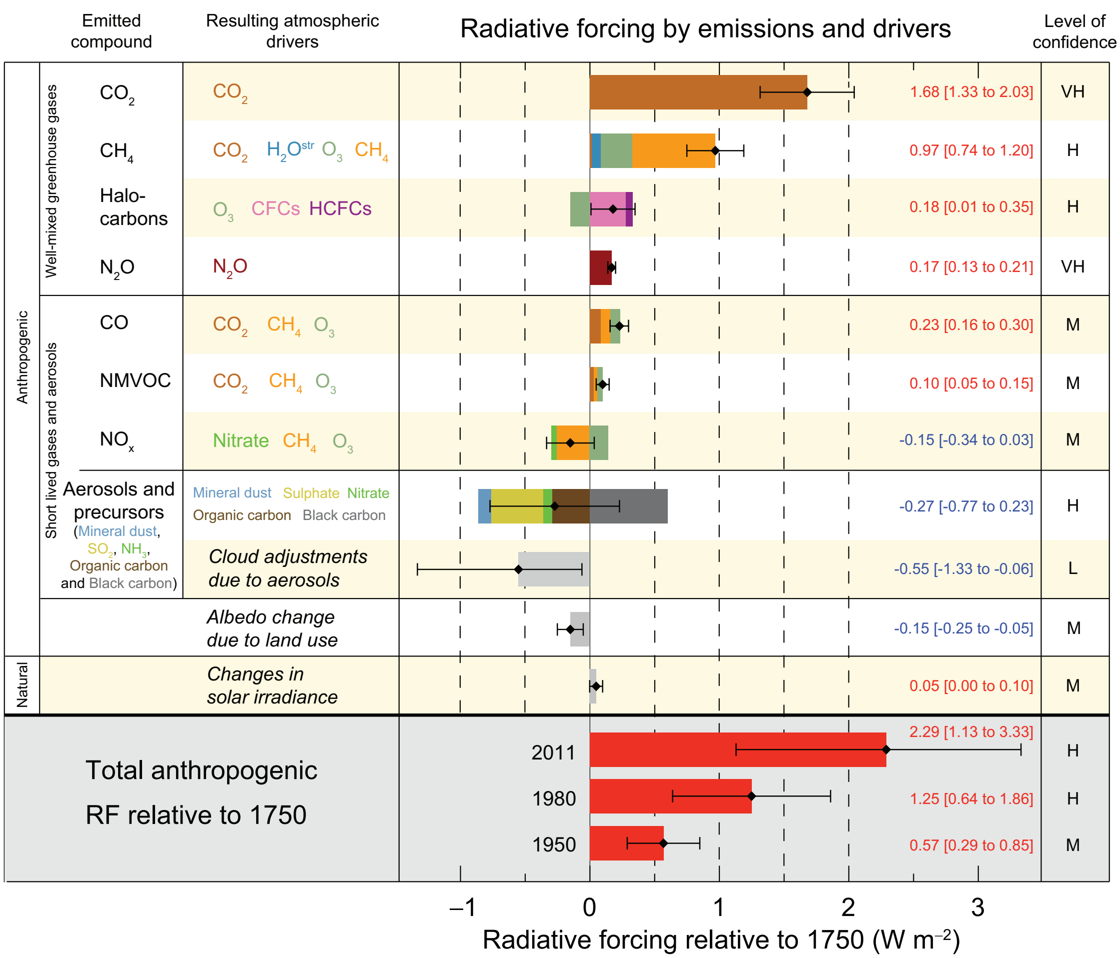

Figure SPM.5 | Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Values are global average radiative forcing (RF[14]), partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative forcing are shown as black diamonds with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing (VH – *very high*, H – *high*, M – *medium*, L – *low*, VL – *very low*). Albedo forcing due to black carbon on snow and ice is included in the black carbon aerosol bar. Small forcings due to contrails (0.05 W m^{-2}, including contrail induced cirrus), and HFCs, PFCs and SF_6 (total 0.03 W m^{-2}) are not shown. Concentration-based RFs for gases can be obtained by summing the like-coloured bars. Volcanic forcing is not included as its episodic nature makes is difficult to compare to other forcing mechanisms. Total anthropogenic radiative forcing is provided for three different years relative to 1750. For further technical details, including uncertainty ranges associated with individual components and processes, see the Technical Summary Supplementary Material. {8.5; Figures 8.14–8.18; Figures TS.6 and TS.7}

D. Understanding the Climate System and its Recent Changes

Understanding recent changes in the climate system results from combining observations, studies of feedback processes, and model simulations. Evaluation of the ability of climate models to simulate recent changes requires consideration of the state of all modelled climate system components at the start of the simulation and the natural and anthropogenic forcing used to drive the models. Compared to AR4, more detailed and longer observations and improved climate models now enable the attribution of a human contribution to detected changes in more climate system components.

Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system. {2–14}

D.1 Evaluation of Climate Models

Climate models have improved since the AR4. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (*very high confidence*). {9.4, 9.6, 9.8}

- The long-term climate model simulations show a trend in global-mean surface temperature from 1951 to 2012 that agrees with the observed trend (*very high confidence*). There are, however, differences between simulated and observed trends over periods as short as 10 to 15 years (e.g., 1998 to 2012). {9.4, Box 9.2}

- The observed reduction in surface warming trend over the period 1998 to 2012 as compared to the period 1951 to 2012, is due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from natural internal variability, which includes a possible redistribution of heat within the ocean (*medium confidence*). The reduced trend in radiative forcing is primarily due to volcanic eruptions and the timing of the downward phase of the 11-year solar cycle. However, there is *low confidence* in quantifying the role of changes in radiative forcing in causing the reduced warming trend. There is *medium confidence* that natural internal decadal variability causes to a substantial degree the difference between observations and the simulations; the latter are not expected to reproduce the timing of natural internal variability. There may also be a contribution from forcing inadequacies and, in some models, an overestimate of the response to increasing greenhouse gas and other anthropogenic forcing (dominated by the effects of aerosols). {9.4, Box 9.2, 10.3, Box 10.2, 11.3}

- On regional scales, the confidence in model capability to simulate surface temperature is less than for the larger scales. However, there is *high confidence* that regional-scale surface temperature is better simulated than at the time of the AR4. {9.4, 9.6}

- There has been substantial progress in the assessment of extreme weather and climate events since AR4. Simulated global-mean trends in the frequency of extreme warm and cold days and nights over the second half of the 20th century are generally consistent with observations. {9.5}

- There has been some improvement in the simulation of continental-scale patterns of precipitation since the AR4. At regional scales, precipitation is not simulated as well, and the assessment is hampered by observational uncertainties. {9.4, 9.6}

- Some important climate phenomena are now better reproduced by models. There is *high confidence* that the statistics of monsoon and El Niño-Southern Oscillation (ENSO) based on multi-model simulations have improved since AR4. {9.5}

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- Climate models now include more cloud and aerosol processes, and their interactions, than at the time of the AR4, but there remains *low confidence* in the representation and quantification of these processes in models. {7.3, 7.6, 9.4, 9.7}

- There is robust evidence that the downward trend in Arctic summer sea ice extent since 1979 is now reproduced by more models than at the time of the AR4, with about one-quarter of the models showing a trend as large as, or larger than, the trend in the observations. Most models simulate a small downward trend in Antarctic sea ice extent, albeit with large inter-model spread, in contrast to the small upward trend in observations. {9.4}

- Many models reproduce the observed changes in upper-ocean heat content (0–700 m) from 1961 to 2005 (*high confidence*), with the multi-model mean time series falling within the range of the available observational estimates for most of the period. {9.4}

- Climate models that include the carbon cycle (Earth System Models) simulate the global pattern of ocean-atmosphere CO_2 fluxes, with outgassing in the tropics and uptake in the mid and high latitudes. In the majority of these models the sizes of the simulated global land and ocean carbon sinks over the latter part of the 20th century are within the range of observational estimates. {9.4}

D.2 Quantification of Climate System Responses

Observational and model studies of temperature change, climate feedbacks and changes in the Earth's energy budget together provide confidence in the magnitude of global warming in response to past and future forcing. {Box 12.2, Box 13.1}

- The net feedback from the combined effect of changes in water vapour, and differences between atmospheric and surface warming is *extremely likely* positive and therefore amplifies changes in climate. The net radiative feedback due to all cloud types combined is *likely* positive. Uncertainty in the sign and magnitude of the cloud feedback is due primarily to continuing uncertainty in the impact of warming on low clouds. {7.2}

- The equilibrium climate sensitivity quantifies the response of the climate system to constant radiative forcing on multi-century time scales. It is defined as the change in global mean surface temperature at equilibrium that is caused by a doubling of the atmospheric CO_2 concentration. Equilibrium climate sensitivity is *likely* in the range 1.5°C to 4.5°C (*high confidence*), *extremely unlikely* less than 1°C (*high confidence*), and *very unlikely* greater than 6°C (*medium confidence*)[16]. The lower temperature limit of the assessed *likely* range is thus less than the 2°C in the AR4, but the upper limit is the same. This assessment reflects improved understanding, the extended temperature record in the atmosphere and ocean, and new estimates of radiative forcing. {TS TFE.6, Figure 1; Box 12.2}

- The rate and magnitude of global climate change is determined by radiative forcing, climate feedbacks and the storage of energy by the climate system. Estimates of these quantities for recent decades are consistent with the assessed *likely* range of the equilibrium climate sensitivity to within assessed uncertainties, providing strong evidence for our understanding of anthropogenic climate change. {Box 12.2, Box 13.1}

- The transient climate response quantifies the response of the climate system to an increasing radiative forcing on a decadal to century timescale. It is defined as the change in global mean surface temperature at the time when the atmospheric CO_2 concentration has doubled in a scenario of concentration increasing at 1% per year. The transient climate response is *likely* in the range of 1.0°C to 2.5°C (*high confidence*) and *extremely unlikely* greater than 3°C. {Box 12.2}

- A related quantity is the transient climate response to cumulative carbon emissions (TCRE). It quantifies the transient response of the climate system to cumulative carbon emissions (see Section E.8). TCRE is defined as the global mean

[16] No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence and studies.

surface temperature change per 1000 GtC emitted to the atmosphere. TCRE is *likely* in the range of 0.8°C to 2.5°C per 1000 GtC and applies for cumulative emissions up to about 2000 GtC until the time temperatures peak (see Figure SPM.10). {12.5, Box 12.2}

- Various metrics can be used to compare the contributions to climate change of emissions of different substances. The most appropriate metric and time horizon will depend on which aspects of climate change are considered most important to a particular application. No single metric can accurately compare all consequences of different emissions, and all have limitations and uncertainties. The Global Warming Potential is based on the cumulative radiative forcing over a particular time horizon, and the Global Temperature Change Potential is based on the change in global mean surface temperature at a chosen point in time. Updated values are provided in the underlying Report. {8.7}

D.3 Detection and Attribution of Climate Change

Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes (see Figure SPM.6 and Table SPM.1). This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. {10.3–10.6, 10.9}

- It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period. {10.3}

- Greenhouse gases contributed a global mean surface warming *likely* to be in the range of 0.5°C to 1.3°C over the period 1951 to 2010, with the contributions from other anthropogenic forcings, including the cooling effect of aerosols, *likely* to be in the range of −0.6°C to 0.1°C. The contribution from natural forcings is *likely* to be in the range of −0.1°C to 0.1°C, and from natural internal variability is *likely* to be in the range of −0.1°C to 0.1°C. Together these assessed contributions are consistent with the observed warming of approximately 0.6°C to 0.7°C over this period. {10.3}

- Over every continental region except Antarctica, anthropogenic forcings have *likely* made a substantial contribution to surface temperature increases since the mid-20th century (see Figure SPM.6). For Antarctica, large observational uncertainties result in *low confidence* that anthropogenic forcings have contributed to the observed warming averaged over available stations. It is *likely* that there has been an anthropogenic contribution to the very substantial Arctic warming since the mid-20th century. {2.4, 10.3}

- It is *very likely* that anthropogenic influence, particularly greenhouse gases and stratospheric ozone depletion, has led to a detectable observed pattern of tropospheric warming and a corresponding cooling in the lower stratosphere since 1961. {2.4, 9.4, 10.3}

- It is *very likely* that anthropogenic forcings have made a substantial contribution to increases in global upper ocean heat content (0–700 m) observed since the 1970s (see Figure SPM.6). There is evidence for human influence in some individual ocean basins. {3.2, 10.4}

- It is *likely* that anthropogenic influences have affected the global water cycle since 1960. Anthropogenic influences have contributed to observed increases in atmospheric moisture content in the atmosphere (*medium confidence*), to global-scale changes in precipitation patterns over land (*medium confidence*), to intensification of heavy precipitation over land regions where data are sufficient (*medium confidence*), and to changes in surface and sub-surface ocean salinity (*very likely*). {2.5, 2.6, 3.3, 7.6, 10.3, 10.4}

SPM

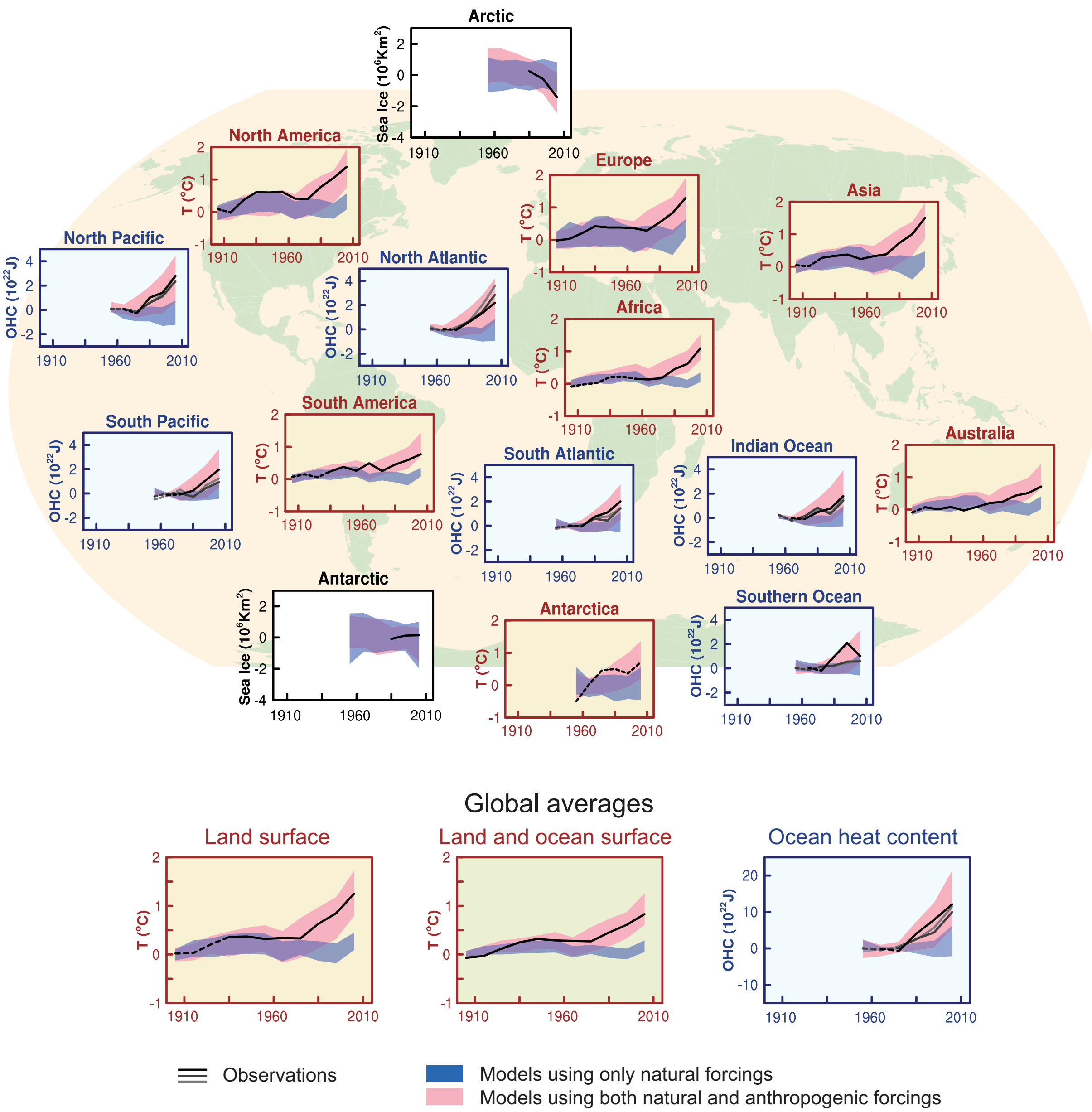

Figure SPM.6 | Comparison of observed and simulated climate change based on three large-scale indicators in the atmosphere, the cryosphere and the ocean: change in continental land surface air temperatures (yellow panels), Arctic and Antarctic September sea ice extent (white panels), and upper ocean heat content in the major ocean basins (blue panels). Global average changes are also given. Anomalies are given relative to 1880–1919 for surface temperatures, 1960–1980 for ocean heat content and 1979–1999 for sea ice. All time-series are decadal averages, plotted at the centre of the decade. For temperature panels, observations are dashed lines if the spatial coverage of areas being examined is below 50%. For ocean heat content and sea ice panels the solid line is where the coverage of data is good and higher in quality, and the dashed line is where the data coverage is only adequate, and thus, uncertainty is larger. Model results shown are Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble ranges, with shaded bands indicating the 5 to 95% confidence intervals. For further technical details, including region definitions see the Technical Summary Supplementary Material. {Figure 10.21; Figure TS.12}

- There has been further strengthening of the evidence for human influence on temperature extremes since the SREX. It is now *very likely* that human influence has contributed to observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century, and *likely* that human influence has more than doubled the probability of occurrence of heat waves in some locations (see Table SPM.1). {10.6}

- Anthropogenic influences have *very likely* contributed to Arctic sea ice loss since 1979. There is *low confidence* in the scientific understanding of the small observed increase in Antarctic sea ice extent due to the incomplete and competing scientific explanations for the causes of change and *low confidence* in estimates of natural internal variability in that region (see Figure SPM.6). {10.5}

- Anthropogenic influences *likely* contributed to the retreat of glaciers since the 1960s and to the increased surface mass loss of the Greenland ice sheet since 1993. Due to a low level of scientific understanding there is *low confidence* in attributing the causes of the observed loss of mass from the Antarctic ice sheet over the past two decades. {4.3, 10.5}

- It is *likely* that there has been an anthropogenic contribution to observed reductions in Northern Hemisphere spring snow cover since 1970. {10.5}

- It is *very likely* that there is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s. This is based on the *high confidence* in an anthropogenic influence on the two largest contributions to sea level rise, that is thermal expansion and glacier mass loss. {10.4, 10.5, 13.3}

- There is *high confidence* that changes in total solar irradiance have not contributed to the increase in global mean surface temperature over the period 1986 to 2008, based on direct satellite measurements of total solar irradiance. There is *medium confidence* that the 11-year cycle of solar variability influences decadal climate fluctuations in some regions. No robust association between changes in cosmic rays and cloudiness has been identified. {7.4, 10.3, Box 10.2}

E. Future Global and Regional Climate Change

Projections of changes in the climate system are made using a hierarchy of climate models ranging from simple climate models, to models of intermediate complexity, to comprehensive climate models, and Earth System Models. These models simulate changes based on a set of scenarios of anthropogenic forcings. A new set of scenarios, the Representative Concentration Pathways (RCPs), was used for the new climate model simulations carried out under the framework of the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the World Climate Research Programme. In all RCPs, atmospheric CO_2 *concentrations are higher in 2100 relative to present day as a result of a further increase of cumulative emissions of* CO_2 *to the atmosphere during the 21st century (see Box SPM.1). Projections in this Summary for Policymakers are for the end of the 21st century (2081–2100) given relative to 1986–2005, unless otherwise stated. To place such projections in historical context, it is necessary to consider observed changes between different periods. Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period is 0.61 [0.55 to 0.67] °C. However, warming has occurred beyond the average of the AR5 reference period. Hence this is not an estimate of historical warming to present (see Chapter 2) .*

Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. {6, 11–14}

- Projections for the next few decades show spatial patterns of climate change similar to those projected for the later 21st century but with smaller magnitude. Natural internal variability will continue to be a major influence on climate, particularly in the near-term and at the regional scale. By the mid-21st century the magnitudes of the projected changes are substantially affected by the choice of emissions scenario (Box SPM.1). {11.3, Box 11.1, Annex I}

- Projected climate change based on RCPs is similar to AR4 in both patterns and magnitude, after accounting for scenario differences. The overall spread of projections for the high RCPs is narrower than for comparable scenarios used in AR4 because in contrast to the SRES emission scenarios used in AR4, the RCPs used in AR5 are defined as concentration pathways and thus carbon cycle uncertainties affecting atmospheric CO_2 concentrations are not considered in the concentration-driven CMIP5 simulations. Projections of sea level rise are larger than in the AR4, primarily because of improved modelling of land-ice contributions.{11.3, 12.3, 12.4, 13.4, 13.5}

E.1 Atmosphere: Temperature

Global surface temperature change for the end of the 21st century is *likely* to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is *likely* to exceed 2°C for RCP6.0 and RCP8.5, and *more likely than not* to exceed 2°C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform (see Figures SPM.7 and SPM.8). {11.3, 12.3, 12.4, 14.8}

- The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will *likely* be in the range of 0.3°C to 0.7°C (*medium confidence*). This assessment is based on multiple lines of evidence and assumes there will be no major volcanic eruptions or secular changes in total solar irradiance. Relative to natural internal variability, near-term increases in seasonal mean and annual mean temperatures are expected to be larger in the tropics and subtropics than in mid-latitudes (*high confidence*). {11.3}

- Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to *likely* be in the ranges derived from the concentration-driven CMIP5 model simulations, that is, 0.3°C to 1.7°C (RCP2.6), 1.1°C to 2.6°C (RCP4.5), 1.4°C to 3.1°C (RCP6.0), 2.6°C to 4.8°C (RCP8.5). The Arctic region will warm more rapidly than the global mean, and mean warming over land will be larger than over the ocean (*very high confidence*) (see Figures SPM.7 and SPM.8, and Table SPM.2). {12.4, 14.8}

- Relative to the average from year 1850 to 1900, global surface temperature change by the end of the 21st century is projected to *likely* exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (*high confidence*). Warming is *likely* to exceed 2°C for RCP6.0 and RCP8.5 (*high confidence*), *more likely than not* to exceed 2°C for RCP4.5 (*high confidence*), but *unlikely* to exceed 2°C for RCP2.6 (*medium confidence*). Warming is *unlikely* to exceed 4°C for RCP2.6, RCP4.5 and RCP6.0 (*high confidence*) and is *about as likely as not* to exceed 4°C for RCP8.5 (*medium confidence*). {12.4}

- It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is *very likely* that heat waves will occur with a higher frequency and duration. Occasional cold winter extremes will continue to occur (see Table SPM.1). {12.4}

E.2 Atmosphere: Water Cycle

Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions (see Figure SPM.8). {12.4, 14.3}

- Projected changes in the water cycle over the next few decades show similar large-scale patterns to those towards the end of the century, but with smaller magnitude. Changes in the near-term, and at the regional scale will be strongly influenced by natural internal variability and may be affected by anthropogenic aerosol emissions. {11.3}

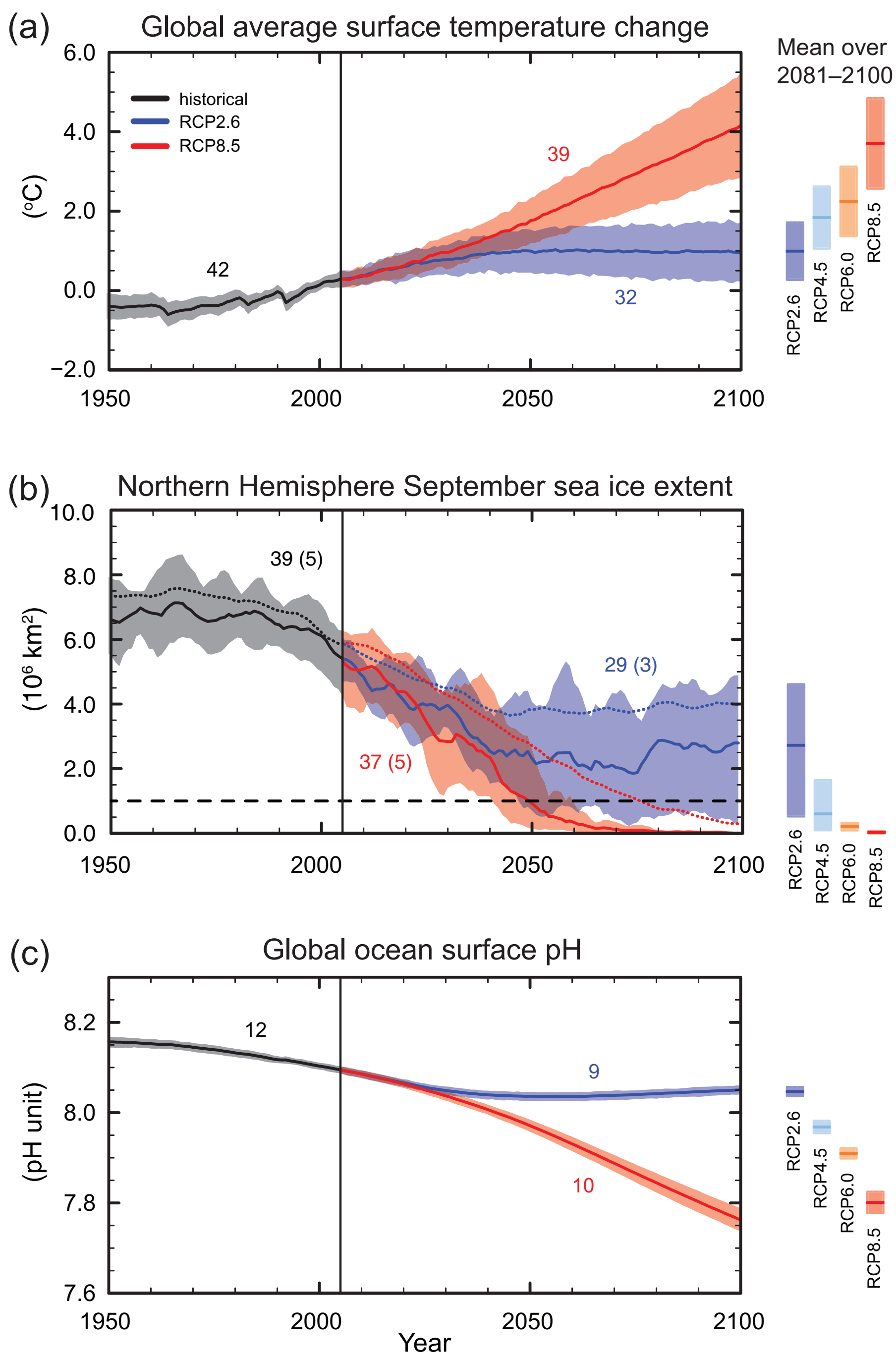

Figure SPM.7 | CMIP5 multi-model simulated time series from 1950 to 2100 for (a) change in global annual mean surface temperature relative to 1986–2005, (b) Northern Hemisphere September sea ice extent (5-year running mean), and (c) global mean ocean surface pH. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as colored vertical bars. The numbers of CMIP5 models used to calculate the multi-model mean is indicated. For sea ice extent (b), the projected mean and uncertainty (minimum-maximum range) of the subset of models that most closely reproduce the climatological mean state and 1979 to 2012 trend of the Arctic sea ice is given (number of models given in brackets). For completeness, the CMIP5 multi-model mean is also indicated with dotted lines. The dashed line represents nearly ice-free conditions (i.e., when sea ice extent is less than 10^6 km^2 for at least five consecutive years). For further technical details see the Technical Summary Supplementary Material {Figures 6.28, 12.5, and 12.28–12.31; Figures TS.15, TS.17, and TS.20}

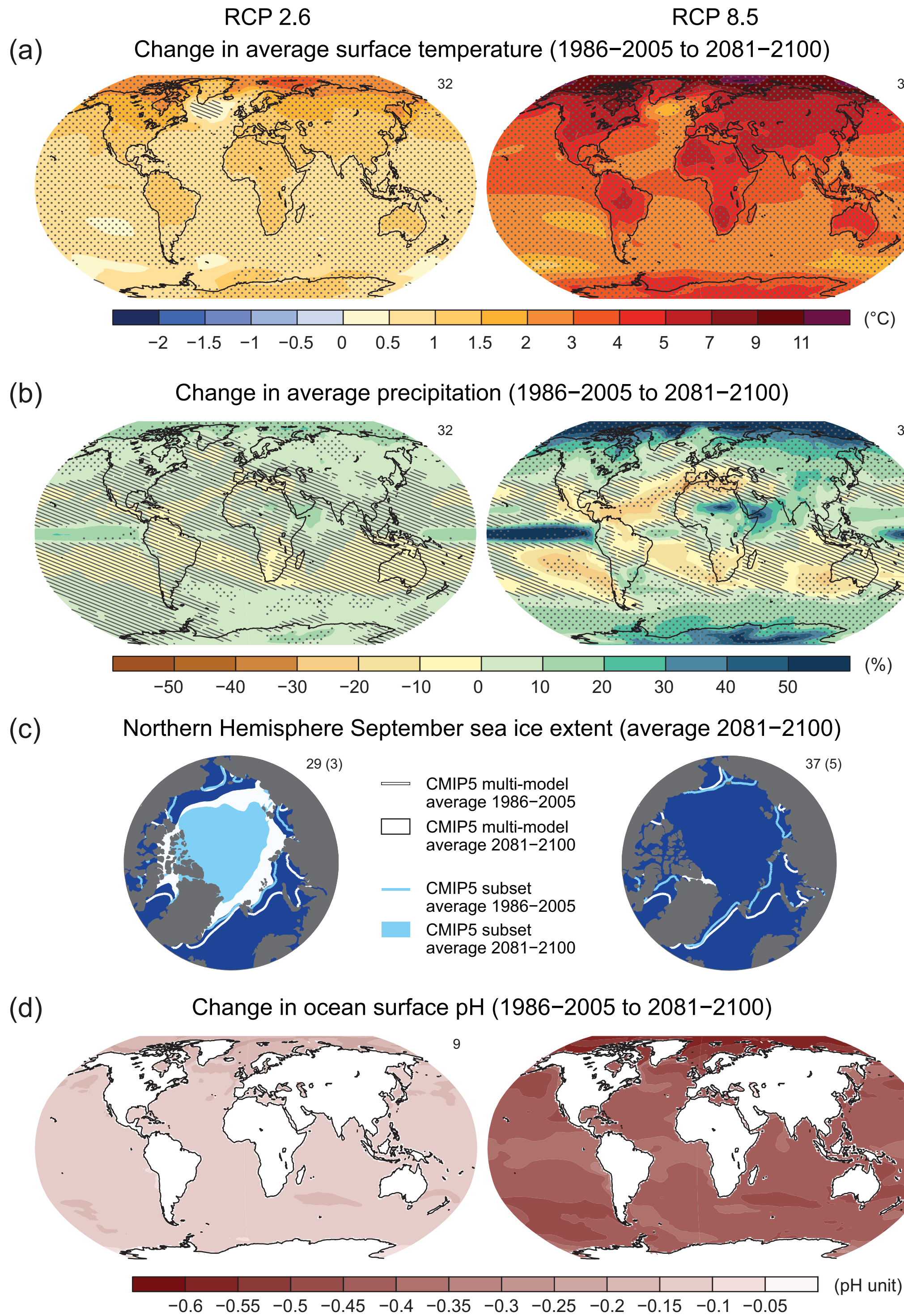

Figure SPM.8 | Maps of CMIP5 multi-model mean results for the scenarios RCP2.6 and RCP8.5 in 2081–2100 of (a) annual mean surface temperature change, (b) average percent change in annual mean precipitation, (c) Northern Hemisphere September sea ice extent, and (d) change in ocean surface pH. Changes in panels (a), (b) and (d) are shown relative to 1986–2005. The number of CMIP5 models used to calculate the multi-model mean is indicated in the upper right corner of each panel. For panels (a) and (b), hatching indicates regions where the multi-model mean is small compared to natural internal variability (i.e., less than one standard deviation of natural internal variability in 20-year means). Stippling indicates regions where the multi-model mean is large compared to natural internal variability (i.e., greater than two standard deviations of natural internal variability in 20-year means) and where at least 90% of models agree on the sign of change (see Box 12.1). In panel (c), the lines are the modelled means for 1986–2005; the filled areas are for the end of the century. The CMIP5 multi-model mean is given in white colour, the projected mean sea ice extent of a subset of models (number of models given in brackets) that most closely reproduce the climatological mean state and 1979 to 2012 trend of the Arctic sea ice extent is given in light blue colour. For further technical details see the Technical Summary Supplementary Material. {Figures 6.28, 12.11, 12.22, and 12.29; Figures TS.15, TS.16, TS.17, and TS.20}

- The high latitudes and the equatorial Pacific Ocean are *likely* to experience an increase in annual mean precipitation by the end of this century under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will *likely* decrease, while in many mid-latitude wet regions, mean precipitation will *likely* increase by the end of this century under the RCP8.5 scenario (see Figure SPM.8). {7.6, 12.4, 14.3}

- Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent by the end of this century, as global mean surface temperature increases (see Table SPM.1). {7.6, 12.4}

- Globally, it is *likely* that the area encompassed by monsoon systems will increase over the 21st century. While monsoon winds are *likely* to weaken, monsoon precipitation is *likely* to intensify due to the increase in atmospheric moisture. Monsoon onset dates are *likely* to become earlier or not to change much. Monsoon retreat dates will *likely* be delayed, resulting in lengthening of the monsoon season in many regions. {14.2}

- There is *high confidence* that the El Niño-Southern Oscillation (ENSO) will remain the dominant mode of interannual variability in the tropical Pacific, with global effects in the 21st century. Due to the increase in moisture availability, ENSO-related precipitation variability on regional scales will *likely* intensify. Natural variations of the amplitude and spatial pattern of ENSO are large and thus *confidence* in any specific projected change in ENSO and related regional phenomena for the 21st century remains *low*. {5.4, 14.4}

Table SPM.2 | Projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century relative to the reference period of 1986–2005. {12.4; Table 12.2, Table 13.5}

		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range[c]**	**Mean**	***Likely* range[c]**
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range[d]**	**Mean**	***Likely* range[d]**
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Notes:

[a] Based on the CMIP5 ensemble; anomalies calculated with respect to 1986–2005. Using HadCRUT4 and its uncertainty estimate (5–95% confidence interval), the observed warming to the reference period 1986–2005 is 0.61 [0.55 to 0.67] °C from 1850–1900, and 0.11 [0.09 to 0.13] °C from 1980–1999, the reference period for projections used in AR4. *Likely* ranges have not been assessed here with respect to earlier reference periods because methods are not generally available in the literature for combining the uncertainties in models and observations. Adding projected and observed changes does not account for potential effects of model biases compared to observations, and for natural internal variability during the observational reference period {2.4; 11.2; Tables 12.2 and 12.3}

[b] Based on 21 CMIP5 models; anomalies calculated with respect to 1986–2005. Where CMIP5 results were not available for a particular AOGCM and scenario, they were estimated as explained in Chapter 13, Table 13.5. The contributions from ice sheet rapid dynamical change and anthropogenic land water storage are treated as having uniform probability distributions, and as largely independent of scenario. This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

[c] Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean surface temperature change in 2046–2065 *confidence* is *medium*, because the relative importance of natural internal variability, and uncertainty in non-greenhouse gas forcing and response, are larger than for 2081–2100. The *likely* ranges for 2046–2065 do not take into account the possible influence of factors that lead to the assessed range for near-term (2016–2035) global mean surface temperature change that is lower than the 5–95% model range, because the influence of these factors on longer term projections has not been quantified due to insufficient scientific understanding. {11.3}

[d] Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean sea level rise *confidence* is *medium* for both time horizons.

E.3 Atmosphere: Air Quality

- The range in projections of air quality (ozone and PM2.5[17] in near-surface air) is driven primarily by emissions (including CH_4), rather than by physical climate change (*medium confidence*). There is *high confidence* that globally, warming decreases background surface ozone. High CH_4 levels (as in RCP8.5) can offset this decrease, raising background surface ozone by year 2100 on average by about 8 ppb (25% of current levels) relative to scenarios with small CH_4 changes (as in RCP4.5 and RCP6.0) (*high confidence*). {11.3}

- Observational and modelling evidence indicates that, all else being equal, locally higher surface temperatures in polluted regions will trigger regional feedbacks in chemistry and local emissions that will increase peak levels of ozone and PM2.5 (*medium confidence*). For PM2.5, climate change may alter natural aerosol sources as well as removal by precipitation, but no confidence level is attached to the overall impact of climate change on PM2.5 distributions. {11.3}

E.4 Ocean

The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation. {11.3, 12.4}

- The strongest ocean warming is projected for the surface in tropical and Northern Hemisphere subtropical regions. At greater depth the warming will be most pronounced in the Southern Ocean (*high confidence*). Best estimates of ocean warming in the top one hundred meters are about 0.6°C (RCP2.6) to 2.0°C (RCP8.5), and about 0.3°C (RCP2.6) to 0.6°C (RCP8.5) at a depth of about 1000 m by the end of the 21st century. {12.4, 14.3}

- It is *very likely* that the Atlantic Meridional Overturning Circulation (AMOC) will weaken over the 21st century. Best estimates and ranges[18] for the reduction are 11% (1 to 24%) in RCP2.6 and 34% (12 to 54%) in RCP8.5. It is *likely* that there will be some decline in the AMOC by about 2050, but there may be some decades when the AMOC increases due to large natural internal variability. {11.3, 12.4}

- It is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered. There is *low confidence* in assessing the evolution of the AMOC beyond the 21st century because of the limited number of analyses and equivocal results. However, a collapse beyond the 21st century for large sustained warming cannot be excluded. {12.5}

E.5 Cryosphere

It is *very likely* that the Arctic sea ice cover will continue to shrink and thin and that Northern Hemisphere spring snow cover will decrease during the 21st century as global mean surface temperature rises. Global glacier volume will further decrease. {12.4, 13.4}

- Year-round reductions in Arctic sea ice extent are projected by the end of the 21st century from multi-model averages. These reductions range from 43% for RCP2.6 to 94% for RCP8.5 in September and from 8% for RCP2.6 to 34% for RCP8.5 in February (*medium confidence*) (see Figures SPM.7 and SPM.8). {12.4}

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[17] PM2.5 refers to particulate matter with a diameter of less than 2.5 micrometres, a measure of atmospheric aerosol concentration.

[18] The ranges in this paragraph indicate a CMIP5 model spread.

- Based on an assessment of the subset of models that most closely reproduce the climatological mean state and 1979 to 2012 trend of the Arctic sea ice extent, a nearly ice-free Arctic Ocean[19] in September before mid-century is *likely* for RCP8.5 (*medium confidence*) (see Figures SPM.7 and SPM.8). A projection of when the Arctic might become nearly ice-free in September in the 21st century cannot be made with confidence for the other scenarios. {11.3, 12.4, 12.5}

- In the Antarctic, a decrease in sea ice extent and volume is projected with *low confidence* for the end of the 21st century as global mean surface temperature rises. {12.4}

- By the end of the 21st century, the global glacier volume, excluding glaciers on the periphery of Antarctica, is projected to decrease by 15 to 55% for RCP2.6, and by 35 to 85% for RCP8.5 (*medium confidence*). {13.4, 13.5}

- The area of Northern Hemisphere spring snow cover is projected to decrease by 7% for RCP2.6 and by 25% in RCP8.5 by the end of the 21st century for the model average (*medium confidence*). {12.4}

- It is *virtually certain* that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases. By the end of the 21st century, the area of permafrost near the surface (upper 3.5 m) is projected to decrease by between 37% (RCP2.6) to 81% (RCP8.5) for the model average (*medium confidence*). {12.4}

E.6 Sea Level

Global mean sea level will continue to rise during the 21st century (see Figure SPM.9). Under all RCP scenarios, the rate of sea level rise will *very likely* exceed that observed during 1971 to 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets. {13.3–13.5}

- Confidence in projections of global mean sea level rise has increased since the AR4 because of the improved physical understanding of the components of sea level, the improved agreement of process-based models with observations, and the inclusion of ice-sheet dynamical changes. {13.3–13.5}

- Global mean sea level rise for 2081–2100 relative to 1986–2005 will *likely* be in the ranges of 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5 (*medium confidence*). For RCP8.5, the rise by the year 2100 is 0.52 to 0.98 m, with a rate during 2081 to 2100 of 8 to 16 mm yr^{-1} (*medium confidence*). These ranges are derived from CMIP5 climate projections in combination with process-based models and literature assessment of glacier and ice sheet contributions (see Figure SPM.9, Table SPM.2). {13.5}

- In the RCP projections, thermal expansion accounts for 30 to 55% of 21st century global mean sea level rise, and glaciers for 15 to 35%. The increase in surface melting of the Greenland ice sheet will exceed the increase in snowfall, leading to a positive contribution from changes in surface mass balance to future sea level (*high confidence*). While surface melting will remain small, an increase in snowfall on the Antarctic ice sheet is expected (*medium confidence*), resulting in a negative contribution to future sea level from changes in surface mass balance. Changes in outflow from both ice sheets combined will *likely* make a contribution in the range of 0.03 to 0.20 m by 2081–2100 (*medium confidence*). {13.3–13.5}

- Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. However, there is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century. {13.4, 13.5}

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19 Conditions in the Arctic Ocean are referred to as nearly ice-free when the sea ice extent is less than 10^6 km^2 for at least five consecutive years.

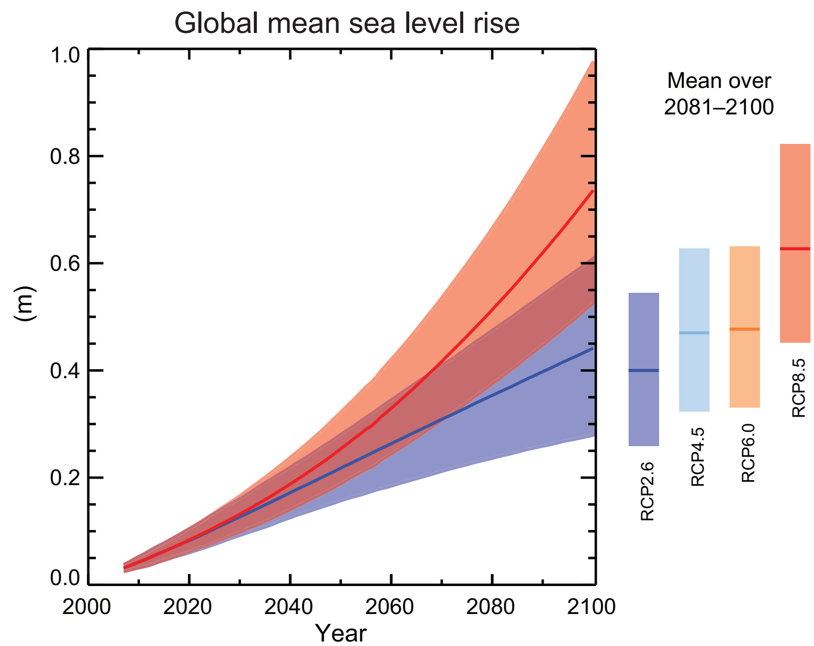

Figure SPM.9 | Projections of global mean sea level rise over the 21st century relative to 1986–2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed *likely* range is shown as a shaded band. The assessed *likely* ranges for the mean over the period 2081–2100 for all RCP scenarios are given as coloured vertical bars, with the corresponding median value given as a horizontal line. For further technical details see the Technical Summary Supplementary Material {Table 13.5, Figures 13.10 and 13.11; Figures TS.21 and TS.22}

- The basis for higher projections of global mean sea level rise in the 21st century has been considered and it has been concluded that there is currently insufficient evidence to evaluate the probability of specific levels above the assessed *likely* range. Many semi-empirical model projections of global mean sea level rise are higher than process-based model projections (up to about twice as large), but there is no consensus in the scientific community about their reliability and there is thus *low confidence* in their projections. {13.5}

- Sea level rise will not be uniform. By the end of the 21st century, it is *very likely* that sea level will rise in more than about 95% of the ocean area. About 70% of the coastlines worldwide are projected to experience sea level change within 20% of the global mean sea level change. {13.1, 13.6}

E.7 Carbon and Other Biogeochemical Cycles

Climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere (*high confidence*). Further uptake of carbon by the ocean will increase ocean acidification. {6.4}

- Ocean uptake of anthropogenic CO_2 will continue under all four RCPs through to 2100, with higher uptake for higher concentration pathways (*very high confidence*). The future evolution of the land carbon uptake is less certain. A majority of models projects a continued land carbon uptake under all RCPs, but some models simulate a land carbon loss due to the combined effect of climate change and land use change. {6.4}

- Based on Earth System Models, there is *high confidence* that the feedback between climate and the carbon cycle is positive in the 21st century; that is, climate change will partially offset increases in land and ocean carbon sinks caused by rising atmospheric CO_2. As a result more of the emitted anthropogenic CO_2 will remain in the atmosphere. A positive feedback between climate and the carbon cycle on century to millennial time scales is supported by paleoclimate observations and modelling. {6.2, 6.4}

Table SPM.3 | Cumulative CO_2 emissions for the 2012 to 2100 period compatible with the RCP atmospheric concentrations simulated by the CMIP5 Earth System Models. {6.4, Table 6.12, Figure TS.19}

Scenario	Cumulative CO_2 Emissions 2012 to 2100[a]			
	GtC		$GtCO_2$	
	Mean	Range	Mean	Range
RCP2.6	270	140 to 410	990	510 to 1505
RCP4.5	780	595 to 1005	2860	2180 to 3690
RCP6.0	1060	840 to 1250	3885	3080 to 4585
RCP8.5	1685	1415 to 1910	6180	5185 to 7005

Notes:
[a] 1 Gigatonne of carbon = 1 GtC = 10^{15} grams of carbon. This corresponds to 3.667 $GtCO_2$.

- Earth System Models project a global increase in ocean acidification for all RCP scenarios. The corresponding decrease in surface ocean pH by the end of 21st century is in the range[18] of 0.06 to 0.07 for RCP2.6, 0.14 to 0.15 for RCP4.5, 0.20 to 0.21 for RCP6.0, and 0.30 to 0.32 for RCP8.5 (see Figures SPM.7 and SPM.8). {6.4}

- Cumulative CO_2 emissions[20] for the 2012 to 2100 period compatible with the RCP atmospheric CO_2 concentrations, as derived from 15 Earth System Models, range[18] from 140 to 410 GtC for RCP2.6, 595 to 1005 GtC for RCP4.5, 840 to 1250 GtC for RCP6.0, and 1415 to 1910 GtC for RCP8.5 (see Table SPM.3). {6.4}

- By 2050, annual CO_2 emissions derived from Earth System Models following RCP2.6 are smaller than 1990 emissions (by 14 to 96%). By the end of the 21st century, about half of the models infer emissions slightly above zero, while the other half infer a net removal of CO_2 from the atmosphere. {6.4, Figure TS.19}

- The release of CO_2 or CH_4 to the atmosphere from thawing permafrost carbon stocks over the 21st century is assessed to be in the range of 50 to 250 GtC for RCP8.5 (*low confidence*). {6.4}

E.8 Climate Stabilization, Climate Change Commitment and Irreversibility

Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond (see Figure SPM.10). Most aspects of climate change will persist for many centuries even if emissions of CO_2 are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of CO_2. {12.5}

- Cumulative total emissions of CO_2 and global mean surface temperature response are approximately linearly related (see Figure SPM.10). Any given level of warming is associated with a range of cumulative CO_2 emissions[21], and therefore, e.g., higher emissions in earlier decades imply lower emissions later. {12.5}

- Limiting the warming caused by anthropogenic CO_2 emissions alone with a probability of >33%, >50%, and >66% to less than 2°C since the period 1861–1880[22], will require cumulative CO_2 emissions from all anthropogenic sources to stay between 0 and about 1570 GtC (5760 $GtCO_2$), 0 and about 1210 GtC (4440 $GtCO_2$), and 0 and about 1000 GtC (3670 $GtCO_2$) since that period, respectively[23]. These upper amounts are reduced to about 900 GtC (3300 $GtCO_2$), 820 GtC (3010 $GtCO_2$), and 790 GtC (2900 $GtCO_2$), respectively, when accounting for non-CO_2 forcings as in RCP2.6. An amount of 515 [445 to 585] GtC (1890 [1630 to 2150] $GtCO_2$), was already emitted by 2011. {12.5}

[20] From fossil fuel, cement, industry, and waste sectors.

[21] Quantification of this range of CO_2 emissions requires taking into account non-CO_2 drivers.

[22] The first 20-year period available from the models.

[23] This is based on the assessment of the transient climate response to cumulative carbon emissions (TCRE, see Section D.2).

- A lower warming target, or a higher likelihood of remaining below a specific warming target, will require lower cumulative CO_2 emissions. Accounting for warming effects of increases in non-CO_2 greenhouse gases, reductions in aerosols, or the release of greenhouse gases from permafrost will also lower the cumulative CO_2 emissions for a specific warming target (see Figure SPM.10). {12.5}

- A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions. Due to the long time scales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries. Depending on the scenario, about 15 to 40% of emitted CO_2 will remain in the atmosphere longer than 1,000 years. {Box 6.1, 12.4, 12.5}

- It is *virtually certain* that global mean sea level rise will continue beyond 2100, with sea level rise due to thermal expansion to continue for many centuries. The few available model results that go beyond 2100 indicate global mean sea level rise above the pre-industrial level by 2300 to be less than 1 m for a radiative forcing that corresponds to CO_2 concentrations that peak and decline and remain below 500 ppm, as in the scenario RCP2.6. For a radiative forcing that corresponds to a CO_2 concentration that is above 700 ppm but below 1500 ppm, as in the scenario RCP8.5, the projected rise is 1 m to more than 3 m (*medium confidence*). {13.5}

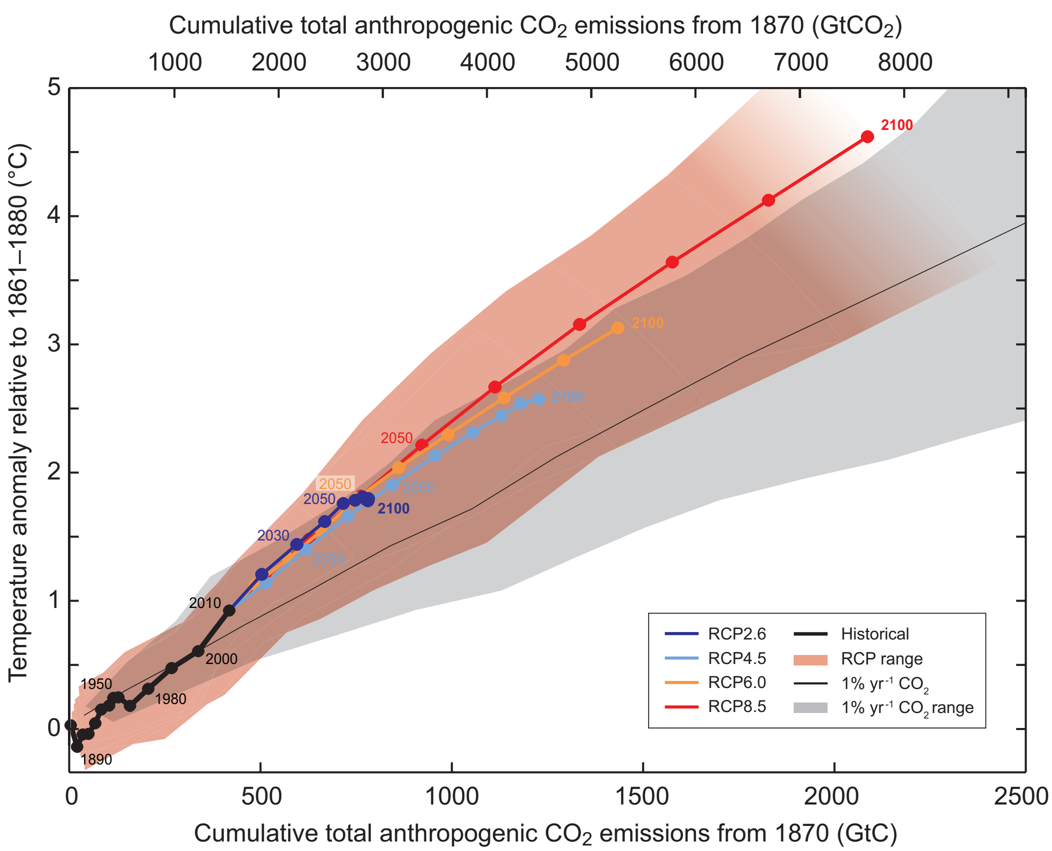

Figure SPM.10 | Global mean surface temperature increase as a function of cumulative total global CO_2 emissions from various lines of evidence. Multi-model results from a hierarchy of climate-carbon cycle models for each RCP until 2100 are shown with coloured lines and decadal means (dots). Some decadal means are labeled for clarity (e.g., 2050 indicating the decade 2040–2049). Model results over the historical period (1860 to 2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. The multi-model mean and range simulated by CMIP5 models, forced by a CO_2 increase of 1% per year (1% yr^{-1} CO_2 simulations), is given by the thin black line and grey area. For a specific amount of cumulative CO_2 emissions, the 1% per year CO_2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO_2 forcings. Temperature values are given relative to the 1861–1880 base period, emissions relative to 1870. Decadal averages are connected by straight lines. For further technical details see the Technical Summary Supplementary Material. {Figure 12.45; TS TFE.8, Figure 1}

- Sustained mass loss by ice sheets would cause larger sea level rise, and some part of the mass loss might be irreversible. There is *high confidence* that sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) global mean warming with respect to pre-industrial. Abrupt and irreversible ice loss from a potential instability of marine-based sectors of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment. {5.8, 13.4, 13.5}

- Methods that aim to deliberately alter the climate system to counter climate change, termed geoengineering, have been proposed. Limited evidence precludes a comprehensive quantitative assessment of both Solar Radiation Management (SRM) and Carbon D ioxide Removal (CDR) and their impact on the climate system. CDR methods have biogeochemical and technological limitations to their potential on a global scale. There is insufficient knowledge to quantify how much CO_2 emissions could be partially offset by CDR on a century timescale. Modelling indicates that SRM methods, if realizable, have the potential to substantially offset a global temperature rise, but they would also modify the global water cycle, and would not reduce ocean acidification. If SRM were terminated for any reason, there is *high confidence* that global surface temperatures would rise very rapidly to values consistent with the greenhouse gas forcing. CDR and SRM methods carry side effects and long-term consequences on a global scale. {6.5, 7.7}

Box SPM.1: Representative Concentration Pathways (RCPs)

Climate change projections in IPCC Working Group I require information about future emissions or concentrations of greenhouse gases, aerosols and other climate drivers. This information is often expressed as a scenario of human activities, which are not assessed in this report. Scenarios used in Working Group I have focused on anthropogenic emissions and do not include changes in natural drivers such as solar or volcanic forcing or natural emissions, for example, of CH_4 and N_2O.

For the Fifth Assessment Report of IPCC, the scientific community has defined a set of four new scenarios, denoted Representative Concentration Pathways (RCPs, see Glossary). They are identified by their approximate total radiative forcing in year 2100 relative to 1750: 2.6 W m^{-2} for RCP2.6, 4.5 W m^{-2} for RCP4.5, 6.0 W m^{-2} for RCP6.0, and 8.5 W m^{-2} for RCP8.5. For the Coupled Model Intercomparison Project Phase 5 (CMIP5) results, these values should be understood as indicative only, as the climate forcing resulting from all drivers varies between models due to specific model characteristics and treatment of short-lived climate forcers. These four RCPs include one mitigation scenario leading to a very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6), and one scenario with very high greenhouse gas emissions (RCP8.5). The RCPs can thus represent a range of 21st century climate policies, as compared with the no-climate policy of the Special Report on Emissions Scenarios (SRES) used in the Third Assessment Report and the Fourth Assessment Report. For RCP6.0 and RCP8.5, radiative forcing does not peak by year 2100; for RCP2.6 it peaks and declines; and for RCP4.5 it stabilizes by 2100. Each RCP provides spatially resolved data sets of land use change and sector-based emissions of air pollutants, and it specifies annual greenhouse gas concentrations and anthropogenic emissions up to 2100. RCPs are based on a combination of integrated assessment models, simple climate models, atmospheric chemistry and global carbon cycle models. While the RCPs span a wide range of total forcing values, they do not cover the full range of emissions in the literature, particularly for aerosols.

Most of the CMIP5 and Earth System Model simulations were performed with prescribed CO_2 concentrations reaching 421 ppm (RCP2.6), 538 ppm (RCP4.5), 670 ppm (RCP6.0), and 936 ppm (RCP 8.5) by the year 2100. Including also the prescribed concentrations of CH_4 and N_2O, the combined CO_2-equivalent concentrations are 475 ppm (RCP2.6), 630 ppm (RCP4.5), 800 ppm (RCP6.0), and 1313 ppm (RCP8.5). For RCP8.5, additional CMIP5 Earth System Model simulations are performed with prescribed CO_2 emissions as provided by the integrated assessment models. For all RCPs, additional calculations were made with updated atmospheric chemistry data and models (including the Atmospheric Chemistry and Climate component of CMIP5) using the RCP prescribed emissions of the chemically reactive gases (CH_4, N_2O, HFCs, NO_x, CO, NMVOC). These simulations enable investigation of uncertainties related to carbon cycle feedbacks and atmospheric chemistry.

Climate Change 2014
Synthesis Report

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Referencing this report

IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

First published 2015

ISBN 978-92-9169-143-2

This publication is identical to the report that was approved (Summary for Policymakers) and adopted (longer report) at the 40th session of the Intergovernmental Panel on Climate Change (IPCC) on 1 November 2014 in Copenhagen, Denmark, but with the inclusion of copy-edits and errata that have been corrected prior to this publication. These pre-publication errata are available at: http://www.ipcc.ch.

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Cover: Design by Laura Biagioni, IPCC Secretariat, WMO

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I - Folgefonna glacier on the high plateaus of Sørfjorden, Norway (60°03’ N - 6°20’ E).
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III - China, Shanghai, aerial view. © Ocean/Corbis

Foreword, Preface and Dedication

Foreword

The Synthesis Report (SYR) distils and integrates the findings of the three Working Group contributions to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the most comprehensive assessment of climate change undertaken thus far by the IPCC: *Climate Change 2013: The Physical Science Basis*; *Climate Change 2014: Impacts, Adaptation, and Vulnerability*; and *Climate Change 2014: Mitigation of Climate Change.* The SYR also incorporates the findings of two Special Reports on *Renewable Energy Sources and Climate Change Mitigation* (2011) and on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (2011).

The SYR confirms that human influence on the climate system is clear and growing, with impacts observed across all continents and oceans. Many of the observed changes since the 1950s are unprecedented over decades to millennia. The IPCC is now 95 percent certain that humans are the main cause of current global warming. In addition, the SYR finds that the more human activities disrupt the climate, the greater the risks of severe, pervasive and irreversible impacts for people and ecosystems, and long-lasting changes in all components of the climate system. The SYR highlights that we have the means to limit climate change and its risks, with many solutions that allow for continued economic and human development. However, stabilizing temperature increase to below 2°C relative to pre-industrial levels will require an urgent and fundamental departure from business as usual. Moreover, the longer we wait to take action, the more it will cost and the greater the technological, economic, social and institutional challenges we will face.

These and the other findings of the SYR have undoubtedly and considerably enhanced our understanding of some of the most critical issues in relation to climate change: the role of greenhouse gas emissions; the severity of potential risks and impacts, especially for the least developed countries and vulnerable communities, given their limited ability to cope; and the options available to us and their underlying requirements to ensure that the effects of climate change remain manageable. As such, the SYR calls for the urgent attention of both policymakers and citizens of the world to tackle this challenge.

The timing of the SYR, which was released on 2nd November 2014 in Copenhagen, was crucial. Policymakers met in December 2014 in Lima at the 20th Conference of Parties under the United Nations Framework Convention on Climate Change (UNFCCC) to prepare the groundwork for the 21st Session in 2015 in Paris, when they have been tasked with concluding a new agreement to deal with climate change. It is our hope that the scientific findings of the SYR will be the basis of their motivation to find the way to a global agreement which can keep climate change to a manageable level, as the SYR gives us the knowledge to make informed choices, and enhances our vital understanding of the rationale for action – and the serious implications of inaction. Ignorance can no longer be an excuse for tergiversation.

As an intergovernmental body jointly established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the Intergovernmental Panel on Climate Change (IPCC) has provided policymakers with the most authoritative and objective scientific and technical assessments in this field. Beginning in 1990, this series of IPCC Assessment Reports, Special Reports, Technical Papers, Methodology Reports and other products have become standard works of reference.

The SYR was made possible thanks to the voluntary work, dedication and commitment of thousands of experts and scientists from around the globe, representing a range of views and disciplines. We would like to express our deep gratitude to all the members of the Core Writing Team of the SYR, members of the Extended Writing Team, and the Review Editors, all of whom enthusiastically took on the huge challenge of producing an outstanding SYR on top of the other tasks they had already committed to during the AR5 cycle. We would also like to thank the staff of the Technical Support Unit of the SYR and the IPCC Secretariat for their dedication in organizing the production of this IPCC report.

We also wish to acknowledge and thank the governments of the IPCC member countries for their support of scientists in developing this report, and for their contributions to the IPCC Trust Fund to provide the essentials for participation of experts from developing countries and countries with economies in transition. We would like to express our appreciation to the government of Wallonia (Belgium) for hosting the Scoping Meeting of the SYR, to the governments of Norway, the Netherlands, Germany and Malaysia for hosting drafting sessions of the SYR, and to the government of Denmark for hosting the 40th Session of the IPCC where the SYR was approved. The generous financial support from the governments of Norway and the Netherlands, from the Korea Energy Economics Institute, and the in-kind support by the Netherlands Environmental Assessment Agency and The Energy and Resources Institute, New Delhi (India), enabled the smooth operation of the Technical Support Unit of the SYR. This is gratefully acknowledged.

We would particularly like to express our thanks to Dr Rajendra K. Pachauri, Chairman of the IPCC, for his leadership and constant guidance throughout the production of this report.

Michel Jarraud
Secretary General
World Meteorological Organization

Achim Steiner
Executive Director
United Nations Environmental Programme

Preface

The Synthesis Report (SYR), constituting the final product of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), is published under the title *Climate Change 2014.* This report distils, synthesizes and integrates the key findings of the three Working Group contributions – *The Physical Science Basis*, *Impacts, Adaptation, and Vulnerability* and *Mitigation of Climate Change* – to the AR5 in a concise document for the benefit of decision makers in the government, the private sector as well as the public at large. The SYR also draws on the findings of the two Special Reports brought out in 2011 dealing with *Renewable Energy Sources and Climate Change Mitigation*, and *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. The SYR, therefore, is a comprehensive up-to-date compilation of assessments dealing with climate change, based on the most recent scientific, technical and socio-economic literature in the field.

Scope of the Report

This document is the result of coordinated and carefully connected cross Working Group efforts to ensure coherent and comprehensive information on various aspects related to climate change. This SYR includes a consistent evaluation and assessment of uncertainties and risks; integrated costing and economic analysis; regional aspects; changes, impacts and responses related to water and earth systems, the carbon cycle including ocean acidification, cryosphere and sea level rise; as well as treatment of mitigation and adaptation options within the framework of sustainable development. Through the entire length of the SYR, information is also provided relevant to Article 2, the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC).

Other aspects of climate change covered in this report include direct impacts of climate change on natural systems as well as both direct and indirect impacts on human systems, such as human health, food security and security of societal conditions. By embedding climate change risk and issues of adaptation and mitigation within the framework of sustainable development, the SYR also highlights the fact that nearly all systems on this planet would be affected by the impacts of a changing climate, and that it is not possible to draw boundaries around climate change, its associated risks and impacts on the one hand and on the other, development which meets the needs of the present generation without compromising the ability of future generations to meet their own needs. The Report, therefore, also focuses on connections between these aspects and provides information on how climate change overlaps with and mainstreams into other developmental issues.

Structure

The Report comprises a Summary for Policymakers (SPM) and a longer report from which the SPM is derived, as well as annexes. Even though the SPM follows a structure and sequence similar to that in the longer report, some specific issues covered under more than one topic of the longer report are summarized in one particular section of the SPM. Each paragraph of the SPM contains references to the respective text in the longer report. In turn, the latter contains extensive references to relevant chapters of the underlying Working Group Reports or the two Special Reports mentioned above. The SYR is essentially self-contained, and its SPM includes the most policy relevant material drawn from the longer report and the entire AR5.

All the three contributions to the AR5 including each Summary for Policymakers, each Technical Summary, frequently asked questions as well as the Synthesis Report in all official UN languages are available online on the IPCC website and in electronic offline versions. In these electronic versions, references in the SYR to relevant parts of the underlying material are provided as hyperlinks, thereby enabling the reader to easily find further scientific, technical and socio-economic information. A user guide, glossary of terms used and listing of acronyms, authors, Review Editors and Expert Reviewers are provided in the annexes to this report.

To facilitate access to the findings of the SYR for a wide readership and to enhance their usability for stakeholders, each section of the SPM carries highlighted headline statements. Taken together, these 21 headline statements provide an overarching summary in simple and completely non-technical language for easy assimilation by readers from different walks of life. These headline statements have been crafted by the authors of the Report, and approved by the member governments of the IPCC.

The longer report is structured around four topic headings as mandated by the Panel:

Observed changes and their causes (Topic 1) integrates new information from the three Working Groups on observed changes in the climate system, including changes in the atmosphere, oceans, cryosphere and sea level; recent and past drivers and human influences affecting emission drivers; observed impacts, including changes in extreme weather and climate events; and attribution of climate changes and impacts.

Future climate changes, risks and impacts (Topic 2) presents information about future climate change, risks and impacts. It integrates information about key drivers of future climate, the relationship between cumulative emissions and temperature change, and projected changes in the climate system in the 21st century and beyond. It assesses future risks and impacts caused by a changing climate and the interaction of climate-related and other hazards. It provides information about long-term changes including sea-level rise and ocean acidification, and the risk of irreversible and abrupt changes.

Future Pathways for Adaptation, Mitigation and Sustainable Development (Topic 3) addresses future pathways for adaptation and mitigation as complementary strategies for reducing and managing the risks of climate change and assesses their interaction with sustainable development. It describes analytical approaches for effective decision-making and differences in risks of climate change, adaptation and mitigation in terms of timescale, magnitude and persistence. It analyses the characteristics of adaptation and mitigation pathways, and associated challenges, limits and benefits, including for different levels of future warming.

Adaptation and Mitigation (Topic 4) brings together information from Working Groups II and III on specific adaptation and mitigation options, including environmentally sound technologies and infrastructure, sustainable livelihoods, behaviour and lifestyle choices. It describes common enabling factors and constraints, and policy approaches, finance and technology on which effective response measures depend. It shows opportunities for integrated responses and links adaptation and mitigation with other societal objectives.

Process

The SYR of the AR5 of the IPCC has been prepared in accordance with the procedures of the IPCC to ensure adequate effort and rigor being achieved in the process. For the AR5 the preparation of the SYR was taken in hand a year earlier than was the case with the Fourth Assessment Report (AR4) – while the Working Group Reports were still being completed – with a view to enhancing integration and ensuring adequate synthesis. A scoping meeting specifically for proposing the detailed outline of the AR5 Synthesis Report was held in Liège, Belgium in August, 2010, and the outline produced in that meeting was approved by the Panel in October, 2010 in Busan, Republic of Korea. In accordance with IPCC procedures, the IPCC Chair in consultation with the Co-Chairs of the Working Groups nominated authors for the Core Writing Team (CWT) of the SYR and a total of 45 CWT members and 9 Review Editors were selected and accepted by the IPCC Bureau in March, 2012. In addition, 14 Extended Writing Team (EWT) authors were selected by the CWT with the approval of the Chair of the IPCC, and this latter group contributed substantially to the material and the text provided in this report. During evolution of the contents of the SYR the IPCC Bureau was approached and it approved the inclusion of 6 additional CWT members and an additional Review Editor. This further enhanced and deepened the expertise required for the preparation of the Report. The final draft report which has undergone a combined review by experts and governments was submitted to the 40th Session of the IPCC, held from 27 October to 1 November 2014 in Copenhagen, Denmark, where governments approved the SPM line by line and adopted the longer report section by section.

Acknowledgements

Our profound gratitude and deep indebtedness goes to the members of the Core Writing Team and the substantial help from the Extended Writing Team members, for their tireless efforts, expertise, and amazing level of dedication throughout the production of the SYR. The SYR could not have been completed successfully without their inspirational commitment to excellence and integrity, and their meticulous attention to detail. We also wish to thank the Review Editors for their invaluable help ensuring that the SYR provides a balanced and complete assessment of current information relevant to climate change. Their role was crucial to ensure transparency of the process which the IPCC can pride itself on. Our thanks go also to all authors of the AR5 and the two Special Reports because without their careful assessment of the huge body of literature on various aspects of climate change and their comments on the draft report, the preparation of the SYR would not have been possible.

Throughout the AR5, we benefitted greatly from the wisdom and insight of our colleagues in the IPCC leadership, especially Dr Thomas Stocker and Dr Qin Dahe, Working Group I Co-Chairs; Dr Chris Field and Dr Vicente Barros, Working Group II Co-Chairs; and Dr Ottmar Edenhofer, Dr Ramón Pichs-Madruga and Dr Youba Sokona, Working Group III Co-Chairs. Their cooperation on issues related to knowledge from the reports of all three Working Groups was a definite asset for the production of a high-quality final document.

We also wish to thank Fredolin Tangang, David Wratt, Eduardo Calvo, Jose Moreno, Jim Skea and Suzana Kahn Ribeiro, who acted as Review Editors during the Approval Session of the SYR, ensuring that the edits made to the SPM during the Session were correctly reflected in the longer report. Their important work guaranteed the high level of trust between the scientists and the governments, enabling them to work smoothly in symbiosis, which is a unique feature of the IPCC and its credibility.

We extend our deep appreciation of the enthusiasm, dedication and professional contributions of Gian-Kasper Plattner, Melinda Tignor and Judith Boschung from the Technical Support Unit of Working Group I, Katie Mach and Eren Bilir from the Technical Support Unit of Working Group II, Ellie Farahani, Jussi Savolainen and Steffen Schlömer from the Technical Support Unit of Working Group III, and Gerrit Hansen from the Potsdam Institute for Climate Impact Research during the Approval Session of the SYR, working as a team with the Technical Support Unit of the SYR, which was indispensable in the successful outcomes of the Session. A special thanks goes to Adrien Michel from the Technical Support Unit of Working Group I for his work on the SYR figures.

Our thanks go to Leo Meyer, Head of the Technical Support Unit of the Synthesis Report, and the members of the Technical Support Unit Sander Brinkman, Line van Kesteren, Noemie Leprince-Ringuet and Fijke van Boxmeer for their capacity to expand their strengths and carry out the mammoth task of coordinating the development and production of the SYR. Each one of them put in tireless efforts, displaying deep commitment and dedication to ensure the production of an outstanding SYR.

We would like to acknowledge the work and innumerable tasks performed in support of the preparation, release and publication of the Report by the staff of the IPCC Secretariat: Gaetano Leone, Carlos Martin-Novella, Jonathan Lynn, Brenda Abrar-Milani, Jesbin Baidya, Laura Biagioni, Mary Jean Burer, Annie Courtin, Judith Ewa, Joelle Fernandez, Nina Peeva, Sophie Schlingemann, Amy Smith and Werani Zabula. Thanks are also due to Francis Hayes and Elhousseine Gouaini for acting as conference officers at the approval Session.

We are appreciative of the member governments of the IPCC who graciously hosted the SYR scoping meeting, four of our Core Writing Meetings and the 40th Session of the IPCC: Belgium, Norway, The Netherlands, Germany, Malaysia and Denmark. We express our thanks

to the governments, WMO, UNEP and the UNFCCC for their contributions to the Trust Fund which supported various elements of expenditure. We wish to particularly thank the Governments of Norway and The Netherlands, and the Korea Energy Economics Institute for their generous financial support of the SYR Technical Support Unit, and The Netherlands Environmental Assessment Agency PBL and The Energy and Resources Institute, New Delhi, for their in-kind support of the SYR Technical Support Unit. We also acknowledge the support of IPCC's parent organizations, UNEP and WMO, and particularly WMO for hosting the IPCC Secretariat and our first Core Writing Team meeting. May we convey our deep gratitude to the UNFCCC for their cooperation at various stages of this enterprise and for the prominence they give to our work in several appropriate fora.

R.K. Pachauri
Chairman of the IPCC

Renate Christ
Secretary of the IPCC

Dedication

Stephen H. Schneider
(11 February 1945 – 19 July 2010)

The Synthesis Report of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is dedicated to the memory of Stephen H. Schneider, one of the foremost climate scientists of our time.

Steve Schneider, born in New York, trained as a plasma physicist, embraced scholarship in the field of climate science almost 40 years ago and continued his relentless efforts creating new knowledge in the field and informing policymakers and the public at large on the growing problem of climate change and solutions for dealing with it. At all times Steve Schneider remained intrepid and forthright in expressing his views. His convictions were driven by the strength of his outstanding scientific expertise. He was highly respected as Founding Editor of the interdisciplinary journal *Climatic Change* and authored hundreds of books and papers, many of which were co-authored with scientists from diverse disciplines. His association with the IPCC began with the First Assessment Report which was published in 1990, and which played a major role in the scientific foundation of the UN Framework Convention on Climate Change. Subsequently, he was Lead Author, Coordinating Lead Author and Expert Reviewer for various Assessment Reports and a member of the Core Writing Team for the Synthesis Report of the Fourth Assessment Report. His life and accomplishments have inspired and motivated members of the Core Writing Team of this Report. Steve Schneider's knowledge was a rare synthesis of several disciplines which are an essential part of the diversity inherent in climate science.

Contents

Sources cited in this Synthesis Report

References for material contained in this report are given in italicized curly brackets *{}* at the end of each paragraph.

In the Summary for Policymakers, the references refer to the numbers of the sections, figures, tables and boxes in the underlying Introduction and Topics of this Synthesis Report.

In the Introduction and Topics of the longer report, the references refer to the contributions of the Working Groups I, II and III (WGI, WGII, WGIII) to the Fifth Assessment Report and other IPCC Reports (in italicized curly brackets), or to other sections of the Synthesis Report itself (in round brackets).

The following abbreviations have been used:
SPM: Summary for Policymakers
TS: Technical Summary
ES: Executive Summary of a chapter
Numbers denote specific chapters and sections of a report.

Other IPCC reports cited in this Synthesis Report:
SREX: Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SRREN: Special Report on Renewable Energy Sources and Climate Change Mitigation
AR4: Fourth Assessment Report

Climate Change 2014

Synthesis Report

Summary for Policymakers

Introduction

This Synthesis Report is based on the reports of the three Working Groups of the Intergovernmental Panel on Climate Change (IPCC), including relevant Special Reports. It provides an integrated view of climate change as the final part of the IPCC's Fifth Assessment Report (AR5).

This summary follows the structure of the longer report which addresses the following topics: Observed changes and their causes; Future climate change, risks and impacts; Future pathways for adaptation, mitigation and sustainable development; Adaptation and mitigation.

In the Synthesis Report, the certainty in key assessment findings is communicated as in the Working Group Reports and Special Reports. It is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from *very low* to *very high*) and, when possible, probabilistically with a quantified likelihood (from *exceptionally unlikely* to *virtually certain*)[1]. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

This report includes information relevant to Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC).

SPM 1. Observed Changes and their Causes

Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems. *{1}*

SPM 1.1 Observed changes in the climate system

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen. *{1.1}*

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was *likely* the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible (*medium confidence*). The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] °C[2] over the period 1880 to 2012, when multiple independently produced datasets exist (Figure SPM.1a). *{1.1.1, Figure 1.1}*

In addition to robust multi-decadal warming, the globally averaged surface temperature exhibits substantial decadal and interannual variability (Figure SPM.1a). Due to this natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over

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[1] Each finding is grounded in an evaluation of underlying evidence and agreement. In many cases, a synthesis of evidence and agreement supports an assignment of confidence. The summary terms for evidence are: limited, medium or robust. For agreement, they are low, medium or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. See for more details: Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe and F.W. Zwiers, 2010: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 4 pp.

[2] Ranges in square brackets or following '±' are expected to have a 90% likelihood of including the value that is being estimated, unless otherwise stated.

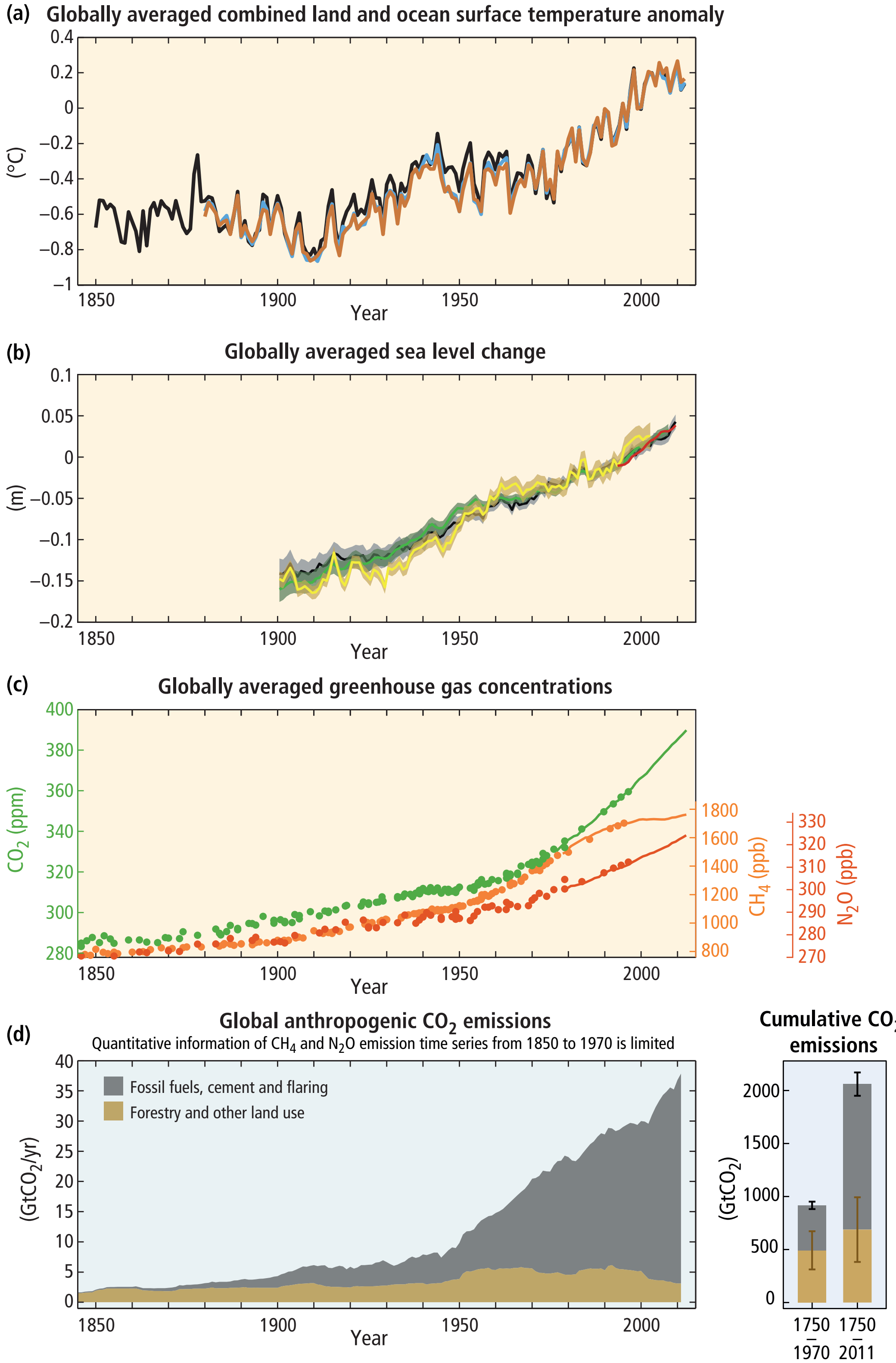

Figure SPM.1 | The complex relationship between the observations (panels a, b, c, yellow background) and the emissions (panel d, light blue background) is addressed in Section 1.2 and Topic 1. Observations and other indicators of a changing global climate system. Observations: **(a)** Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. Colours indicate different data sets. **(b)** Annually and globally averaged sea level change relative to the average over the period 1986 to 2005 in the longest-running dataset. Colours indicate different data sets. All datasets are aligned to have the same value in 1993, the first year of satellite altimetry data (red). Where assessed, uncertainties are indicated by coloured shading. **(c)** Atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2, green), methane (CH_4, orange) and nitrous oxide (N_2O, red) determined from ice core data (dots) and from direct atmospheric measurements (lines). Indicators: **(d)** Global anthropogenic CO_2 emissions from forestry and other land use as well as from burning of fossil fuel, cement production and flaring. Cumulative emissions of CO_2 from these sources and their uncertainties are shown as bars and whiskers, respectively, on the right hand side. The global effects of the accumulation of CH_4 and N_2O emissions are shown in panel c. Greenhouse gas emission data from 1970 to 2010 are shown in Figure SPM.2. *{Figures 1.1, 1.3, 1.5}*

SPM

the past 15 years (1998–2012; 0.05 [–0.05 to 0.15] °C per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] °C per decade). *{1.1.1, Box 1.1}*

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*), with only about 1% stored in the atmosphere. On a global scale, the ocean warming is largest near the surface, and the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010. It is *virtually certain* that the upper ocean (0–700 m) warmed from 1971 to 2010, and it *likely* warmed between the 1870s and 1971. *{1.1.2, Figure 1.2}*

Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudes, area-averaged long-term positive or negative trends have *low confidence*. Observations of changes in ocean surface salinity also provide indirect evidence for changes in the global water cycle over the ocean (*medium confidence*). It is *very likely* that regions of high salinity, where evaporation dominates, have become more saline, while regions of low salinity, where precipitation dominates, have become fresher since the 1950s. *{1.1.1, 1.1.2}*

Since the beginning of the industrial era, oceanic uptake of CO_2 has resulted in acidification of the ocean; the pH of ocean surface water has decreased by 0.1 (*high confidence*), corresponding to a 26% increase in acidity, measured as hydrogen ion concentration. *{1.1.2}*

Over the period 1992 to 2011, the Greenland and Antarctic ice sheets have been losing mass (*high confidence*), *likely* at a larger rate over 2002 to 2011. Glaciers have continued to shrink almost worldwide (*high confidence*). Northern Hemisphere spring snow cover has continued to decrease in extent (*high confidence*). There is *high confidence* that permafrost temperatures have increased in most regions since the early 1980s in response to increased surface temperature and changing snow cover. *{1.1.3}*

The annual mean Arctic sea-ice extent decreased over the period 1979 to 2012, with a rate that was *very likely* in the range 3.5 to 4.1% per decade. Arctic sea-ice extent has decreased in every season and in every successive decade since 1979, with the most rapid decrease in decadal mean extent in summer (*high confidence*). It is *very likely* that the annual mean Antarctic sea-ice extent increased in the range of 1.2 to 1.8% per decade between 1979 and 2012. However, there is *high confidence* that there are strong regional differences in Antarctica, with extent increasing in some regions and decreasing in others. *{1.1.3, Figure 1.1}*

Over the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m (Figure SPM.1b). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). *{1.1.4, Figure 1.1}*

SPM 1.2 Causes of climate change

Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are *extremely likely* to have been the dominant cause of the observed warming since the mid-20th century. *{1.2, 1.3.1}*

Anthropogenic greenhouse gas (GHG) emissions since the pre-industrial era have driven large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Figure SPM.1c). Between 1750 and 2011, cumulative anthropogenic CO_2 emissions to the atmosphere were 2040 ± 310 $GtCO_2$. About 40% of these emissions have remained in the atmosphere (880 ± 35 $GtCO_2$); the rest was removed from the atmosphere and stored on land (in plants and soils) and in the ocean. The ocean has absorbed about 30% of the emitted anthropogenic CO_2, causing ocean acidification. About half of the anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years (*high confidence*) (Figure SPM.1d). *{1.2.1, 1.2.2}*

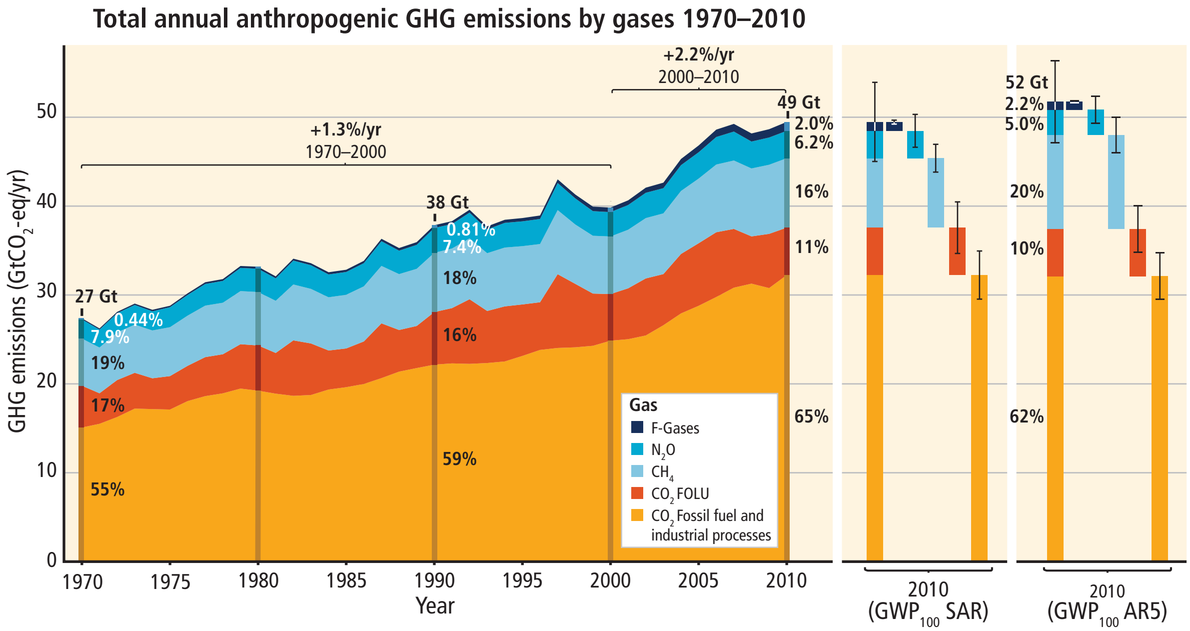

Figure SPM.2 | Total annual anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$-eq/yr) for the period 1970 to 2010 by gases: CO_2 from fossil fuel combustion and industrial processes; CO_2 from Forestry and Other Land Use (FOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases covered under the Kyoto Protocol (F-gases). Right hand side shows 2010 emissions, using alternatively CO_2-equivalent emission weightings based on IPCC Second Assessment Report (SAR) and AR5 values. Unless otherwise stated, CO_2-equivalent emissions in this report include the basket of Kyoto gases (CO_2, CH_4, N_2O as well as F-gases) calculated based on 100-year Global Warming Potential (GWP_{100}) values from the SAR (see Glossary). Using the most recent GWP_{100} values from the AR5 (right-hand bars) would result in higher total annual GHG emissions (52 $GtCO_2$-eq/yr) from an increased contribution of methane, but does not change the long-term trend significantly. *{Figure 1.6, Box 3.2}*

Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010, despite a growing number of climate change mitigation policies. Anthropogenic GHG emissions in 2010 have reached 49 ± 4.5 $GtCO_2$-eq/yr [3]. Emissions of CO_2 from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions increase from 1970 to 2010, with a similar percentage contribution for the increase during the period 2000 to 2010 (*high confidence*) (Figure SPM.2). Globally, economic and population growth continued to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to the previous three decades, while the contribution of economic growth has risen sharply. Increased use of coal has reversed the long-standing trend of gradual decarbonization (i.e., reducing the carbon intensity of energy) of the world's energy supply (*high confidence*). *{1.2.2}*

The evidence for human influence on the climate system has grown since the IPCC Fourth Assessment Report (AR4). It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together. The best estimate of the human-induced contribution to warming is similar to the observed warming over this period (Figure SPM.3). Anthropogenic forcings have *likely* made a substantial contribution to surface temperature increases since the mid-20th century over every continental region except Antarctica[4]. Anthropogenic influences have *likely* affected the global water cycle since 1960 and contributed to the retreat of glaciers since the 1960s and to the increased surface melting of the Greenland ice sheet since 1993. Anthropogenic influences have *very likely* contributed to Arctic sea-ice loss since 1979 and have *very likely* made a substantial contribution to increases in global upper ocean heat content (0–700 m) and to global mean sea level rise observed since the 1970s. *{1.3, Figure 1.10}*

[3] Greenhouse gas emissions are quantified as CO_2-equivalent ($GtCO_2$-eq) emissions using weightings based on the 100-year Global Warming Potentials, using IPCC Second Assessment Report values unless otherwise stated. *{Box 3.2}*

[4] For Antarctica, large observational uncertainties result in *low confidence* that anthropogenic forcings have contributed to the observed warming averaged over available stations.

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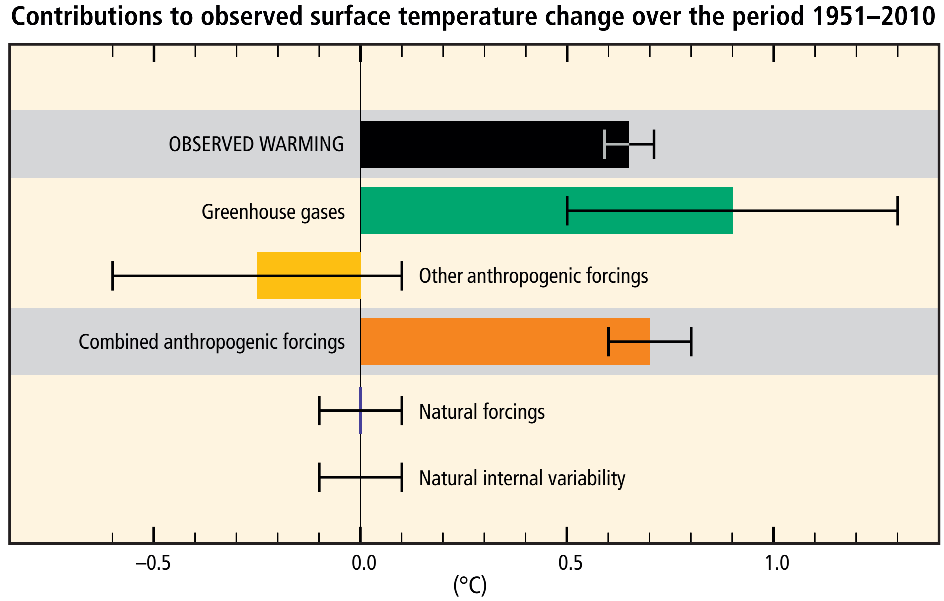

Figure SPM.3 | Assessed *likely* ranges (whiskers) and their mid-points (bars) for warming trends over the 1951–2010 period from well-mixed greenhouse gases, other anthropogenic forcings (including the cooling effect of aerosols and the effect of land use change), combined anthropogenic forcings, natural forcings and natural internal climate variability (which is the element of climate variability that arises spontaneously within the climate system even in the absence of forcings). The observed surface temperature change is shown in black, with the 5 to 95% uncertainty range due to observational uncertainty. The attributed warming ranges (colours) are based on observations combined with climate model simulations, in order to estimate the contribution of an individual external forcing to the observed warming. The contribution from the combined anthropogenic forcings can be estimated with less uncertainty than the contributions from greenhouse gases and from other anthropogenic forcings separately. This is because these two contributions partially compensate, resulting in a combined signal that is better constrained by observations. *{Figure 1.9}*

SPM 1.3 Impacts of climate change

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate. *{1.3.2}*

Evidence of observed climate change impacts is strongest and most comprehensive for natural systems. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*). Many terrestrial, freshwater and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to ongoing climate change (*high confidence*). Some impacts on human systems have also been attributed to climate change, with a major or minor contribution of climate change distinguishable from other influences (Figure SPM.4). Assessment of many studies covering a wide range of regions and crops shows that negative impacts of climate change on crop yields have been more common than positive impacts (*high confidence*). Some impacts of ocean acidification on marine organisms have been attributed to human influence (*medium confidence*). *{1.3.2}*

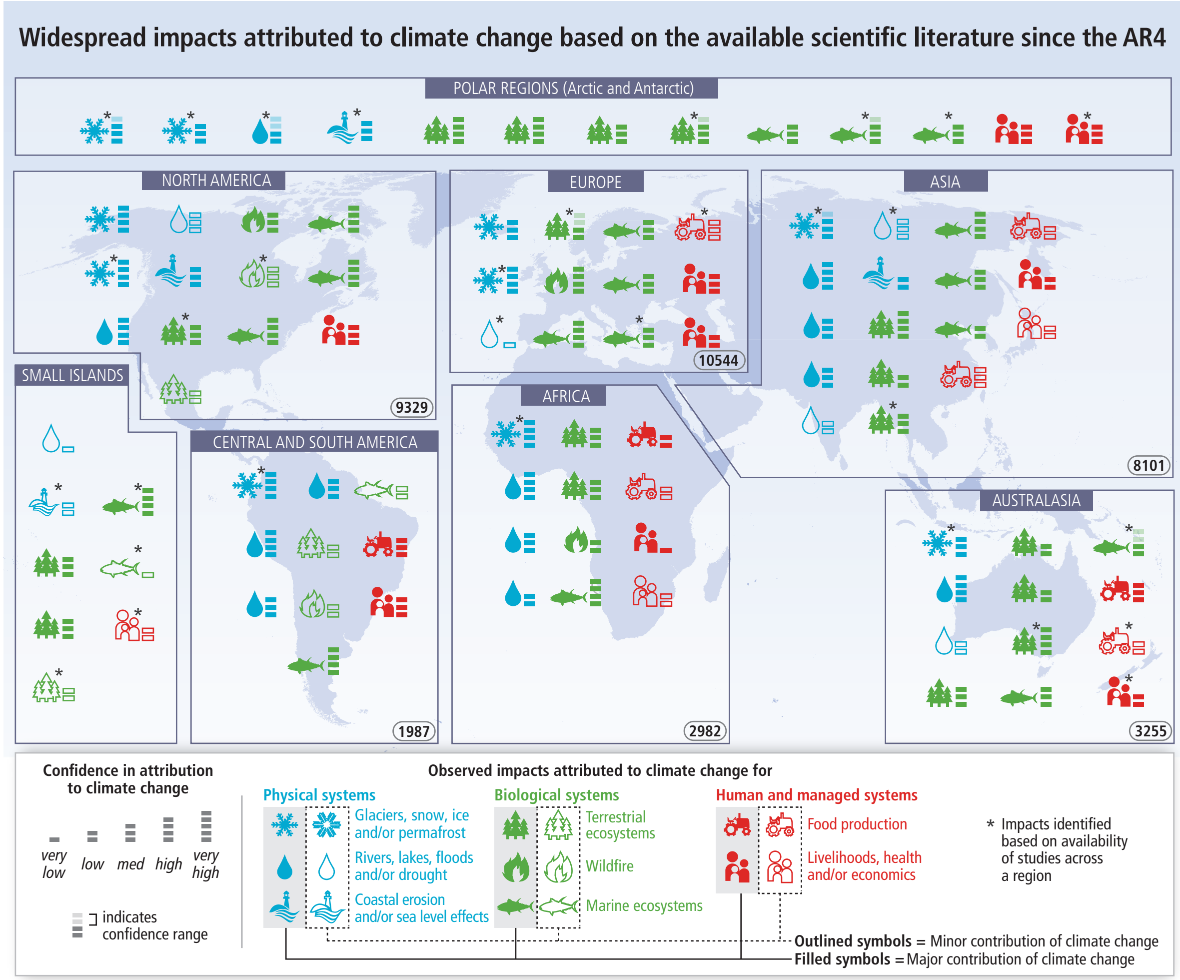

Figure SPM.4 | Based on the available scientific literature since the IPCC Fourth Assessment Report (AR4), there are substantially more impacts in recent decades now attributed to climate change. Attribution requires defined scientific evidence on the role of climate change. Absence from the map of additional impacts attributed to climate change does not imply that such impacts have not occurred. The publications supporting attributed impacts reflect a growing knowledge base, but publications are still limited for many regions, systems and processes, highlighting gaps in data and studies. Symbols indicate categories of attributed impacts, the relative contribution of climate change (major or minor) to the observed impact and confidence in attribution. Each symbol refers to one or more entries in WGII Table SPM.A1, grouping related regional-scale impacts. Numbers in ovals indicate regional totals of climate change publications from 2001 to 2010, based on the Scopus bibliographic database for publications in English with individual countries mentioned in title, abstract or key words (as of July 2011). These numbers provide an overall measure of the available scientific literature on climate change across regions; they do not indicate the number of publications supporting attribution of climate change impacts in each region. Studies for polar regions and small islands are grouped with neighbouring continental regions. The inclusion of publications for assessment of attribution followed IPCC scientific evidence criteria defined in WGII Chapter 18. Publications considered in the attribution analyses come from a broader range of literature assessed in the WGII AR5. See WGII Table SPM.A1 for descriptions of the attributed impacts. *{Figure 1.11}*

SPM 1.4 Extreme events

Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels and an increase in the number of heavy precipitation events in a number of regions. *{1.4}*

It is *very likely* that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. It is *likely* that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. It is *very likely* that human influence has contributed to the observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century. It is *likely* that human influence has more than doubled the probability of occurrence of heat waves in some locations. There is *medium confidence* that the observed warming has increased heat-related human mortality and decreased cold-related human mortality in some regions. *{1.4}*

There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. Recent detection of increasing trends in extreme precipitation and discharge in some catchments implies greater risks of flooding at regional scale (*medium confidence*). It is *likely* that extreme sea levels (for example, as experienced in storm surges) have increased since 1970, being mainly a result of rising mean sea level. *{1.4}*

Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (*very high confidence*). *{1.4}*

SPM 2. Future Climate Changes, Risks and Impacts

Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks. *{2}*

SPM 2.1 Key drivers of future climate

Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Projections of greenhouse gas emissions vary over a wide range, depending on both socio-economic development and climate policy. *{2.1}*

Anthropogenic GHG emissions are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy. The Representative Concentration Pathways (RCPs), which are used for making projections based on these factors, describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5 (Figure SPM.5a). RCP2.6 is representative of a scenario that aims to keep global warming *likely* below 2°C above pre-industrial temperatures. The RCPs are consistent with the wide range of scenarios in the literature as assessed by WGIII[5]. *{2.1, Box 2.2, 4.3}*

Multiple lines of evidence indicate a strong, consistent, almost linear relationship between cumulative CO_2 emissions and projected global temperature change to the year 2100 in both the RCPs and the wider set of mitigation scenarios analysed in WGIII (Figure SPM.5b). Any given level of warming is associated with a range of cumulative CO_2 emissions[6], and therefore, e.g., higher emissions in earlier decades imply lower emissions later. *{2.2.5, Table 2.2}*

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[5] Roughly 300 baseline scenarios and 900 mitigation scenarios are categorized by CO_2-equivalent concentration (CO_2-eq) by 2100. The CO_2-eq includes the forcing due to all GHGs (including halogenated gases and tropospheric ozone), aerosols and albedo change.

[6] Quantification of this range of CO_2 emissions requires taking into account non-CO_2 drivers.

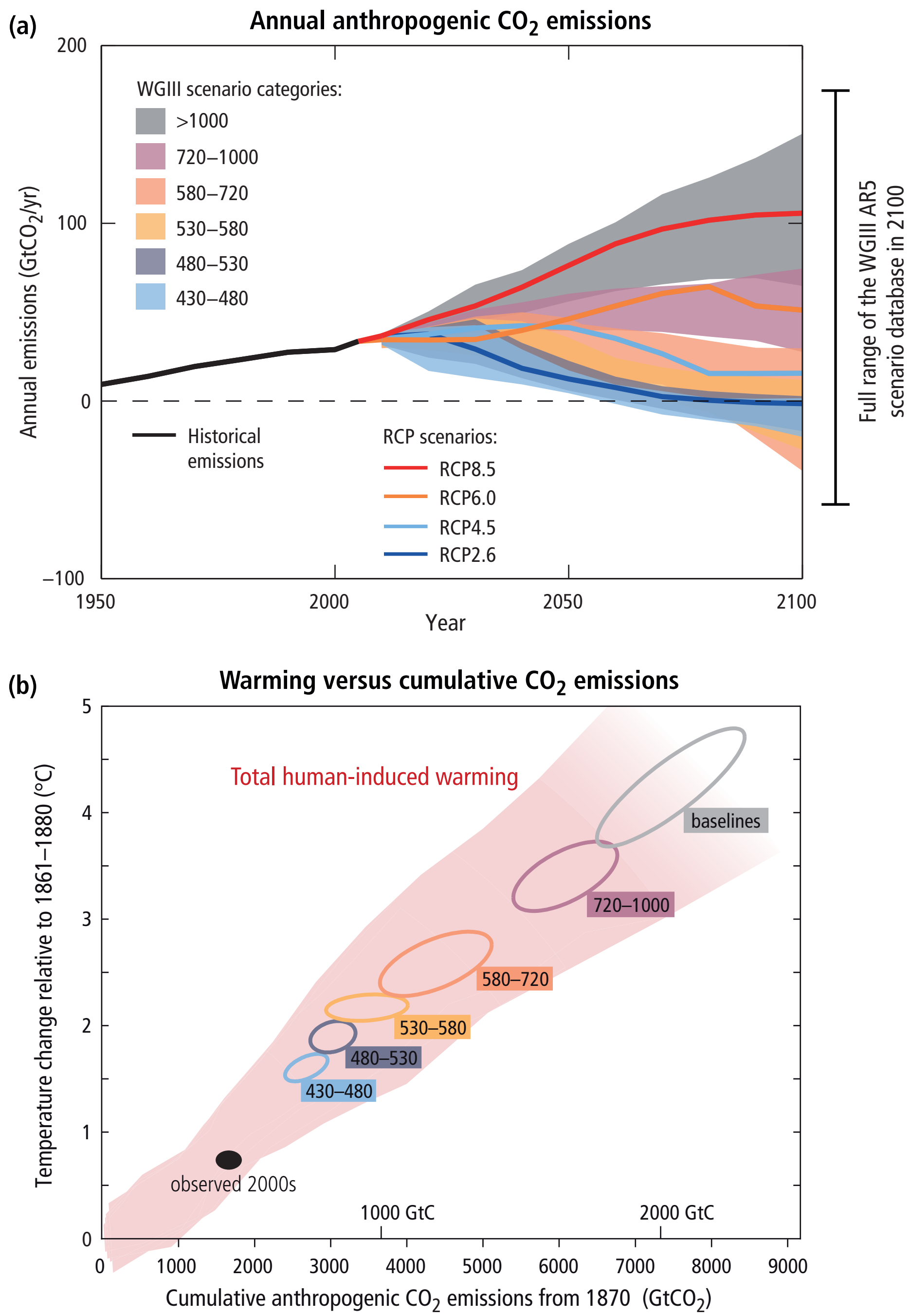

Figure SPM.5 | (a) Emissions of carbon dioxide (CO_2) alone in the Representative Concentration Pathways (RCPs) (lines) and the associated scenario categories used in WGIII (coloured areas show 5 to 95% range). The WGIII scenario categories summarize the wide range of emission scenarios published in the scientific literature and are defined on the basis of CO_2-eq concentration levels (in ppm) in 2100. The time series of other greenhouse gas emissions are shown in Box 2.2, Figure 1. **(b)** Global mean surface temperature increase at the time global CO_2 emissions reach a given net cumulative total, plotted as a function of that total, from various lines of evidence. Coloured plume shows the spread of past and future projections from a hierarchy of climate-carbon cycle models driven by historical emissions and the four RCPs over all times out to 2100, and fades with the decreasing number of available models. Ellipses show total anthropogenic warming in 2100 versus cumulative CO_2 emissions from 1870 to 2100 from a simple climate model (median climate response) under the scenario categories used in WGIII. The width of the ellipses in terms of temperature is caused by the impact of different scenarios for non-CO_2 climate drivers. The filled black ellipse shows observed emissions to 2005 and observed temperatures in the decade 2000–2009 with associated uncertainties. *{Box 2.2, Figure 1; Figure 2.3}*

Multi-model results show that limiting total human-induced warming to less than 2°C relative to the period 1861–1880 with a probability of >66%[7] would require cumulative CO_2 emissions from all anthropogenic sources since 1870 to remain below about 2900 $GtCO_2$ (with a range of 2550 to 3150 $GtCO_2$ depending on non-CO_2 drivers). About 1900 $GtCO_2$[8] had already been emitted by 2011. For additional context see Table 2.2. *{2.2.5}*

SPM 2.2 Projected changes in the climate system

Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is *very likely* that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise. *{2.2}*

The projected changes in Section SPM 2.2 are for 2081–2100 relative to 1986–2005, unless otherwise indicated.

Future climate will depend on committed warming caused by past anthropogenic emissions, as well as future anthropogenic emissions and natural climate variability. The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is similar for the four RCPs and will *likely* be in the range 0.3°C to 0.7°C (*medium confidence*). This assumes that there will be no major volcanic eruptions or changes in some natural sources (e.g., CH_4 and N_2O), or unexpected changes in total solar irradiance. By mid-21st century, the magnitude of the projected climate change is substantially affected by the choice of emissions scenario. *{2.2.1, Table 2.1}*

Relative to 1850–1900, global surface temperature change for the end of the 21st century (2081–2100) is projected to *likely* exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (*high confidence*). Warming is *likely* to exceed 2°C for RCP6.0 and RCP8.5 (*high confidence*), *more likely than not* to exceed 2°C for RCP4.5 (*medium confidence*), but *unlikely* to exceed 2°C for RCP2.6 (*medium confidence*). *{2.2.1}*

The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is *likely* to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5[9]. The Arctic region will continue to warm more rapidly than the global mean (Figure SPM.6a, Figure SPM.7a). *{2.2.1, Figure 2.1, Figure 2.2, Table 2.1}*

It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases. It is *very likely* that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur. *{2.2.1}*

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[7] Corresponding figures for limiting warming to 2°C with a probability of >50% and >33% are 3000 $GtCO_2$ (range of 2900 to 3200 $GtCO_2$) and 3300 $GtCO_2$ (range of 2950 to 3800 $GtCO_2$) respectively. Higher or lower temperature limits would imply larger or lower cumulative emissions respectively.

[8] This corresponds to about two thirds of the 2900 $GtCO_2$ that would limit warming to less than 2°C with a probability of >66%; to about 63% of the total amount of 3000 $GtCO_2$ that would limit warming to less than 2°C with a probability of >50%; and to about 58% of the total amount of 3300 $GtCO_2$ that would limit warming to less than 2°C with a probability of >33%.

[9] The period 1986–2005 is approximately 0.61 [0.55 to 0.67] °C warmer than 1850–1900. *{2.2.1}*

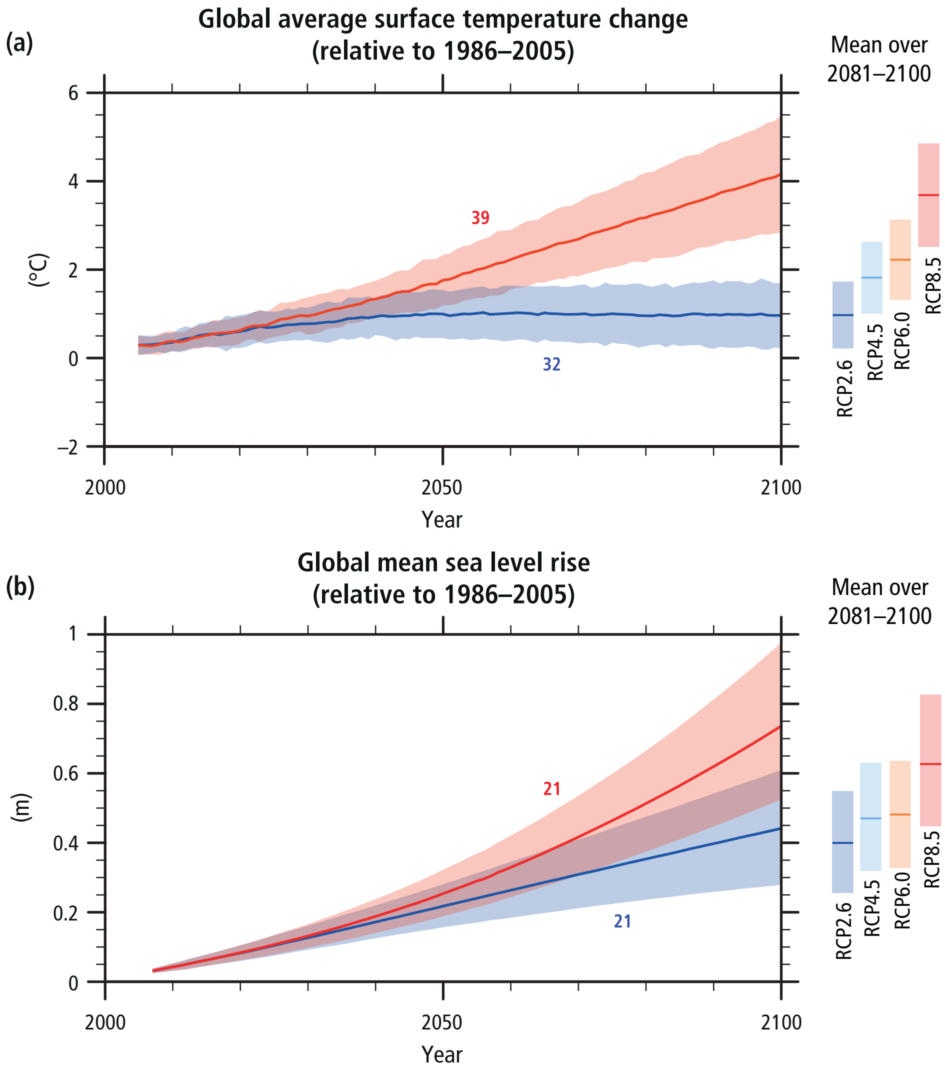

Figure SPM.6 | Global average surface temperature change **(a)** and global mean sea level rise[10] **(b)** from 2006 to 2100 as determined by multi-model simulations. All changes are relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as coloured vertical bars at the right hand side of each panel. The number of Coupled Model Intercomparison Project Phase 5 (CMIP5) models used to calculate the multi-model mean is indicated. *{2.2, Figure 2.1}*

Changes in precipitation will not be uniform. The high latitudes and the equatorial Pacific are *likely* to experience an increase in annual mean precipitation under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will *likely* decrease, while in many mid-latitude wet regions, mean precipitation will *likely* increase under the RCP8.5 scenario (Figure SPM.7b). Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent. *{2.2.2, Figure 2.2}*

The global ocean will continue to warm during the 21st century, with the strongest warming projected for the surface in tropical and Northern Hemisphere subtropical regions (Figure SPM.7a). *{2.2.3, Figure 2.2}*

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[10] Based on current understanding (from observations, physical understanding and modelling), only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

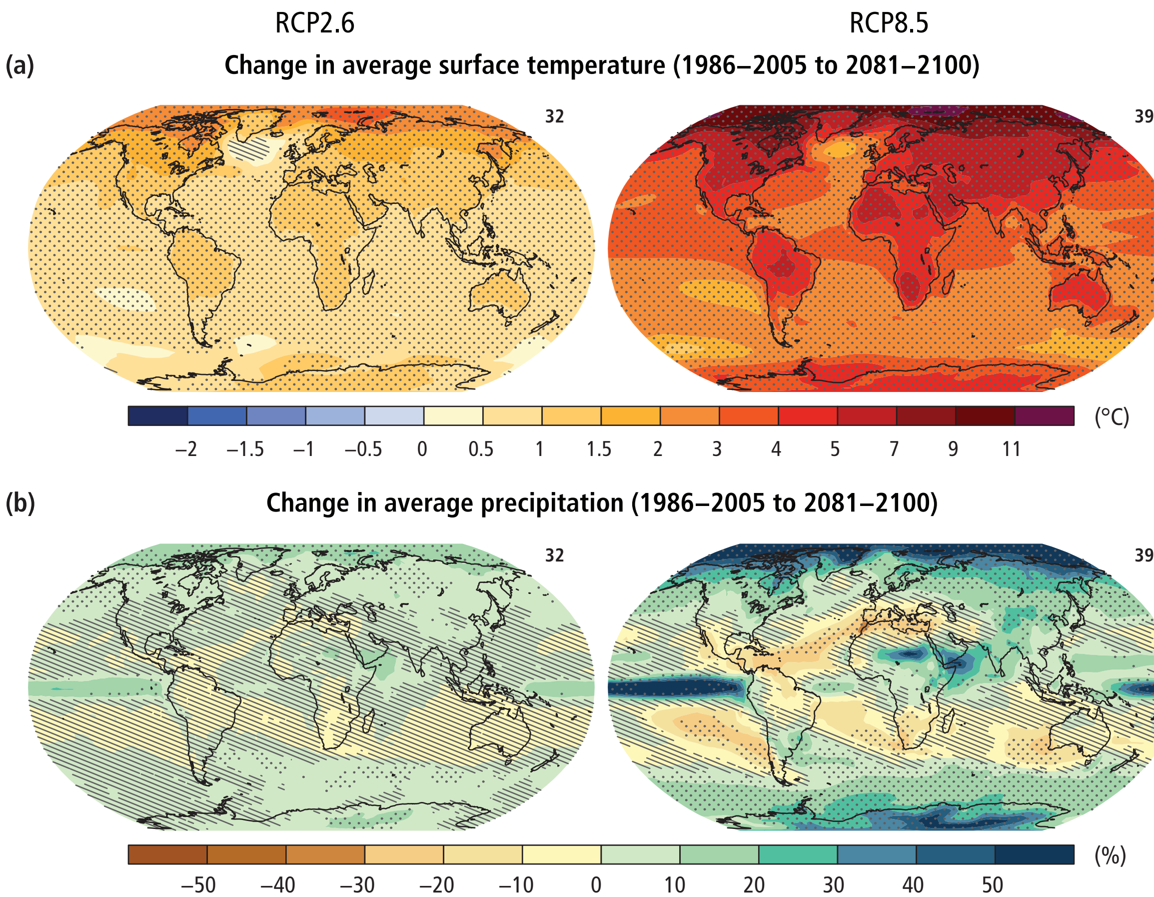

Figure SPM.7 | Change in average surface temperature **(a)** and change in average precipitation **(b)** based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios. The number of models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (i.e., dots) shows regions where the projected change is large compared to natural internal variability and where at least 90% of models agree on the sign of change. Hatching (i.e., diagonal lines) shows regions where the projected change is less than one standard deviation of the natural internal variability. *{2.2, Figure 2.2}*

Earth System Models project a global increase in ocean acidification for all RCP scenarios by the end of the 21st century, with a slow recovery after mid-century under RCP2.6. The decrease in surface ocean pH is in the range of 0.06 to 0.07 (15 to 17% increase in acidity) for RCP2.6, 0.14 to 0.15 (38 to 41%) for RCP4.5, 0.20 to 0.21 (58 to 62%) for RCP6.0 and 0.30 to 0.32 (100 to 109%) for RCP8.5. *{2.2.4, Figure 2.1}*

Year-round reductions in Arctic sea ice are projected for all RCP scenarios. A nearly ice-free[11] Arctic Ocean in the summer sea-ice minimum in September before mid-century is *likely* for RCP8.5[12] (*medium confidence*). *{2.2.3, Figure 2.1}*

It is *virtually certain* that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases, with the area of permafrost near the surface (upper 3.5 m) projected to decrease by 37% (RCP2.6) to 81% (RCP8.5) for the multi-model average (*medium confidence*). *{2.2.3}*

The global glacier volume, excluding glaciers on the periphery of Antarctica (and excluding the Greenland and Antarctic ice sheets), is projected to decrease by 15 to 55% for RCP2.6 and by 35 to 85% for RCP8.5 (*medium confidence*). *{2.2.3}*

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[11] When sea-ice extent is less than one million km^2 for at least five consecutive years.

[12] Based on an assessment of the subset of models that most closely reproduce the climatological mean state and 1979–2012 trend of the Arctic sea-ice extent.

There has been significant improvement in understanding and projection of sea level change since the AR4. Global mean sea level rise will continue during the 21st century, *very likely* at a faster rate than observed from 1971 to 2010. For the period 2081–2100 relative to 1986–2005, the rise will *likely* be in the ranges of 0.26 to 0.55 m for RCP2.6, and of 0.45 to 0.82 m for RCP8.5 (*medium confidence*)[10] (Figure SPM.6b). Sea level rise will not be uniform across regions. By the end of the 21st century, it is *very likely* that sea level will rise in more than about 95% of the ocean area. About 70% of the coastlines worldwide are projected to experience a sea level change within ±20% of the global mean. *{2.2.3}*

SPM 2.3 Future risks and impacts caused by a changing climate

Climate change will amplify existing risks and create new risks for natural and human systems. Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. *{2.3}*

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Rising rates and magnitudes of warming and other changes in the climate system, accompanied by ocean acidification, increase the risk of severe, pervasive and in some cases irreversible detrimental impacts. Some risks are particularly relevant for individual regions (Figure SPM.8), while others are global. The overall risks of future climate change impacts can be reduced by limiting the rate and magnitude of climate change, including ocean acidification. The precise levels of climate change sufficient to trigger abrupt and irreversible change remain uncertain, but the risk associated with crossing such thresholds increases with rising temperature (*medium confidence*). For risk assessment, it is important to evaluate the widest possible range of impacts, including low-probability outcomes with large consequences. *{1.5, 2.3, 2.4, 3.3, Box Introduction.1, Box 2.3, Box 2.4}*

A large fraction of species faces increased extinction risk due to climate change during and beyond the 21st century, especially as climate change interacts with other stressors (*high confidence*). Most plant species cannot naturally shift their geographical ranges sufficiently fast to keep up with current and high projected rates of climate change in most landscapes; most small mammals and freshwater molluscs will not be able to keep up at the rates projected under RCP4.5 and above in flat landscapes in this century (*high confidence*). Future risk is indicated to be high by the observation that natural global climate change at rates lower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years. Marine organisms will face progressively lower oxygen levels and high rates and magnitudes of ocean acidification (*high confidence*), with associated risks exacerbated by rising ocean temperature extremes (*medium confidence*). Coral reefs and polar ecosystems are highly vulnerable. Coastal systems and low-lying areas are at risk from sea level rise, which will continue for centuries even if the global mean temperature is stabilized (*high confidence*). *{2.3, 2.4, Figure 2.5}*

Climate change is projected to undermine food security (Figure SPM.9). Due to projected climate change by the mid-21st century and beyond, global marine species redistribution and marine biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity and other ecosystem services (*high confidence*). For wheat, rice and maize in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late 20th century levels, although individual locations may benefit (*medium confidence*). Global temperature increases of ~4°C or more[13] above late 20th century levels, combined with increasing food demand, would pose large risks to food security globally (*high confidence*). Climate change is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions (*robust evidence*, *high agreement*), intensifying competition for water among sectors (*limited evidence*, *medium agreement*). *{2.3.1, 2.3.2}*

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[13] Projected warming averaged over land is larger than global average warming for all RCP scenarios for the period 2081–2100 relative to 1986–2005. For regional projections, see Figure SPM.7. *{2.2}*

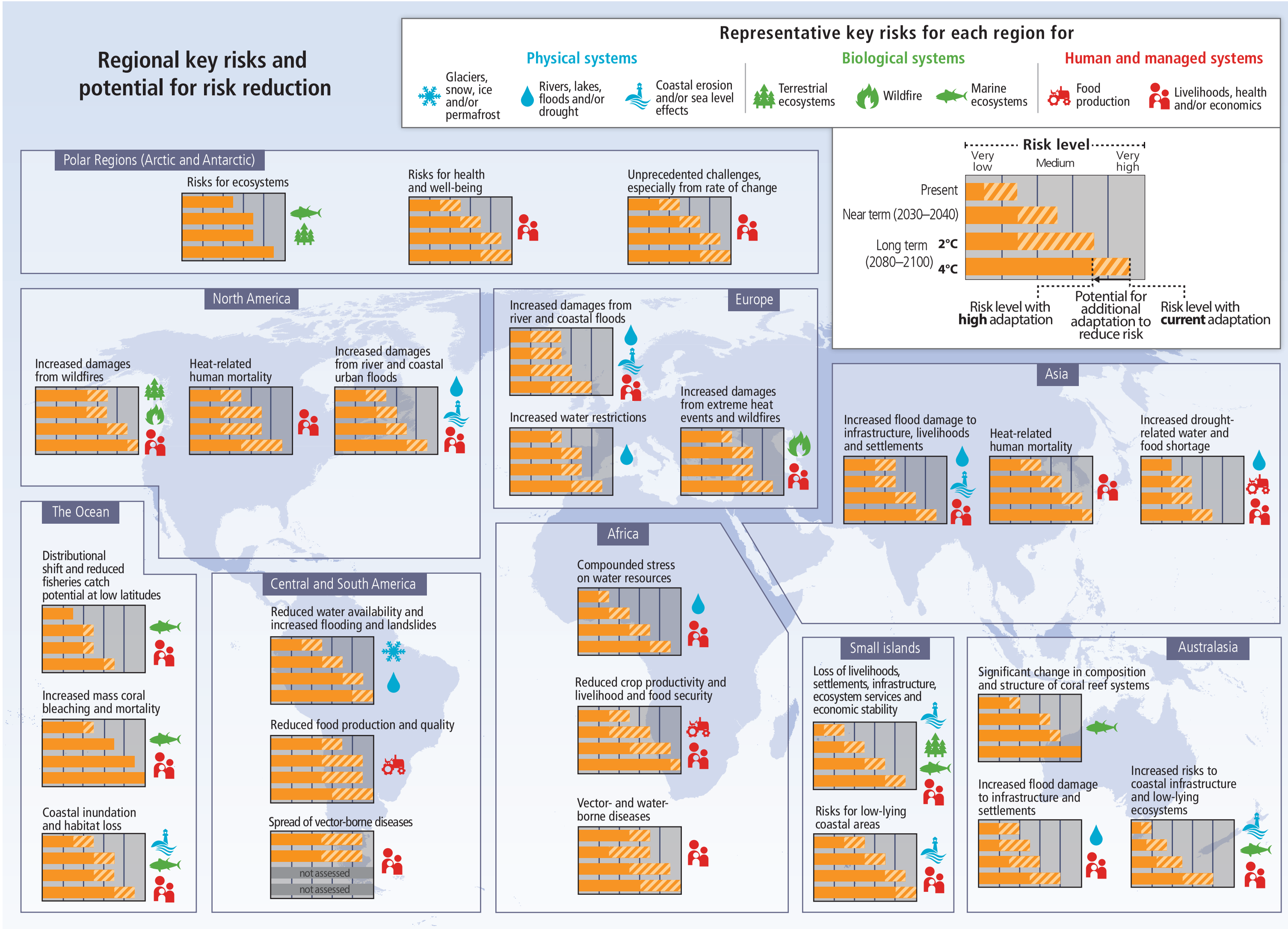
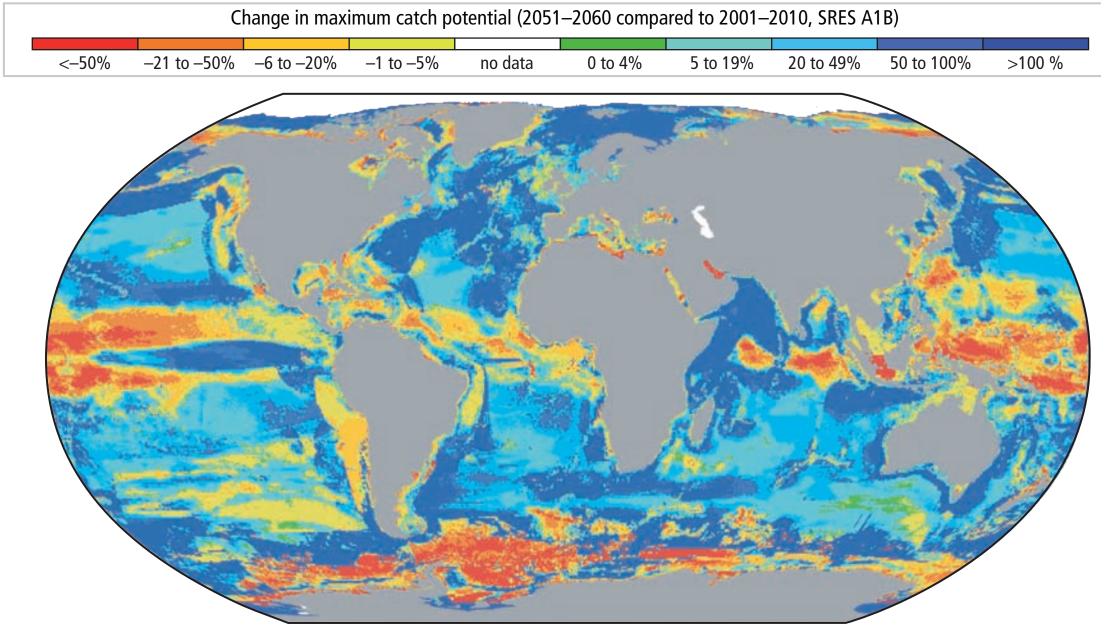


Figure SPM.8 | Representative key risks[14] for each region, including the potential for risk reduction through adaptation and mitigation, as well as limits to adaptation. Each key risk is assessed as very low, low, medium, high or very high. Risk levels are presented for three time frames: present, near term (here, for 2030–2040) and long term (here, for 2080–2100). In the near term, projected levels of global mean temperature increase do not diverge substantially across different emission scenarios. For the long term, risk levels are presented for two possible futures (2°C and 4°C global mean temperature increase above pre-industrial levels). For each timeframe, risk levels are indicated for a continuation of current adaptation and assuming high levels of current or future adaptation. Risk levels are not necessarily comparable, especially across regions. *{Figure 2.4}*

[14] Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation.

Climate change poses risks for food production

(a)



(b)

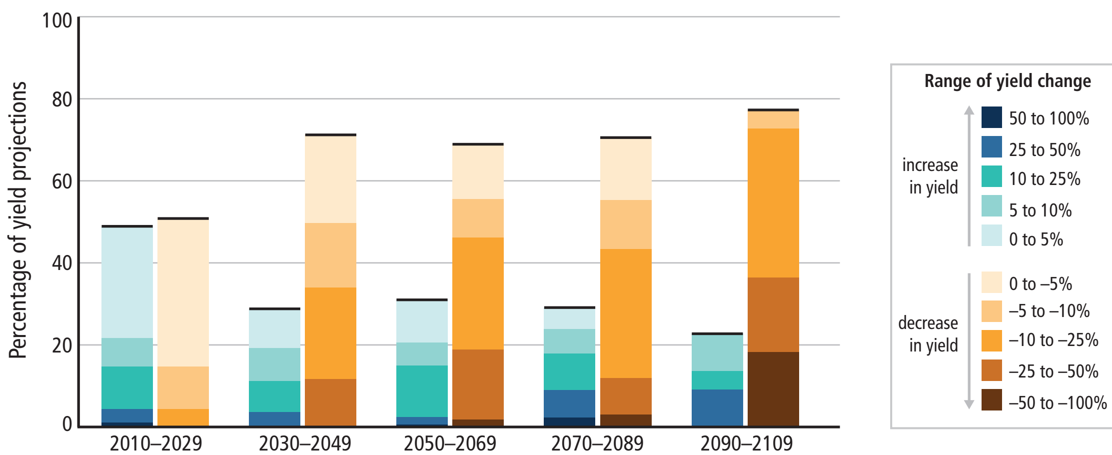


Figure SPM.9 | **(a)** Projected global redistribution of maximum catch potential of ~1000 exploited marine fish and invertebrate species. Projections compare the 10-year averages 2001–2010 and 2051–2060 using ocean conditions based on a single climate model under a moderate to high warming scenario, without analysis of potential impacts of overfishing or ocean acidification. **(b)** Summary of projected changes in crop yields (mostly wheat, maize, rice and soy), due to climate change over the 21st century. Data for each timeframe sum to 100%, indicating the percentage of projections showing yield increases versus decreases. The figure includes projections (based on 1090 data points) for different emission scenarios, for tropical and temperate regions and for adaptation and no-adaptation cases combined. Changes in crop yields are relative to late 20th century levels. *{Figure 2.6a, Figure 2.7}*

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). By 2100 for RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is expected to compromise common human activities, including growing food and working outdoors (*high confidence*). *{2.3.2}*

In urban areas climate change is projected to increase risks for people, assets, economies and ecosystems, including risks from heat stress, storms and extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, water scarcity, sea level rise and storm surges (*very high confidence*). These risks are amplified for those lacking essential infrastructure and services or living in exposed areas. *{2.3.2}*

Rural areas are expected to experience major impacts on water availability and supply, food security, infrastructure and agricultural incomes, including shifts in the production areas of food and non-food crops around the world (*high confidence*). *{2.3.2}*

Aggregate economic losses accelerate with increasing temperature (*limited evidence, high agreement*), but global economic impacts from climate change are currently difficult to estimate. From a poverty perspective, climate change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales. *{2.3.2}*

Climate change is projected to increase displacement of people (*medium evidence, high agreement*). Populations that lack the resources for planned migration experience higher exposure to extreme weather events, particularly in developing countries with low income. Climate change can indirectly increase risks of violent conflicts by amplifying well-documented drivers of these conflicts such as poverty and economic shocks (*medium confidence*). *{2.3.2}*

SPM 2.4 Climate change beyond 2100, irreversibility and abrupt changes

Many aspects of climate change and associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases. *{2.4}*

Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions. A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial timescale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period. *{2.4, Figure 2.8}*

Stabilization of global average surface temperature does not imply stabilization for all aspects of the climate system. Shifting biomes, soil carbon, ice sheets, ocean temperatures and associated sea level rise all have their own intrinsic long timescales which will result in changes lasting hundreds to thousands of years after global surface temperature is stabilized. *{2.1, 2.4}*

There is *high confidence* that ocean acidification will increase for centuries if CO_2 emissions continue, and will strongly affect marine ecosystems. *{2.4}*

It is *virtually certain* that global mean sea level rise will continue for many centuries beyond 2100, with the amount of rise dependent on future emissions. The threshold for the loss of the Greenland ice sheet over a millennium or more, and an associated sea level rise of up to 7 m, is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) of global warming with respect to pre-industrial temperatures. Abrupt and irreversible ice loss from the Antarctic ice sheet is possible, but current evidence and understanding is insufficient to make a quantitative assessment. *{2.4}*

Magnitudes and rates of climate change associated with medium- to high-emission scenarios pose an increased risk of abrupt and irreversible regional-scale change in the composition, structure and function of marine, terrestrial and freshwater ecosystems, including wetlands (*medium confidence*). A reduction in permafrost extent is *virtually certain* with continued rise in global temperatures. *{2.4}*

SPM 3. Future Pathways for Adaptation, Mitigation and Sustainable Development

Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. Substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development. *{3.2, 3.3, 3.4}*

SPM 3.1 Foundations of decision-making about climate change

Effective decision-making to limit climate change and its effects can be informed by a wide range of analytical approaches for evaluating expected risks and benefits, recognizing the importance of governance, ethical dimensions, equity, value judgments, economic assessments and diverse perceptions and responses to risk and uncertainty. *{3.1}*

Sustainable development and equity provide a basis for assessing climate policies. Limiting the effects of climate change is necessary to achieve sustainable development and equity, including poverty eradication. Countries' past and future contributions to the accumulation of GHGs in the atmosphere are different, and countries also face varying challenges and circumstances and have different capacities to address mitigation and adaptation. Mitigation and adaptation raise issues of equity, justice and fairness. Many of those most vulnerable to climate change have contributed and contribute little to GHG emissions. Delaying mitigation shifts burdens from the present to the future, and insufficient adaptation responses to emerging impacts are already eroding the basis for sustainable development. Comprehensive strategies in response to climate change that are consistent with sustainable development take into account the co-benefits, adverse side effects and risks that may arise from both adaptation and mitigation options. *{3.1, 3.5, Box 3.4}*

The design of climate policy is influenced by how individuals and organizations perceive risks and uncertainties and take them into account. Methods of valuation from economic, social and ethical analysis are available to assist decision-making. These methods can take account of a wide range of possible impacts, including low-probability outcomes with large consequences. But they cannot identify a single best balance between mitigation, adaptation and residual climate impacts. *{3.1}*

Climate change has the characteristics of a collective action problem at the global scale, because most GHGs accumulate over time and mix globally, and emissions by any agent (e.g., individual, community, company, country) affect other agents. Effective mitigation will not be achieved if individual agents advance their own interests independently. Cooperative responses, including international cooperation, are therefore required to effectively mitigate GHG emissions and address other climate change issues. The effectiveness of adaptation can be enhanced through complementary actions across levels, including international cooperation. The evidence suggests that outcomes seen as equitable can lead to more effective cooperation. *{3.1}*

SPM 3.2 Climate change risks reduced by mitigation and adaptation

Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*). Mitigation involves some level of co-benefits and of risks due to adverse side effects, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change, increasing the benefits from near-term mitigation efforts. *{3.2, 3.4}*

Mitigation and adaptation are complementary approaches for reducing risks of climate change impacts over different timescales (*high confidence*). Mitigation, in the near term and through the century, can substantially reduce climate change impacts in the latter decades of the 21st century and beyond. Benefits from adaptation can already be realized in addressing current risks, and can be realized in the future for addressing emerging risks. *{3.2, 4.5}*

Five Reasons For Concern (RFCs) aggregate climate change risks and illustrate the implications of warming and of adaptation limits for people, economies and ecosystems across sectors and regions. The five RFCs are associated with: (1) Unique and threatened systems, (2) Extreme weather events, (3) Distribution of impacts, (4) Global aggregate impacts, and (5) Large-scale singular events. In this report, the RFCs provide information relevant to Article 2 of UNFCCC. *{Box 2.4}*

Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*) (Figure SPM.10). In most scenarios without additional mitigation efforts (those with 2100 atmospheric concentrations

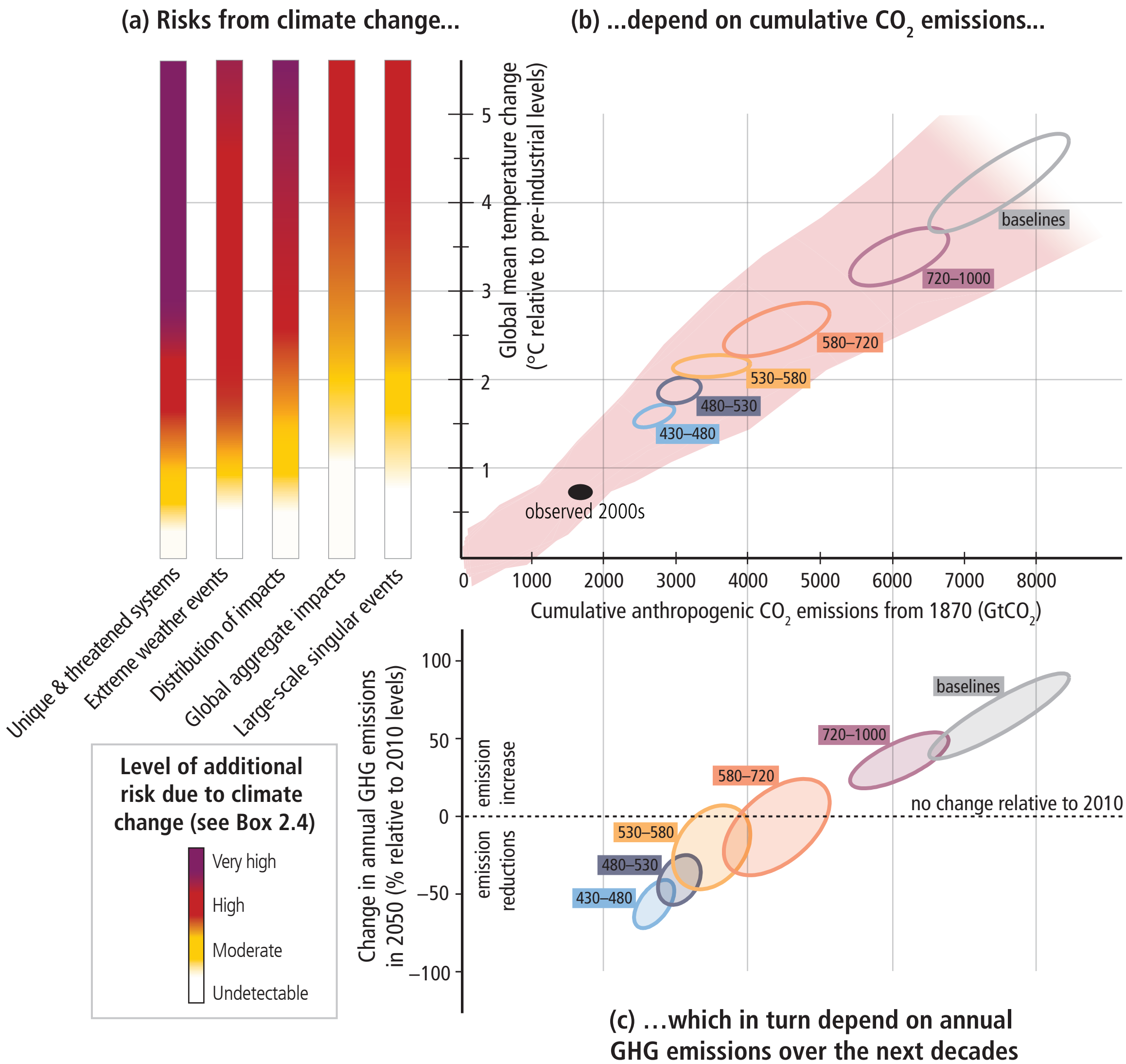


Figure SPM.10 | The relationship between risks from climate change, temperature change, cumulative carbon dioxide (CO_2) emissions and changes in annual greenhouse gas (GHG) emissions by 2050. Limiting risks across Reasons For Concern **(a)** would imply a limit for cumulative emissions of CO_2 **(b)** which would constrain annual GHG emissions over the next few decades **(c)**. **Panel a** reproduces the five Reasons For Concern *{Box 2.4}*. **Panel b** links temperature changes to cumulative CO_2 emissions (in $GtCO_2$) from 1870. They are based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (pink plume) and on a simple climate model (median climate response in 2100), for the baselines and five mitigation scenario categories (six ellipses). Details are provided in Figure SPM.5. **Panel c** shows the relationship between the cumulative CO_2 emissions (in $GtCO_2$) of the scenario categories and their associated change in annual GHG emissions by 2050, expressed in percentage change (in percent $GtCO_2$-eq per year) relative to 2010. The ellipses correspond to the same scenario categories as in Panel b, and are built with a similar method (see details in Figure SPM.5). *{Figure 3.1}*

>1000 ppm CO_2-eq), warming is *more likely than not* to exceed 4°C above pre-industrial levels by 2100 (Table SPM.1). The risks associated with temperatures at or above 4°C include substantial species extinction, global and regional food insecurity, consequential constraints on common human activities and limited potential for adaptation in some cases (*high confidence*). Some risks of climate change, such as risks to unique and threatened systems and risks associated with extreme weather events, are moderate to high at temperatures 1°C to 2°C above pre-industrial levels. *{2.3, Figure 2.5, 3.2, 3.4, Box 2.4, Table SPM.1}*

Substantial cuts in GHG emissions over the next few decades can substantially reduce risks of climate change by limiting warming in the second half of the 21st century and beyond. Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Limiting risks across RFCs would imply a limit for cumulative emissions of CO_2. Such a limit would require that global net emissions of CO_2 eventually decrease to zero and would constrain annual emissions over the next few decades (Figure SPM.10) (*high confidence*). But some risks from climate damages are unavoidable, even with mitigation and adaptation. *{2.2.5, 3.2, 3.4}*

Mitigation involves some level of co-benefits and risks, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change. Inertia in the economic and climate system and the possibility of irreversible impacts from climate change increase the benefits from near-term mitigation efforts (*high confidence*). Delays in additional mitigation or constraints on technological options increase the longer-term mitigation costs to hold climate change risks at a given level (Table SPM.2). *{3.2, 3.4}*

SPM 3.3 Characteristics of adaptation pathways

Adaptation can reduce the risks of climate change impacts, but there are limits to its effectiveness, especially with greater magnitudes and rates of climate change. Taking a longer-term perspective, in the context of sustainable development, increases the likelihood that more immediate adaptation actions will also enhance future options and preparedness. *{3.3}*

Adaptation can contribute to the well-being of populations, the security of assets and the maintenance of ecosystem goods, functions and services now and in the future. Adaptation is place- and context-specific (*high confidence*). A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability (*high confidence*). Integration of adaptation into planning, including policy design, and decision-making can promote synergies with development and disaster risk reduction. Building adaptive capacity is crucial for effective selection and implementation of adaptation options (*robust evidence, high agreement*). *{3.3}*

Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (*high confidence*). National governments can coordinate adaptation efforts of local and sub-national governments, for example by protecting vulnerable groups, by supporting economic diversification and by providing information, policy and legal frameworks and financial support (*robust evidence*, *high agreement*). Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households and civil society and in managing risk information and financing (*medium evidence*, *high agreement*). *{3.3}*

Adaptation planning and implementation at all levels of governance are contingent on societal values, objectives and risk perceptions (*high confidence*). Recognition of diverse interests, circumstances, social-cultural contexts and expectations can benefit decision-making processes. Indigenous, local and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change, but these have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation. *{3.3}*

Constraints can interact to impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: limited financial and human resources; limited integration or coordination of governance; uncertainties about projected impacts; different perceptions of risks; competing values; absence of key adaptation leaders and advocates; and limited tools to monitor adaptation effectiveness. Another constraint includes insufficient research, monitoring, and observation and the finance to maintain them. *{3.3}*

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). Limits to adaptation emerge from the interaction among climate change and biophysical and/or socio-economic constraints. Further, poor planning or implementation, overemphasizing short-term outcomes or failing to sufficiently anticipate consequences can result in maladaptation, increasing the vulnerability or exposure of the target group in the future or the vulnerability of other people, places or sectors (*medium evidence, high agreement*). Underestimating the complexity of adaptation as a social process can create unrealistic expectations about achieving intended adaptation outcomes. *{3.3}*

Significant co-benefits, synergies and trade-offs exist between mitigation and adaptation and among different adaptation responses; interactions occur both within and across regions (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use and biodiversity, but tools to understand and manage these interactions remain limited. Examples of actions with co-benefits include (i) improved energy efficiency and cleaner energy sources, leading to reduced emissions of health-damaging, climate-altering air pollutants; (ii) reduced energy and water consumption in urban areas through greening cities and recycling water; (iii) sustainable agriculture and forestry; and (iv) protection of ecosystems for carbon storage and other ecosystem services. *{3.3}*

Transformations in economic, social, technological and political decisions and actions can enhance adaptation and promote sustainable development (*high confidence*). At the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. Restricting adaptation responses to incremental changes to existing systems and structures, without considering transformational change, may increase costs and losses and miss opportunities. Planning and implementation of transformational adaptation could reflect strengthened, altered or aligned paradigms and may place new and increased demands on governance structures to reconcile different goals and visions for the future and to address possible equity and ethical implications. Adaptation pathways are enhanced by iterative learning, deliberative processes and innovation. *{3.3}*

SPM 3.4 Characteristics of mitigation pathways

There are multiple mitigation pathways that are *likely* to limit warming to below 2°C relative to pre-industrial levels. These pathways would require substantial emissions reductions over the next few decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century. Implementing such reductions poses substantial technological, economic, social and institutional challenges, which increase with delays in additional mitigation and if key technologies are not available. Limiting warming to lower or higher levels involves similar challenges but on different timescales. *{3.4}*

Without additional efforts to reduce GHG emissions beyond those in place today, global emissions growth is expected to persist, driven by growth in global population and economic activities. Global mean surface temperature increases in 2100 in baseline scenarios—those without additional mitigation—range from 3.7°C to 4.8°C above the average for 1850–1900 for a median climate response. They range from 2.5°C to 7.8°C when including climate uncertainty (5th to 95th percentile range) (*high confidence*). *{3.4}*

Emissions scenarios leading to CO_2-equivalent concentrations in 2100 of about 450 ppm or lower are *likely* to maintain warming below 2°C over the 21st century relative to pre-industrial levels[15]. These scenarios are characterized by 40 to 70% global anthropogenic GHG emissions reductions by 2050 compared to 2010[16], and emissions levels near zero or below in 2100. Mitigation scenarios reaching concentration levels of about 500 ppm CO_2-eq by 2100 are *more likely than not* to limit temperature change to less than 2°C, unless they temporarily overshoot concentration levels of roughly 530 ppm CO_2-eq

[15] For comparison, the CO_2-eq concentration in 2011 is estimated to be 430 ppm (uncertainty range 340 to 520 ppm)

[16] This range differs from the range provided for a similar concentration category in the AR4 (50 to 85% lower than 2000 for CO_2 only). Reasons for this difference include that this report has assessed a substantially larger number of scenarios than in the AR4 and looks at all GHGs. In addition, a large proportion of the new scenarios include Carbon Dioxide Removal (CDR) technologies (see below). Other factors include the use of 2100 concentration levels instead of stabilization levels and the shift in reference year from 2000 to 2010.

before 2100, in which case they are *about as likely as not* to achieve that goal. In these 500 ppm CO_2-eq scenarios, global 2050 emissions levels are 25 to 55% lower than in 2010. Scenarios with higher emissions in 2050 are characterized by a greater reliance on Carbon Dioxide Removal (CDR) technologies beyond mid-century (and vice versa). Trajectories that are *likely* to limit warming to 3°C relative to pre-industrial levels reduce emissions less rapidly than those limiting warming to 2°C. A limited number of studies provide scenarios that are *more likely than not* to limit warming to 1.5°C by 2100; these scenarios are characterized by concentrations below 430 ppm CO_2-eq by 2100 and 2050 emission reduction between 70% and 95% below 2010. For a comprehensive overview of the characteristics of emissions scenarios, their CO_2-equivalent concentrations and their likelihood to keep warming to below a range of temperature levels, see Figure SPM.11 and Table SPM.1. *{3.4}*

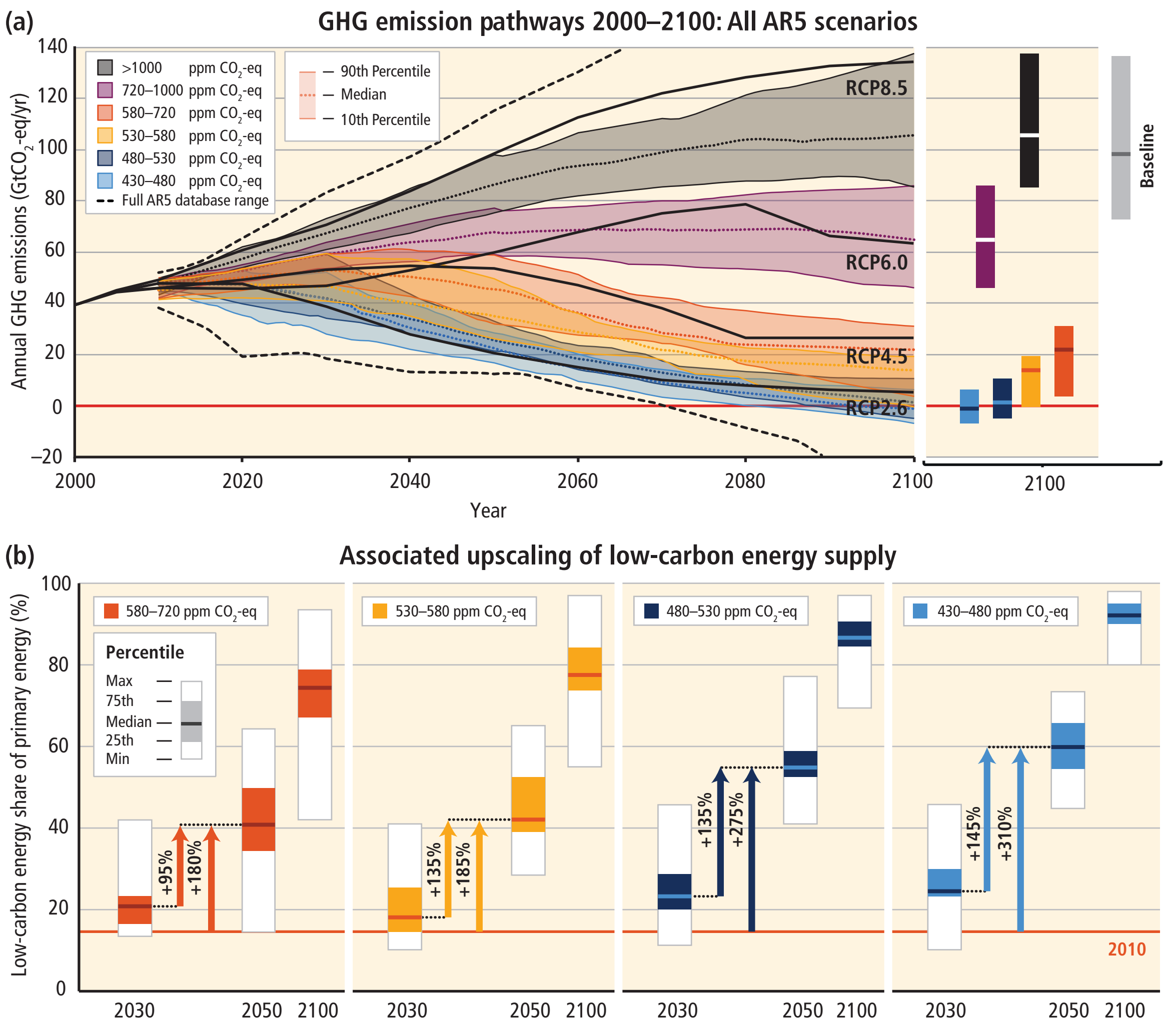


Figure SPM.11 | Global greenhouse gas emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$-eq/yr) in baseline and mitigation scenarios for different long-term concentration levels **(a)** and associated upscaling requirements of low-carbon energy (% of primary energy) for 2030, 2050 and 2100 compared to 2010 levels in mitigation scenarios **(b)**. *{Figure 3.2}*

SPM

Table SPM.1 | Key characteristics of the scenarios collected and assessed for WGIII AR5. For all parameters the 10th to 90th percentile of the scenarios is shown [a]. *{Table 3.1}*

<table>
<tr><th rowspan="2">CO_2-eq Concentrations in 2100 (ppm CO_2-eq) [f]

Category label (conc. range)</th><th rowspan="2">Subcategories</th><th rowspan="2">Relative position of the RCPs [d]</th><th colspan="2">Change in CO_2-eq emissions compared to 2010 (in %) [c]</th><th colspan="4">Likelihood of staying below a specific temperature level over the 21st century (relative to 1850–1900) [d, e]</th></tr>
<tr><th>2050</th><th>2100</th><th>1.5°C</th><th>2°C</th><th>3°C</th><th>4°C</th></tr>
<tr><td><430</td><td colspan="8">Only a limited number of individual model studies have explored levels below 430 ppm CO_2-eq [j]</td></tr>
<tr><td>450
(430 to 480)</td><td>Total range [a, g]</td><td>RCP2.6</td><td>–72 to –41</td><td>–118 to –78</td><td>More unlikely than likely</td><td>Likely</td><td rowspan="6">Likely</td><td rowspan="8">Likely</td></tr>
<tr><td rowspan="2">500
(480 to 530)</td><td>No overshoot of 530 ppm CO_2-eq</td><td></td><td>–57 to –42</td><td>–107 to –73</td><td rowspan="6">Unlikely</td><td>More likely than not</td></tr>
<tr><td>Overshoot of 530 ppm CO_2-eq</td><td></td><td>–55 to –25</td><td>–114 to –90</td><td>About as likely as not</td></tr>
<tr><td rowspan="2">550
(530 to 580)</td><td>No overshoot of 580 ppm CO_2-eq</td><td></td><td>–47 to –19</td><td>–81 to –59</td><td rowspan="3">More unlikely than likely [i]</td></tr>
<tr><td>Overshoot of 580 ppm CO_2-eq</td><td></td><td>–16 to 7</td><td>–183 to –86</td></tr>
<tr><td>(580 to 650)</td><td>Total range</td><td rowspan="2">RCP4.5</td><td>–38 to 24</td><td>–134 to –50</td></tr>
<tr><td>(650 to 720)</td><td>Total range</td><td>–11 to 17</td><td>–54 to –21</td><td rowspan="2">Unlikely</td><td>More likely than not</td></tr>
<tr><td>(720 to 1000) [b]</td><td>Total range</td><td>RCP6.0</td><td>18 to 54</td><td>–7 to 72</td><td rowspan="2">Unlikely [h]</td><td>More unlikely than likely</td></tr>
<tr><td>>1000 [b]</td><td>Total range</td><td>RCP8.5</td><td>52 to 95</td><td>74 to 178</td><td>Unlikely [h]</td><td>Unlikely</td><td>More unlikely than likely</td></tr>
</table>

Notes:

[a] The 'total range' for the 430 to 480 ppm CO_2-eq concentrations scenarios corresponds to the range of the 10th to 90th percentile of the subcategory of these scenarios shown in Table 6.3 of the Working Group III Report.

[b] Baseline scenarios fall into the >1000 and 720 to 1000 ppm CO_2-eq categories. The latter category also includes mitigation scenarios. The baseline scenarios in the latter category reach a temperature change of 2.5°C to 5.8°C above the average for 1850–1900 in 2100. Together with the baseline scenarios in the >1000 ppm CO_2-eq category, this leads to an overall 2100 temperature range of 2.5°C to 7.8°C (range based on median climate response: 3.7°C to 4.8°C) for baseline scenarios across both concentration categories.

[c] The global 2010 emissions are 31% above the 1990 emissions (consistent with the historic greenhouse gas emission estimates presented in this report). CO_2-eq emissions include the basket of Kyoto gases (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) as well as fluorinated gases).

[d] The assessment here involves a large number of scenarios published in the scientific literature and is thus not limited to the Representative Concentration Pathways (RCPs). To evaluate the CO_2-eq concentration and climate implications of these scenarios, the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) was used in a probabilistic mode. For a comparison between MAGICC model results and the outcomes of the models used in WGI, see WGI 12.4.1.2, 12.4.8 and WGIII 6.3.2.6.

[e] The assessment in this table is based on the probabilities calculated for the full ensemble of scenarios in WGIII AR5 using MAGICC and the assessment in WGI of the uncertainty of the temperature projections not covered by climate models. The statements are therefore consistent with the statements in WGI, which are based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) runs of the RCPs and the assessed uncertainties. Hence, the likelihood statements reflect different lines of evidence from both WGs. This WGI method was also applied for scenarios with intermediate concentration levels where no CMIP5 runs are available. The likelihood statements are indicative only *{WGIII 6.3}* and follow broadly the terms used by the WGI SPM for temperature projections: likely 66–100%, more likely than not >50–100%, about as likely as not 33–66%, and unlikely 0–33%. In addition the term more unlikely than likely 0–<50% is used.

[f] The CO_2-equivalent concentration (see Glossary) is calculated on the basis of the total forcing from a simple carbon cycle/climate model, MAGICC. The CO_2-equivalent concentration in 2011 is estimated to be 430 ppm (uncertainty range 340 to 520 ppm). This is based on the assessment of total anthropogenic radiative forcing for 2011 relative to 1750 in WGI, i.e., 2.3 W/m^2, uncertainty range 1.1 to 3.3 W/m^2.

[g] The vast majority of scenarios in this category overshoot the category boundary of 480 ppm CO_2-eq concentration.

[h] For scenarios in this category, no CMIP5 run or MAGICC realization stays below the respective temperature level. Still, an *unlikely* assignment is given to reflect uncertainties that may not be reflected by the current climate models.

[i] Scenarios in the 580 to 650 ppm CO_2-eq category include both overshoot scenarios and scenarios that do not exceed the concentration level at the high end of the category (e.g., RCP4.5). The latter type of scenarios, in general, have an assessed probability of *more unlikely than likely* to stay below the 2°C temperature level, while the former are mostly assessed to have an *unlikely* probability of staying below this level.

[j] In these scenarios, global CO_2-eq emissions in 2050 are between 70 to 95% below 2010 emissions, and they are between 110 to 120% below 2010 emissions in 2100.

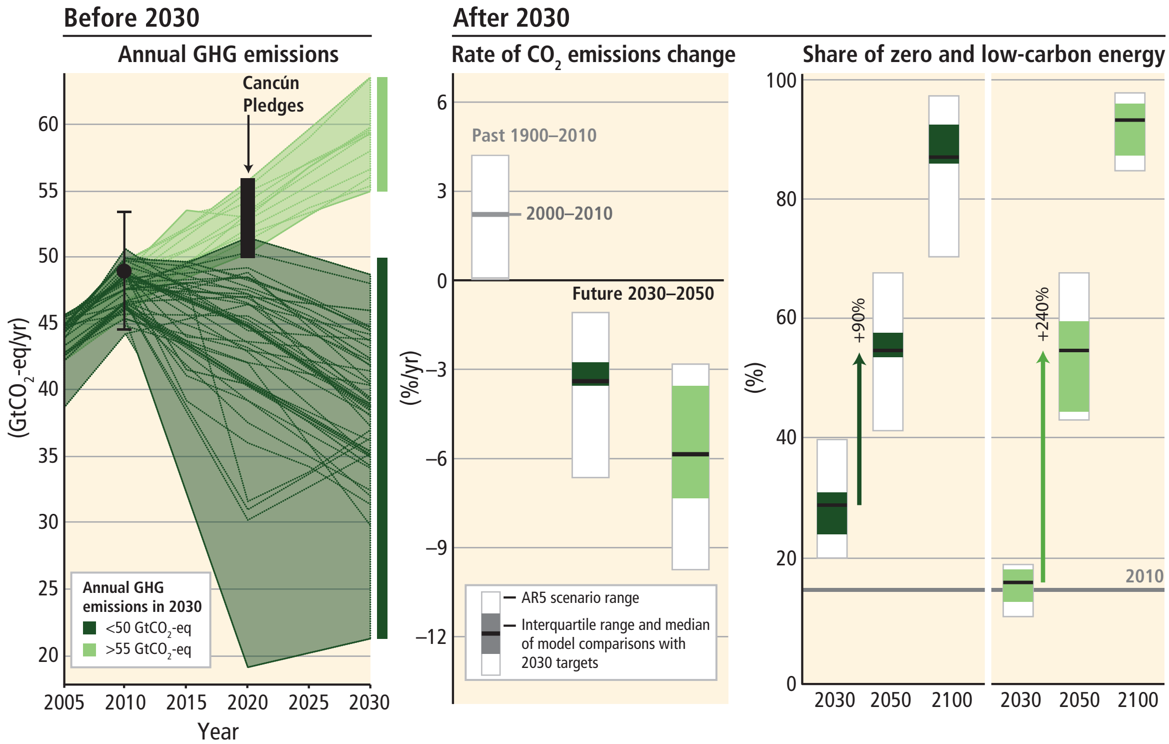


Figure SPM.12 | The implications of different 2030 greenhouse gas (GHG) emissions levels for the rate of carbon dioxide (CO_2) emissions reductions and low-carbon energy upscaling in mitigation scenarios that are at least *about as likely as not* to keep warming throughout the 21st century below 2°C relative to pre-industrial levels (2100 CO_2-equivalent concentrations of 430 to 530 ppm). The scenarios are grouped according to different emissions levels by 2030 (coloured in different shades of green). The left panel shows the pathways of GHG emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$-eq/yr) leading to these 2030 levels. The black dot with whiskers gives historic GHG emission levels and associated uncertainties in 2010 as reported in Figure SPM.2. The black bar shows the estimated uncertainty range of GHG emissions implied by the Cancún Pledges. The middle panel denotes the average annual CO_2 emissions reduction rates for the period 2030–2050. It compares the median and interquartile range across scenarios from recent inter-model comparisons with explicit 2030 interim goals to the range of scenarios in the Scenario Database for WGIII AR5. Annual rates of historical emissions change (sustained over a period of 20 years) and the average annual CO_2 emission change between 2000 and 2010 are shown as well. The arrows in the right panel show the magnitude of zero and low-carbon energy supply upscaling from 2030 to 2050 subject to different 2030 GHG emissions levels. Zero- and low-carbon energy supply includes renewables, nuclear energy and fossil energy with carbon dioxide capture and storage (CCS) or bioenergy with CCS (BECCS). [Note: Only scenarios that apply the full, unconstrained mitigation technology portfolio of the underlying models (default technology assumption) are shown. Scenarios with large net negative global emissions (>20 $GtCO_2$-eq/yr), scenarios with exogenous carbon price assumptions and scenarios with 2010 emissions significantly outside the historical range are excluded.] *{Figure 3.3}*

Mitigation scenarios reaching about 450 ppm CO_2-eq in 2100 (consistent with a *likely* chance to keep warming below 2°C relative to pre-industrial levels) typically involve temporary overshoot[17] of atmospheric concentrations, as do many scenarios reaching about 500 ppm CO_2-eq to about 550 ppm CO_2-eq in 2100 (Table SPM.1). Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and afforestation in the second half of the century. The availability and scale of these and other CDR technologies and methods are uncertain and CDR technologies are, to varying degrees, associated with challenges and risks[18]. CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive (*high confidence*). *{3.4, Box 3.3}*

Reducing emissions of non-CO_2 agents can be an important element of mitigation strategies. All current GHG emissions and other forcing agents affect the rate and magnitude of climate change over the next few decades, although long-term warming is mainly driven by CO_2 emissions. Emissions of non-CO_2 forcers are often expressed as 'CO_2-equivalent emissions', but the choice of metric to calculate these emissions, and the implications for the emphasis and timing of abatement of the various climate forcers, depends on application and policy context and contains value judgments. *{3.4, Box 3.2}*

17 In concentration 'overshoot' scenarios, concentrations peak during the century and then decline.

18 CDR methods have biogeochemical and technological limitations to their potential on the global scale. There is insufficient knowledge to quantify how much CO_2 emissions could be partially offset by CDR on a century timescale. CDR methods may carry side effects and long-term consequences on a global scale.

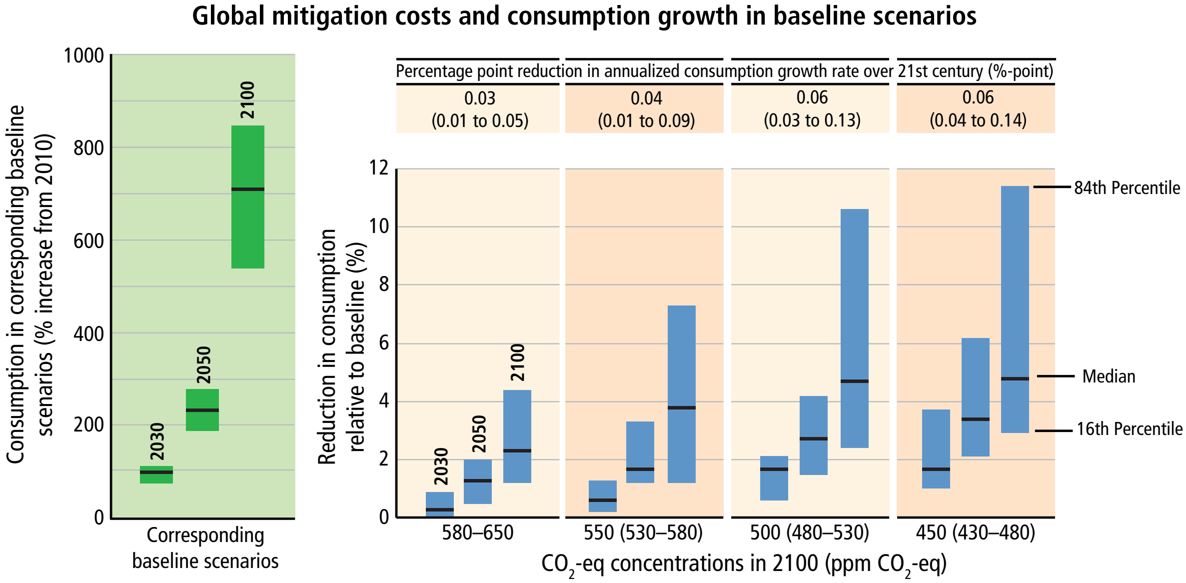


Figure SPM.13 | Global mitigation costs in cost-effective scenarios at different atmospheric concentrations levels in 2100. Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price, and impose no additional limitations on technology relative to the models' default technology assumptions. Consumption losses are shown relative to a baseline development without climate policy (left panel). The table at the top shows percentage points of annualized consumption growth reductions relative to consumption growth in the baseline of 1.6 to 3% per year (e.g., if the reduction is 0.06 percentage points per year due to mitigation, and baseline growth is 2.0% per year, then the growth rate with mitigation would be 1.94% per year). Cost estimates shown in this table do not consider the benefits of reduced climate change or co-benefits and adverse side effects of mitigation. Estimates at the high end of these cost ranges are from models that are relatively inflexible to achieve the deep emissions reductions required in the long run to meet these goals and/or include assumptions about market imperfections that would raise costs. *{Figure 3.4}*

Delaying additional mitigation to 2030 will substantially increase the challenges associated with limiting warming over the 21st century to below 2°C relative to pre-industrial levels. It will require substantially higher rates of emissions reductions from 2030 to 2050; a much more rapid scale-up of low-carbon energy over this period; a larger reliance on CDR in the long term; and higher transitional and long-term economic impacts. Estimated global emissions levels in 2020 based on the Cancún Pledges are not consistent with cost-effective mitigation trajectories that are at least *about as likely as not* to limit warming to below 2°C relative to pre-industrial levels, but they do not preclude the option to meet this goal (*high confidence*) (Figure SPM.12, Table SPM.2). *{3.4}*

Estimates of the aggregate economic costs of mitigation vary widely depending on methodologies and assumptions, but increase with the stringency of mitigation. Scenarios in which all countries of the world begin mitigation immediately, in which there is a single global carbon price, and in which all key technologies are available have been used as a cost-effective benchmark for estimating macro-economic mitigation costs (Figure SPM.13). Under these assumptions mitigation scenarios that are *likely* to limit warming to below 2°C through the 21st century relative to pre-industrial levels entail losses in global consumption—not including benefits of reduced climate change as well as co-benefits and adverse side effects of mitigation—of 1 to 4% (median: 1.7%) in 2030, 2 to 6% (median: 3.4%) in 2050 and 3 to 11% (median: 4.8%) in 2100 relative to consumption in baseline scenarios that grows anywhere from 300% to more than 900% over the century (Figure SPM.13). These numbers correspond to an annualized reduction of consumption growth by 0.04 to 0.14 (median: 0.06) percentage points over the century relative to annualized consumption growth in the baseline that is between 1.6 and 3% per year (*high confidence*). *{3.4}*

In the absence or under limited availability of mitigation technologies (such as bioenergy, CCS and their combination BECCS, nuclear, wind/solar), mitigation costs can increase substantially depending on the technology considered. Delaying additional mitigation increases mitigation costs in the medium to long term. Many models could not limit *likely* warming to below 2°C over the 21st century relative to pre-industrial levels if additional mitigation is considerably delayed. Many models could not limit *likely* warming to below 2°C if bioenergy, CCS and their combination (BECCS) are limited (*high confidence*) (Table SPM.2). *{3.4}*

Table SPM.2 | Increase in global mitigation costs due to either limited availability of specific technologies or delays in additional mitigation [a] relative to cost-effective scenarios [b]. The increase in costs is given for the median estimate and the 16th to 84th percentile range of the scenarios (in parentheses) [c]. In addition, the sample size of each scenario set is provided in the coloured symbols. The colours of the symbols indicate the fraction of models from systematic model comparison exercises that could successfully reach the targeted concentration level. *{Table 3.2}*

Mitigation cost increases in scenarios with limited availability of technologies [d] *[% increase in total discounted [e] mitigation costs (2015–2100) relative to default technology assumptions]*					**Mitigation cost increases due to delayed additional mitigation until 2030** *[% increase in mitigation costs relative to immediate mitigation]*	
2100 concentrations (ppm CO_2-eq)	no CCS	nuclear phase out	limited solar/wind	limited bioenergy	medium term costs (2030–2050)	long term costs (2050–2100)
450 (430 to 480)	138% (29 to 297%) 4	7% (4 to 18%) 8	6% (2 to 29%) 8	64% (44 to 78%) 8	} 44% (2 to 78%) 29	37% (16 to 82%) 29
500 (480 to 530)	not available (n.a.)	n.a.	n.a.	n.a.		
550 (530 to 580)	39% (18 to 78%) 11	13% (2 to 23%) 10	8% (5 to 15%) 10	18% (4 to 66%) 12	} 15% (3 to 32%)	16% (5 to 24%)
580 to 650	n.a.	n.a.	n.a.	n.a.		

Symbol legend—fraction of models successful in producing scenarios (numbers indicate the number of successful models)

(green): all models successful	(orange): between 50 and 80% of models successful
(tan): between 80 and 100% of models successful	(red): less than 50% of models successful

Notes:

[a] Delayed mitigation scenarios are associated with greenhouse gas emission of more than 55 $GtCO_2$-eq in 2030, and the increase in mitigation costs is measured relative to cost-effective mitigation scenarios for the same long-term concentration level.

[b] Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price, and impose no additional limitations on technology relative to the models' default technology assumptions.

[c] The range is determined by the central scenarios encompassing the 16th to 84th percentile range of the scenario set. Only scenarios with a time horizon until 2100 are included. Some models that are included in the cost ranges for concentration levels above 530 ppm CO_2-eq in 2100 could not produce associated scenarios for concentration levels below 530 ppm CO_2-eq in 2100 with assumptions about limited availability of technologies and/or delayed additional mitigation.

[d] No CCS: carbon dioxide capture and storage is not included in these scenarios. Nuclear phase out: no addition of nuclear power plants beyond those under construction, and operation of existing plants until the end of their lifetime. Limited Solar/Wind: a maximum of 20% global electricity generation from solar and wind power in any year of these scenarios. Limited Bioenergy: a maximum of 100 EJ/yr modern bioenergy supply globally (modern bioenergy used for heat, power, combinations and industry was around 18 EJ/yr in 2008). EJ = Exajoule = 10^{18} Joule.

[e] Percentage increase of net present value of consumption losses in percent of baseline consumption (for scenarios from general equilibrium models) and abatement costs in percent of baseline gross domestic product (GDP, for scenarios from partial equilibrium models) for the period 2015–2100, discounted at 5% per year.

Mitigation scenarios reaching about 450 or 500 ppm CO_2-eq by 2100 show reduced costs for achieving air quality and energy security objectives, with significant co-benefits for human health, ecosystem impacts and sufficiency of resources and resilience of the energy system. *{4.4.2.2}*

Mitigation policy could devalue fossil fuel assets and reduce revenues for fossil fuel exporters, but differences between regions and fuels exist (*high confidence*). Most mitigation scenarios are associated with reduced revenues from coal and oil trade for major exporters (*high confidence*). The availability of CCS would reduce the adverse effects of mitigation on the value of fossil fuel assets (*medium confidence*). *{4.4.2.2}*

Solar Radiation Management (SRM) involves large-scale methods that seek to reduce the amount of absorbed solar energy in the climate system. SRM is untested and is not included in any of the mitigation scenarios. If it were deployed, SRM would entail numerous uncertainties, side effects, risks and shortcomings and has particular governance and ethical implications. SRM would not reduce ocean acidification. If it were terminated, there is *high confidence* that surface temperatures would rise very rapidly impacting ecosystems susceptible to rapid rates of change. *{Box 3.3}*

SPM 4. Adaptation and Mitigation

Many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself. Effective implementation depends on policies and cooperation at all scales and can be enhanced through integrated responses that link adaptation and mitigation with other societal objectives. *{4}*

SPM 4.1 Common enabling factors and constraints for adaptation and mitigation responses

Adaptation and mitigation responses are underpinned by common enabling factors. These include effective institutions and governance, innovation and investments in environmentally sound technologies and infrastructure, sustainable livelihoods and behavioural and lifestyle choices. *{4.1}*

Inertia in many aspects of the socio-economic system constrains adaptation and mitigation options (*medium evidence, high agreement*). Innovation and investments in environmentally sound infrastructure and technologies can reduce GHG emissions and enhance resilience to climate change (*very high confidence*). *{4.1}*

Vulnerability to climate change, GHG emissions and the capacity for adaptation and mitigation are strongly influenced by livelihoods, lifestyles, behaviour and culture (*medium evidence, medium agreement*). Also, the social acceptability and/or effectiveness of climate policies are influenced by the extent to which they incentivize or depend on regionally appropriate changes in lifestyles or behaviours. *{4.1}*

For many regions and sectors, enhanced capacities to mitigate and adapt are part of the foundation essential for managing climate change risks (*high confidence*). Improving institutions as well as coordination and cooperation in governance can help overcome regional constraints associated with mitigation, adaptation and disaster risk reduction (*very high confidence*). *{4.1}*

SPM 4.2 Response options for adaptation

Adaptation options exist in all sectors, but their context for implementation and potential to reduce climate-related risks differs across sectors and regions. Some adaptation responses involve significant co-benefits, synergies and trade-offs. Increasing climate change will increase challenges for many adaptation options. *{4.2}*

Adaptation experience is accumulating across regions in the public and private sectors and within communities. There is increasing recognition of the value of social (including local and indigenous), institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Adaptation is becoming embedded in some planning processes, with more limited implementation of responses (*high confidence*). *{1.6, 4.2, 4.4.2.1}*

The need for adaptation along with associated challenges is expected to increase with climate change (*very high confidence*). Adaptation options exist in all sectors and regions, with diverse potential and approaches depending on their context in vulnerability reduction, disaster risk management or proactive adaptation planning (Table SPM.3). Effective strategies and actions consider the potential for co-benefits and opportunities within wider strategic goals and development plans. *{4.2}*

Table SPM.3 | Approaches for managing the risks of climate change through adaptation. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Examples are presented in no specific order and can be relevant to more than one category. *{Table 4.2}*

Overlapping Approaches	Category	Examples
Vulnerability & Exposure Reduction through development, planning & practices including many low-regrets measures	Human development	Improved access to education, nutrition, health facilities, energy, safe housing & settlement structures, & social support structures; Reduced gender inequality & marginalization in other forms.
	Poverty alleviation	Improved access to & control of local resources; Land tenure; Disaster risk reduction; Social safety nets & social protection; Insurance schemes.
	Livelihood security	Income, asset & livelihood diversification; Improved infrastructure; Access to technology & decision-making fora; Increased decision-making power; Changed cropping, livestock & aquaculture practices; Reliance on social networks.
	Disaster risk management	Early warning systems; Hazard & vulnerability mapping; Diversifying water resources; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements.
	Ecosystem management	Maintaining wetlands & urban green spaces; Coastal afforestation; Watershed & reservoir management; Reduction of other stressors on ecosystems & of habitat fragmentation; Maintenance of genetic diversity; Manipulation of disturbance regimes; Community-based natural resource management.
	Spatial or land-use planning	Provisioning of adequate housing, infrastructure & services; Managing development in flood prone & other high risk areas; Urban planning & upgrading programs; Land zoning laws; Easements; Protected areas.
Adaptation including incremental & transformational adjustments	Structural/physical	***Engineered & built-environment options***: Sea walls & coastal protection structures; Flood levees; Water storage; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements; Floating houses; Power plant & electricity grid adjustments.
		Technological options: New crop & animal varieties; Indigenous, traditional & local knowledge, technologies & methods; Efficient irrigation; Water-saving technologies; Desalinisation; Conservation agriculture; Food storage & preservation facilities; Hazard & vulnerability mapping & monitoring; Early warning systems; Building insulation; Mechanical & passive cooling; Technology development, transfer & diffusion.
		Ecosystem-based options: Ecological restoration; Soil conservation; Afforestation & reforestation; Mangrove conservation & replanting; Green infrastructure (e.g., shade trees, green roofs); Controlling overfishing; Fisheries co-management; Assisted species migration & dispersal; Ecological corridors; Seed banks, gene banks & other *ex situ* conservation; Community-based natural resource management.
		Services: Social safety nets & social protection; Food banks & distribution of food surplus; Municipal services including water & sanitation; Vaccination programs; Essential public health services; Enhanced emergency medical services.
	Institutional	***Economic options***: Financial incentives; Insurance; Catastrophe bonds; Payments for ecosystem services; Pricing water to encourage universal provision and careful use; Microfinance; Disaster contingency funds; Cash transfers; Public-private partnerships.
		Laws & regulations: Land zoning laws; Building standards & practices; Easements; Water regulations & agreements; Laws to support disaster risk reduction; Laws to encourage insurance purchasing; Defined property rights & land tenure security; Protected areas; Fishing quotas; Patent pools & technology transfer.
		National & government policies & programs: National & regional adaptation plans including mainstreaming; Sub-national & local adaptation plans; Economic diversification; Urban upgrading programs; Municipal water management programs; Disaster planning & preparedness; Integrated water resource management; Integrated coastal zone management; Ecosystem-based management; Community-based adaptation.
	Social	***Educational options***: Awareness raising & integrating into education; Gender equity in education; Extension services; Sharing indigenous, traditional & local knowledge; Participatory action research & social learning; Knowledge-sharing & learning platforms.
		Informational options: Hazard & vulnerability mapping; Early warning & response systems; Systematic monitoring & remote sensing; Climate services; Use of indigenous climate observations; Participatory scenario development; Integrated assessments.
		Behavioural options: Household preparation & evacuation planning; Migration; Soil & water conservation; Storm drain clearance; Livelihood diversification; Changed cropping, livestock & aquaculture practices; Reliance on social networks.
Transformation	Spheres of change	***Practical***: Social & technical innovations, behavioural shifts, or institutional & managerial changes that produce substantial shifts in outcomes.
		Political: Political, social, cultural & ecological decisions & actions consistent with reducing vulnerability & risk & supporting adaptation, mitigation & sustainable development.
		Personal: Individual & collective assumptions, beliefs, values & worldviews influencing climate-change responses.

SPM

SPM 4.3 Response options for mitigation

Mitigation options are available in every major sector. Mitigation can be more cost-effective if using an integrated approach that combines measures to reduce energy use and the greenhouse gas intensity of end-use sectors, decarbonize energy supply, reduce net emissions and enhance carbon sinks in land-based sectors. *{4.3}*

Well-designed systemic and cross-sectoral mitigation strategies are more cost-effective in cutting emissions than a focus on individual technologies and sectors, with efforts in one sector affecting the need for mitigation in others (*medium confidence*). Mitigation measures intersect with other societal goals, creating the possibility of co-benefits or adverse side effects. These intersections, if well-managed, can strengthen the basis for undertaking climate action. *{4.3}*

Emissions ranges for baseline scenarios and mitigation scenarios that limit CO_2-equivalent concentrations to low levels (about 450 ppm CO_2-eq, *likely* to limit warming to 2°C above pre-industrial levels) are shown for different sectors and gases in Figure SPM.14. Key measures to achieve such mitigation goals include decarbonizing (i.e., reducing the carbon intensity of) electricity generation (*medium evidence, high agreement*) as well as efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development (*robust evidence, high agreement*). In scenarios reaching 450 ppm CO_2-eq concentrations by 2100, global CO_2 emissions from the energy supply sector are projected to decline over the next decade and are characterized by reductions of 90% or more below 2010 levels between 2040 and 2070. In the majority of low-concentration stabilization scenarios (about 450 to about 500 ppm CO_2-eq, at least *about as likely as not* to limit warming to 2°C above pre-industrial levels), the share of low-carbon electricity supply (comprising renewable energy (RE), nuclear and carbon dioxide capture and storage (CCS) including bioenergy with carbon dioxide capture and storage (BECCS)) increases from the current share of approximately 30% to more than 80% by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100. *{4.3}*

Direct CO_2 emissions by major sectors, and non-CO_2 emissions, for baseline and mitigation scenarios

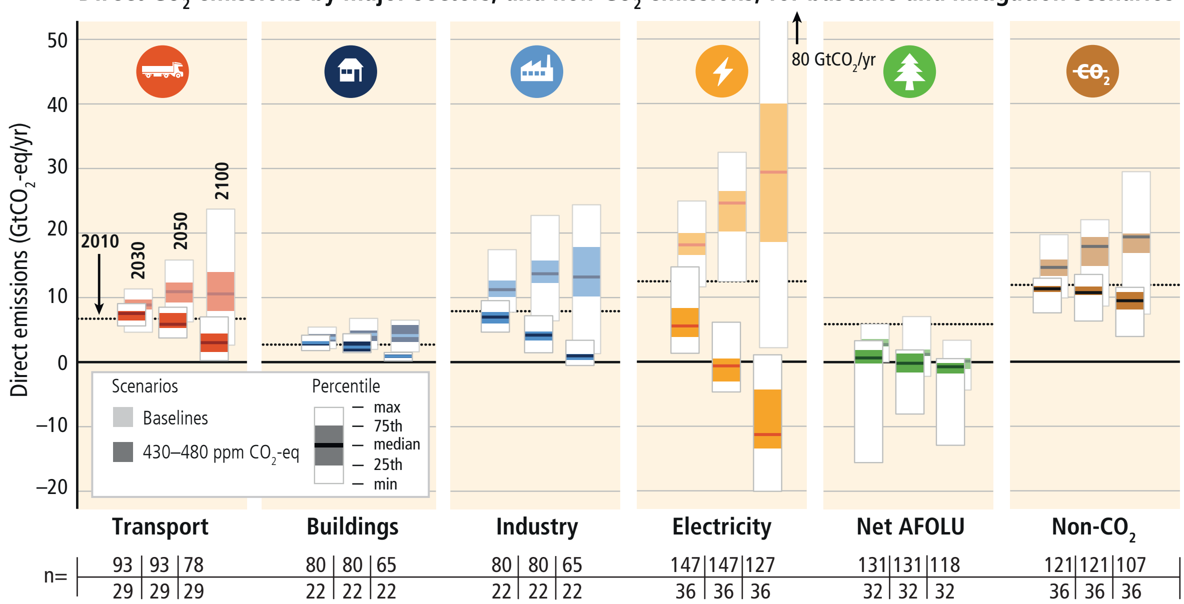


Figure SPM.14 | Carbon dioxide (CO_2) emissions by sector and total non-CO_2 greenhouse gases (Kyoto gases) across sectors in baseline (faded bars) and mitigation scenarios (solid colour bars) that reach about 450 (430 to 480) ppm CO_2-eq concentrations in 2100 (*likely* to limit warming to 2°C above pre-industrial levels). Mitigation in the end-use sectors leads also to indirect emissions reductions in the upstream energy supply sector. Direct emissions of the end-use sectors thus do not include the emission reduction potential at the supply-side due to, for example, reduced electricity demand. The numbers at the bottom of the graphs refer to the number of scenarios included in the range (upper row: baseline scenarios; lower row: mitigation scenarios), which differs across sectors and time due to different sectoral resolution and time horizon of models. Emissions ranges for mitigation scenarios include the full portfolio of mitigation options; many models cannot reach 450 ppm CO_2-eq concentration by 2100 in the absence of carbon dioxide capture and storage (CCS). Negative emissions in the electricity sector are due to the application of bioenergy with carbon dioxide capture and storage (BECCS). 'Net' agriculture, forestry and other land use (AFOLU) emissions consider afforestation, reforestation as well as deforestation activities. *{4.3, Figure 4.1}*

Near-term reductions in energy demand are an important element of cost-effective mitigation strategies, provide more flexibility for reducing carbon intensity in the energy supply sector, hedge against related supply-side risks, avoid lock-in to carbon-intensive infrastructures, and are associated with important co-benefits. The most cost-effective mitigation options in forestry are afforestation, sustainable forest management and reducing deforestation, with large differences in their relative importance across regions; and in agriculture, cropland management, grazing land management and restoration of organic soils (*medium evidence, high agreement*). *{4.3, Figures 4.1, 4.2, Table 4.3}*

Behaviour, lifestyle and culture have a considerable influence on energy use and associated emissions, with high mitigation potential in some sectors, in particular when complementing technological and structural change (*medium evidence, medium agreement*). Emissions can be substantially lowered through changes in consumption patterns, adoption of energy savings measures, dietary change and reduction in food wastes. *{4.1, 4.3}*

SPM 4.4 Policy approaches for adaptation and mitigation, technology and finance

Effective adaptation and mitigation responses will depend on policies and measures across multiple scales: international, regional, national and sub-national. Policies across all scales supporting technology development, diffusion and transfer, as well as finance for responses to climate change, can complement and enhance the effectiveness of policies that directly promote adaptation and mitigation. *{4.4}*

International cooperation is critical for effective mitigation, even though mitigation can also have local co-benefits. Adaptation focuses primarily on local to national scale outcomes, but its effectiveness can be enhanced through coordination across governance scales, including international cooperation: *{3.1, 4.4.1}*

- The United Nations Framework Convention on Climate Change (UNFCCC) is the main multilateral forum focused on addressing climate change, with nearly universal participation. Other institutions organized at different levels of governance have resulted in diversifying international climate change cooperation. *{4.4.1}*

- The Kyoto Protocol offers lessons towards achieving the ultimate objective of the UNFCCC, particularly with respect to participation, implementation, flexibility mechanisms and environmental effectiveness (*medium evidence, low agreement*). *{4.4.1}*

- Policy linkages among regional, national and sub-national climate policies offer potential climate change mitigation benefits (*medium evidence, medium agreement*). Potential advantages include lower mitigation costs, decreased emission leakage and increased market liquidity. *{4.4.1}*

- International cooperation for supporting adaptation planning and implementation has received less attention historically than mitigation but is increasing and has assisted in the creation of adaptation strategies, plans and actions at the national, sub-national and local level (*high confidence*). *{4.4.1}*

There has been a considerable increase in national and sub-national plans and strategies on both adaptation and mitigation since the AR4, with an increased focus on policies designed to integrate multiple objectives, increase co-benefits and reduce adverse side effects (*high confidence*): *{4.4.2.1, 4.4.2.2}*

- National governments play key roles in adaptation planning and implementation (*robust evidence, high agreement*) through coordinating actions and providing frameworks and support. While local government and the private sector have different functions, which vary regionally, they are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households and civil society and in managing risk information and financing (*medium evidence, high agreement*). *{4.4.2.1}*

- Institutional dimensions of adaptation governance, including the integration of adaptation into planning and decision-making, play a key role in promoting the transition from planning to implementation of adaptation (*robust evidence,* *high agreement*). Examples of institutional approaches to adaptation involving multiple actors include economic options (e.g., insurance, public-private partnerships), laws and regulations (e.g., land-zoning laws) and national and government policies and programmes (e.g., economic diversification). *{4.2, 4.4.2.1, Table SPM.3}*

- In principle, mechanisms that set a carbon price, including cap and trade systems and carbon taxes, can achieve mitigation in a cost-effective way but have been implemented with diverse effects due in part to national circumstances as well as policy design. The short-run effects of cap and trade systems have been limited as a result of loose caps or caps that have not proved to be constraining (*limited evidence, medium agreement*). In some countries, tax-based policies specifically aimed at reducing GHG emissions—alongside technology and other policies—have helped to weaken the link between GHG emissions and GDP (*high confidence*). In addition, in a large group of countries, fuel taxes (although not necessarily designed for the purpose of mitigation) have had effects that are akin to sectoral carbon taxes. *{4.4.2.2}*

- Regulatory approaches and information measures are widely used and are often environmentally effective (*medium evidence, medium agreement*). Examples of regulatory approaches include energy efficiency standards; examples of information programmes include labelling programmes that can help consumers make better-informed decisions. *{4.4.2.2}*

- Sector-specific mitigation policies have been more widely used than economy-wide policies (*medium evidence, high agreement*). Sector-specific policies may be better suited to address sector-specific barriers or market failures and may be bundled in packages of complementary policies. Although theoretically more cost-effective, administrative and political barriers may make economy-wide policies harder to implement. Interactions between or among mitigation policies may be synergistic or may have no additive effect on reducing emissions. *{4.4.2.2}*

- Economic instruments in the form of subsidies may be applied across sectors, and include a variety of policy designs, such as tax rebates or exemptions, grants, loans and credit lines. An increasing number and variety of renewable energy (RE) policies including subsidies—motivated by many factors—have driven escalated growth of RE technologies in recent years. At the same time, reducing subsidies for GHG-related activities in various sectors can achieve emission reductions, depending on the social and economic context (*high confidence*). *{4.4.2.2}*

Co-benefits and adverse side effects of mitigation could affect achievement of other objectives such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods and equitable sustainable development. The potential for co-benefits for energy end-use measures outweighs the potential for adverse side effects whereas the evidence suggests this may not be the case for all energy supply and agriculture, forestry and other land use (AFOLU) measures. Some mitigation policies raise the prices for some energy services and could hamper the ability of societies to expand access to modern energy services to underserved populations (*low confidence*). These potential adverse side effects on energy access can be avoided with the adoption of complementary policies such as income tax rebates or other benefit transfer mechanisms (*medium confidence*). Whether or not side effects materialize, and to what extent side effects materialize, will be case- and site-specific, and depend on local circumstances and the scale, scope and pace of implementation. Many co-benefits and adverse side effects have not been well-quantified. *{4.3, 4.4.2.2, Box 3.4}*

Technology policy (development, diffusion and transfer) complements other mitigation policies across all scales, from international to sub-national; many adaptation efforts also critically rely on diffusion and transfer of technologies and management practices (*high confidence*). Policies exist to address market failures in R&D, but the effective use of technologies can also depend on capacities to adopt technologies appropriate to local circumstances. *{4.4.3}*

Substantial reductions in emissions would require large changes in investment patterns (*high confidence*). For mitigation scenarios that stabilize concentrations (without overshoot) in the range of 430 to 530 ppm CO_2-eq by 2100[19], annual investments in low carbon electricity supply and energy efficiency in key sectors (transport, industry and buildings) are projected in the scenarios to rise by several hundred billion dollars per year before 2030. Within appropriate enabling environments, the private sector, along with the public sector, can play important roles in financing mitigation and adaptation (*medium evidence, high agreement*). *{4.4.4}*

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[19] This range comprises scenarios that reach 430 to 480 ppm CO_2-eq by 2100 (*likely* to limit warming to 2°C above pre-industrial levels) and scenarios that reach 480 to 530 ppm CO_2-eq by 2100 (without overshoot: *more likely than* not to limit warming to 2°C above pre-industrial levels).

Financial resources for adaptation have become available more slowly than for mitigation in both developed and developing countries. Limited evidence indicates that there is a gap between global adaptation needs and the funds available for adaptation (*medium confidence*). There is a need for better assessment of global adaptation costs, funding and investment. Potential synergies between international finance for disaster risk management and adaptation have not yet been fully realized (*high confidence*). *{4.4.4}*

SPM 4.5 Trade-offs, synergies and interactions with sustainable development

Climate change is a threat to sustainable development. Nonetheless, there are many opportunities to link mitigation, adaptation and the pursuit of other societal objectives through integrated responses (*high confidence*). Successful implementation relies on relevant tools, suitable governance structures and enhanced capacity to respond (*medium confidence*). *{3.5, 4.5}*

Climate change exacerbates other threats to social and natural systems, placing additional burdens particularly on the poor (*high confidence*). Aligning climate policy with sustainable development requires attention to both adaptation and mitigation (*high confidence*). Delaying global mitigation actions may reduce options for climate-resilient pathways and adaptation in the future. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, encompassing connections among human health, water, energy, land use and biodiversity (*medium evidence, high agreement*). *{3.1, 3.5, 4.5}*

Strategies and actions can be pursued now which will move towards climate-resilient pathways for sustainable development, while at the same time helping to improve livelihoods, social and economic well-being and effective environmental management. In some cases, economic diversification can be an important element of such strategies. The effectiveness of integrated responses can be enhanced by relevant tools, suitable governance structures and adequate institutional and human capacity (*medium confidence*). Integrated responses are especially relevant to energy planning and implementation; interactions among water, food, energy and biological carbon sequestration; and urban planning, which provides substantial opportunities for enhanced resilience, reduced emissions and more sustainable development (*medium confidence*). *{3.5, 4.4, 4.5}*

Climate Change 2014
Synthesis Report

Introduction

Introduction

The Synthesis Report (SYR) of the IPCC Fifth Assessment Report (AR5) provides an overview of the state of knowledge concerning the science of climate change, emphasizing new results since the publication of the IPCC Fourth Assessment Report (AR4) in 2007. The SYR synthesizes the main findings of the AR5 based on contributions from Working Group I (*The Physical Science Basis*), Working Group II (*Impacts, Adaptation and Vulnerability*) and Working Group III (*Mitigation of Climate Change*), plus two additional IPCC reports (*Special Report on Renewable Energy Sources and Climate Change Mitigation* and *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*).

The AR5 SYR longer report is divided into four topics. Topic 1 (Observed Changes and their Causes) focuses on observational evidence for a changing climate, the impacts caused by this change and the human contributions to it. Topic 2 (Future Climate Changes, Risks and Impacts) assesses projections of future climate change and the resultant projected impacts and risks. Topic 3 (Future Pathways for Adaptation, Mitigation and Sustainable Development) considers adaptation and mitigation as complementary strategies for reducing and managing the risks of climate change. Topic 4 (Adaptation and Mitigation) describes individual adaptation and mitigation options and policy approaches. It also addresses integrated responses that link mitigation and adaptation with other societal objectives.

The challenges of understanding and managing risks and uncertainties are important themes in this report. See Box 1 (Risk and the Management of an Uncertain Future) and Box 2 (Communicating the Degree of Certainty in Assessment Findings).

This report includes information relevant to Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC).

Box Introduction.1 | Risk and the Management of an Uncertain Future

Climate change exposes people, societies, economic sectors and ecosystems to risk. Risk is the potential for consequences when something of value is at stake and the outcome is uncertain, recognizing the diversity of values. *{WGII SPM Background Box SPM.2, WGIII 2.1, SYR Glossary}*

Risks from climate change impacts arise from the interaction between hazard (triggered by an event or trend related to climate change), vulnerability (susceptibility to harm) and exposure (people, assets or ecosystems at risk). Hazards include processes that range from brief events, such as severe storms, to slow trends, such as multi-decade droughts or multi-century sea level rise. Vulnerability and exposure are both sensitive to a wide range of social and economic processes, with possible increases or decreases depending on development pathways. Risks and co-benefits also arise from policies that aim to mitigate climate change or to adapt to it. (1.5)

Risk is often represented as the probability of occurrence of hazardous events or trends multiplied by the magnitude of the consequences if these events occur. Therefore, high risk can result not only from high probability outcomes but also from low probability outcomes with very severe consequences. This makes it important to assess the full range of possible outcomes, from low probability tail outcomes to very likely outcomes. For example, it is unlikely that global mean sea level will rise by more than one meter in this century, but the consequence of a greater rise could be so severe that this possibility becomes a significant part of risk assessment. Similarly, low confidence but high consequence outcomes are also policy relevant; for instance the possibility that the response of Amazon forest could substantially amplify climate change merits consideration despite our currently imperfect ability to project the outcome. (2.4, Table 2.3) *{WGI Table 13.5, WGII SPM A-3, 4.4, Box 4-3, WGIII Box 3-9, SYR Glossary}*

Risk can be understood either qualitatively or quantitatively. It can be reduced and managed using a wide range of formal or informal tools and approaches that are often iterative. Useful approaches for managing risk do not necessarily require that risk levels can be accurately quantified. Approaches recognizing diverse qualitative values, goals and priorities, based on ethical, psychological, cultural or social factors, could increase the effectiveness of risk management. *{WGII 1.1.2, 2.4, 2.5, 19.3, WGIII 2.4, 2.5, 3.4}*

Box Introduction.2 | Communicating the Degree of Certainty in Assessment Findings

An integral feature of IPCC reports is the communication of the strength of and uncertainties in scientific understanding underlying assessment findings. Uncertainty can result from a wide range of sources. Uncertainties in the past and present are the result of limitations of available measurements, especially for rare events, and the challenges of evaluating causation in complex or multi-component processes that can span physical, biological and human systems. For the future, climate change involves changing likelihoods of diverse outcomes. Many processes and mechanisms are well understood, but others are not. Complex interactions among multiple climatic and non-climatic influences changing over time lead to persistent uncertainties, which in turn lead to the possibility of surprises. Compared to past IPCC reports, the AR5 assesses a substantially larger knowledge base of scientific, technical and socio-economic literature. *{WGI 1.4, WGII SPM A-3, 1.1.2, WGIII 2.3}*

The IPCC Guidance Note on Uncertainty[a] defines a common approach to evaluating and communicating the degree of certainty in findings of the assessment process. Each finding is grounded in an evaluation of underlying evidence and agreement. In many cases, a synthesis of evidence and agreement supports an assignment of confidence, especially for findings with stronger agreement and multiple independent lines of evidence. The degree of certainty in each key finding of the assessment is based on the type, amount, quality and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. The summary terms for evidence are: limited, medium or robust. For agreement, they are low, medium or high. Levels of confidence include five qualifiers: very low, low, medium, high and very high, and are typeset in italics, e.g., *medium confidence*. The likelihood, or probability, of some well-defined outcome having occurred or occurring in the future can be described quantitatively through the following terms: virtually certain, 99–100% probability; extremely likely, 95–100%; very likely, 90–100%; likely, 66–100%; more likely than not, >50–100%; about as likely as not, 33–66%; unlikely, 0–33%; very unlikely, 0–10%; extremely unlikely, 0–5%; and exceptionally unlikely, 0–1%. Additional terms (extremely likely, 95–100%; more likely than not, >50–100%; more unlikely than likely, 0–<50%; and extremely unlikely, 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high confidence*. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers. *{WGI SPM B, WGII Background Box SPM.3, WGIII 2.1}*

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[a] Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe and F.W. Zwiers, 2010: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 4 pp.

1 Observed Changes and their Causes

Topic 1: Observed Changes and their Causes

Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems.

Topic 1 focuses on observational evidence of a changing climate, the impacts caused by this change and the human contributions to it. It discusses observed changes in climate (1.1) and external influences on climate (forcings), differentiating those forcings that are of anthropogenic origin, and their contributions by economic sectors and greenhouse gases (GHGs) (1.2). Section 1.3 attributes observed climate change to its causes and attributes impacts on human and natural systems to climate change, determining the degree to which those impacts can be attributed to climate change. The changing probability of extreme events and their causes are discussed in Section 1.4, followed by an account of exposure and vulnerability within a risk context (1.5) and a section on adaptation and mitigation experience (1.6).

1.1 Observed changes in the climate system

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen.

1.1.1 Atmosphere

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was *very likely* the warmest 30-year period of the last 800 years in the Northern Hemisphere, where such assessment is possible (*high confidence*) and *likely* the warmest 30-year period of the last 1400 years (*medium confidence*). *{WGI 2.4.3, 5.3.5}*

The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] °C[20] over the period 1880 to 2012, for which multiple independently produced datasets exist. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85] °C, based on the single longest dataset available. For the longest period when calculation of regional trends is sufficiently complete (1901 to 2012), almost the entire globe has experienced surface warming (Figure 1.1). *{WGI SPM B.1, 2.4.3}*

In addition to robust multi-decadal warming, the globally averaged surface temperature exhibits substantial decadal and interannual variability (Figure 1.1). Due to this natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over the past 15 years (1998–2012; 0.05 [–0.05 to 0.15] °C per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] °C per decade; see Box 1.1). *{WGI SPM B.1, 2.4.3}*

Based on multiple independent analyses of measurements, it is *virtually certain* that globally the troposphere has warmed and the lower stratosphere has cooled since the mid-20th century. There is *medium confidence* in the rate of change and its vertical structure in the Northern Hemisphere extratropical troposphere. *{WGI SPM B.1, 2.4.4}*

Confidence in precipitation change averaged over global land areas since 1901 is *low* prior to 1951 and *medium* afterwards. Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has *likely* increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudes area-averaged long-term positive or negative trends have *low confidence* (Figure 1.1). *{WGI SPM B.1, Figure SPM.2, 2.5.1}*

1.1.2 Ocean

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*) with only about 1% stored in the atmosphere (Figure 1.2). On a global scale, the ocean warming is largest near the surface, and the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010. It is *virtually certain* that the upper ocean (0–700 m) warmed from 1971 to 2010, and it *likely* warmed between the 1870s and 1971. It is *likely* that the ocean warmed from 700 to 2000 m from 1957 to 2009 and from 3000 m to the bottom for the period 1992 to 2005 (Figure 1.2). *{WGI SPM B.2, 3.2, Box 3.1}*

It is *very likely* that regions of high surface salinity, where evaporation dominates, have become more saline, while regions of low salinity, where precipitation dominates, have become fresher since the 1950s. These regional trends in ocean salinity provide indirect evidence for changes in evaporation and precipitation over the oceans and thus for changes in the global water cycle (*medium confidence*). There is no observational evidence of a long-term trend in the Atlantic Meridional Overturning Circulation (AMOC). *{WGI SPM B.2, 2.5, 3.3, 3.4.3, 3.5, 3.6.3}*

[20] Ranges in square brackets indicate a 90% uncertainty interval unless otherwise stated. The 90% uncertainty interval is expected to have a 90% likelihood of covering the value that is being estimated. Uncertainty intervals are not necessarily symmetric about the corresponding best estimate. A best estimate of that value is also given where available.

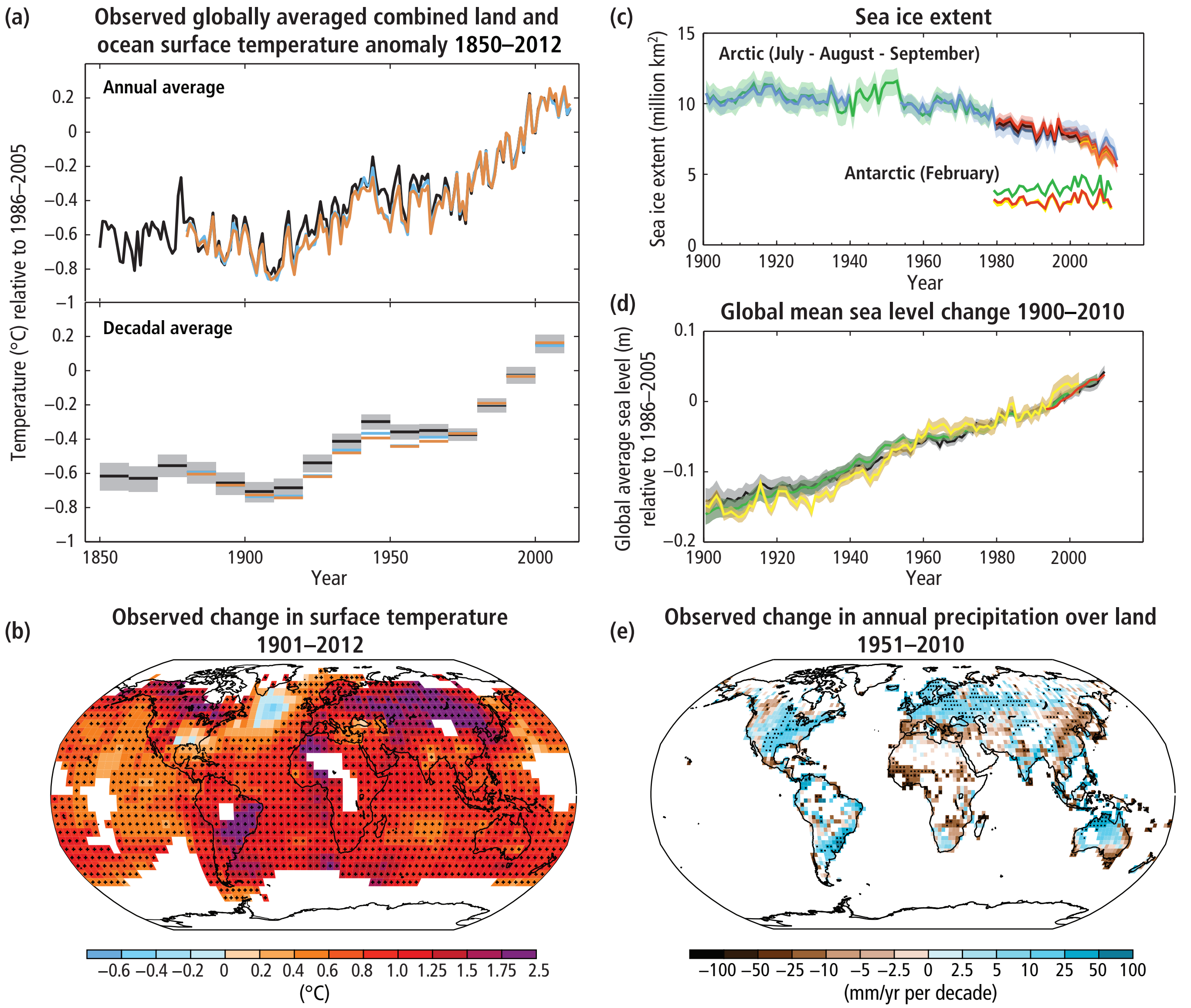


Figure 1.1 | Multiple observed indicators of a changing global climate system. **(a)** Observed globally averaged combined land and ocean surface temperature anomalies (relative to the mean of 1986 to 2005 period, as annual and decadal averages) with an estimate of decadal mean uncertainty included for one data set (grey shading). *{WGI Figure SPM.1, Figure 2.20; a listing of data sets and further technical details are given in the WGI Technical Summary Supplementary Material WGI TS.SM.1.1}* **(b)** Map of the observed surface temperature change, from 1901 to 2012, derived from temperature trends determined by linear regression from one data set (orange line in Panel a). Trends have been calculated where data availability permitted a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period), other areas are white. Grid boxes where the trend is significant, at the 10% level, are indicated by a + sign. *{WGI Figure SPM.1, Figure 2.21, Figure TS.2; a listing of data sets and further technical details are given in the WGI Technical Summary Supplementary Material WGI TS.SM.1.2}* **(c)** Arctic (July to September average) and Antarctic (February) sea ice extent. *{WGI Figure SPM.3, Figure 4.3, Figure 4.SM.2; a listing of data sets and further technical details are given in the WGI Technical Summary Supplementary Material WGI TS.SM.3.2}*. **(d)** Global mean sea level relative to the 1986–2005 mean of the longest running data set, and with all data sets aligned to have the same value in 1993, the first year of satellite altimetry data. All time series (coloured lines indicating different data sets) show annual values, and where assessed, uncertainties are indicated by coloured shading. *{WGI Figure SPM.3, Figure 3.13; a listing of data sets and further technical details are given in the WGI Technical Summary Supplementary Material WGI TS.SM.3.4}*. **(e)** Map of observed precipitation change, from 1951 to 2010; trends in annual accumulation calculated using the same criteria as in Panel b. *{WGI Figure SPM.2, TS TFE.1, Figure 2, Figure 2.29. A listing of data sets and further technical details are given in the WGI Technical Summary Supplementary Material WGI TS.SM.2.1}*

Since the beginning of the industrial era, oceanic uptake of CO_2 has resulted in acidification of the ocean; the pH of ocean surface water has decreased by 0.1 (*high confidence*), corresponding to a 26% increase in acidity, measured as hydrogen ion concentration. There is *medium confidence* that, in parallel to warming, oxygen concentrations have decreased in coastal waters and in the open ocean thermocline in many ocean regions since the 1960s, with a *likely* expansion of tropical oxygen minimum zones in recent decades. *{WGI SPM B.5, TS2.8.5, 3.8.1, 3.8.2, 3.8.3, 3.8.5, Figure 3.20}*

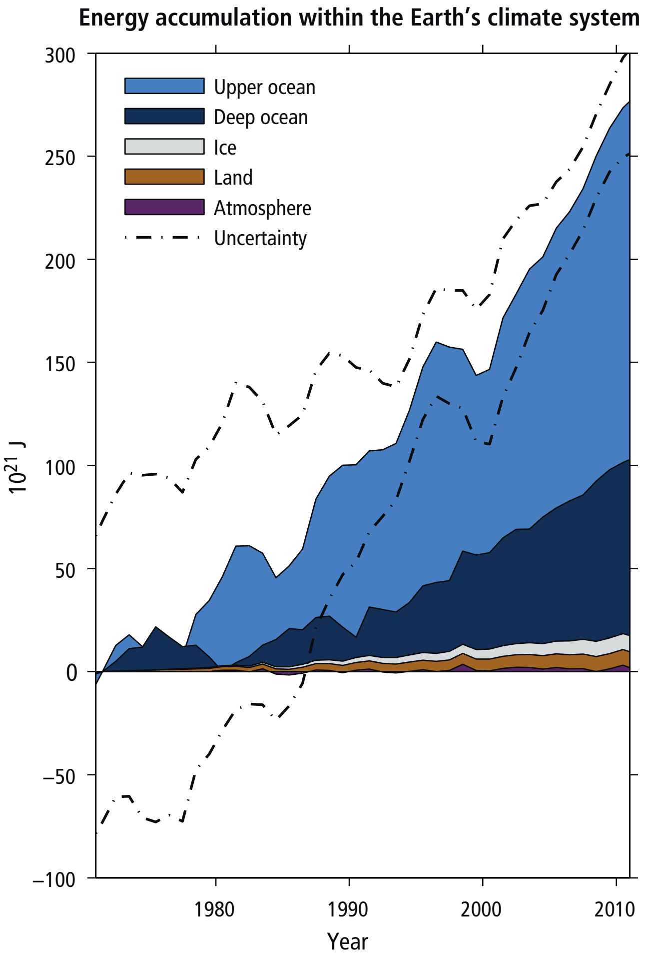


Figure 1.2 | Energy accumulation within the Earth's climate system. Estimates are in 10^{21} J, and are given relative to 1971 and from 1971 to 2010, unless otherwise indicated. Components included are upper ocean (above 700 m), deep ocean (below 700 m; including below 2000 m estimates starting from 1992), ice melt (for glaciers and ice caps, Greenland and Antarctic ice sheet estimates starting from 1992, and Arctic sea ice estimate from 1979 to 2008), continental (land) warming, and atmospheric warming (estimate starting from 1979). Uncertainty is estimated as error from all five components at 90% confidence intervals. *{WGI Box 3.1, Figure 1}*

1.1.3 Cryosphere

Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass (*high confidence*). Glaciers have continued to shrink almost worldwide (*high confidence*). Northern Hemisphere spring snow cover has continued to decrease in extent (*high confidence*). There is *high confidence* that there are strong regional differences in the trend in Antarctic sea ice extent, with a *very likely* increase in total extent. *{WGI SPM B.3, 4.2–4.7}*

Glaciers have lost mass and contributed to sea level rise throughout the 20th century. The rate of ice mass loss from the Greenland ice sheet has *very likely* substantially increased over the period 1992 to 2011, resulting in a larger mass loss over 2002 to 2011 than over 1992 to 2011. The rate of ice mass loss from the Antarctic ice sheet, mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica, is also *likely* larger over 2002 to 2011. *{WGI SPM B.3, SPM B.4, 4.3.3, 4.4.2, 4.4.3}*

The annual mean Arctic sea ice extent decreased over the period 1979 (when satellite observations commenced) to 2012. The rate of decrease was *very likely* in the range 3.5 to 4.1% per decade. Arctic sea ice extent has decreased in every season and in every successive decade since 1979, with the most rapid decrease in decadal mean extent in summer (*high confidence*). For the summer sea ice minimum, the decrease was *very likely* in the range of 9.4 to 13.6% per decade (range of 0.73 to 1.07 million km^2 per decade) (see Figure 1.1). It is *very likely* that the annual mean Antarctic sea ice extent increased in the range of 1.2 to 1.8% per decade (range of 0.13 to 0.20 million km^2 per decade) between 1979 and 2012. However, there is *high confidence* that there are strong regional differences in Antarctica, with extent increasing in some regions and decreasing in others. *{WGI SPM B.5, 4.2.2, 4.2.3}*

There is *very high confidence* that the extent of Northern Hemisphere snow cover has decreased since the mid-20th century by 1.6 [0.8 to 2.4] % per decade for March and April, and 11.7% per decade for June, over the 1967 to 2012 period. There is *high confidence* that permafrost temperatures have increased in most regions of the Northern Hemisphere since the early 1980s, with reductions in thickness and areal extent in some regions. The increase in permafrost temperatures has occurred in response to increased surface temperature and changing snow cover. *{WGI SPM B.3, 4.5, 4.7.2}*

1.1.4 Sea level

Over the period 1901–2010, global mean sea level rose by 0.19 [0.17 to 0.21] m (Figure 1.1). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). *{WGI SPM B.4, 3.7.2, 5.6.3, 13.2}*

It is *very likely* that the mean rate of global averaged sea level rise was 1.7 [1.5 to 1.9] mm/yr between 1901 and 2010 and 3.2 [2.8 to 3.6] mm/yr between 1993 and 2010. Tide gauge and satellite altimeter data are consistent regarding the higher rate during the latter period. It is *likely* that similarly high rates occurred between 1920 and 1950. *{WGI SPM B.4, 3.7, 13.2}*

Since the early 1970s, glacier mass loss and ocean thermal expansion from warming together explain about 75% of the observed global mean sea level rise (*high confidence*). Over the period 1993–2010, global mean sea level rise is, with *high confidence*, consistent with the sum of the observed contributions from ocean thermal expansion, due to warming, from changes in glaciers, the Greenland ice sheet, the Antarctic ice sheet and land water storage. *{WGI SPM B.4, 13.3.6}*

Rates of sea level rise over broad regions can be several times larger or smaller than the global mean sea level rise for periods of several decades, due to fluctuations in ocean circulation. Since 1993, the regional rates for the Western Pacific are up to three times larger than the global mean, while those for much of the Eastern Pacific are near zero or negative. *{WGI 3.7.3, FAQ 13.1}*

There is *very high confidence* that maximum global mean sea level during the last interglacial period (129,000 to 116,000 years ago) was, for several thousand years, at least 5 m higher than present and

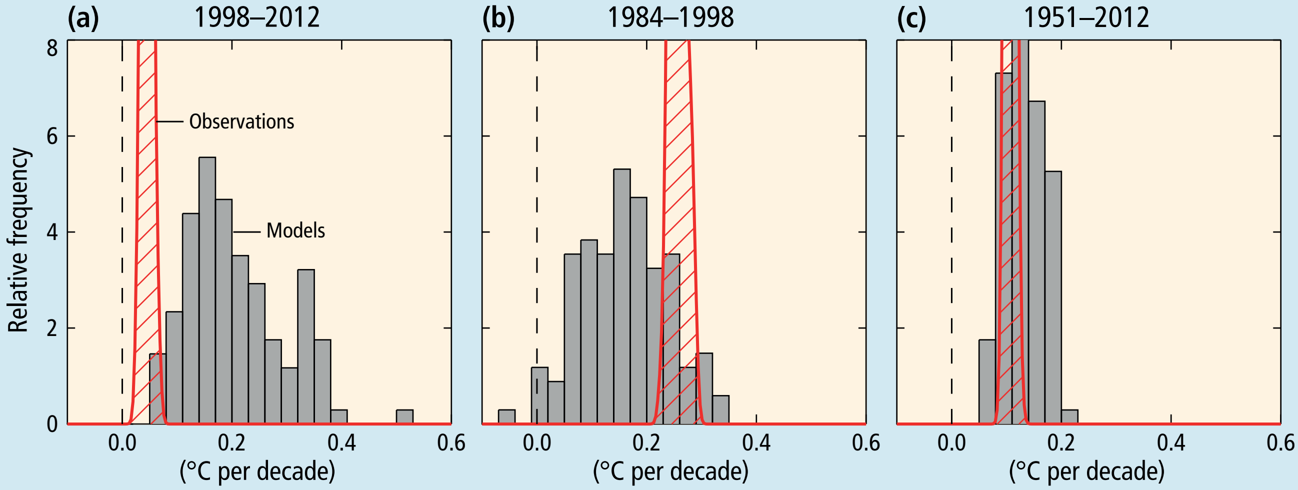
Box 1.1 | Recent Temperature Trends and their Implications

The observed reduction in surface warming trend over the period 1998 to 2012 as compared to the period 1951 to 2012, is due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from natural internal variability, which includes a possible redistribution of heat within the ocean (*medium confidence*). The rate of warming of the observed global mean surface temperature over the period from 1998 to 2012 is estimated to be around one-third to one-half of the trend over the period from 1951 to 2012 (Box 1.1, Figures 1a and 1c). Even with this reduction in surface warming trend, the climate system has *very likely* continued to accumulate heat since 1998 (Figure 1.2) and sea level has continued to rise (Figure 1.1). *{WGI SPM D.1, Box 9.2}*

The radiative forcing of the climate system has continued to increase during the 2000s, as has its largest contributor, the atmospheric concentration of CO_2. However, the radiative forcing has been increasing at a lower rate over the period from 1998 to 2011, compared to 1984 to 1998 or 1951 to 2011, due to cooling effects from volcanic eruptions and the cooling phase of the solar cycle over the period from 2000 to 2009. There is, however, *low confidence* in quantifying the role of the forcing trend in causing the reduction in the rate of surface warming. *{WGI 8.5.2, Box 9.2}*

For the period from 1998 to 2012, 111 of the 114 available climate-model simulations show a surface warming trend larger than the observations (Box 1.1, Figure 1a). There is *medium confidence* that this difference between models and observations is to a substantial degree caused by natural internal climate variability, which sometimes enhances and sometimes counteracts the long-term externally forced warming trend (compare Box 1.1, Figures 1a and 1b; during the period from 1984 to 1998, most model simulations show a smaller warming trend than observed). Natural internal variability thus diminishes the relevance of short trends for long-term climate change. The difference between models and observations may also contain contributions from inadequacies in the solar, volcanic and aerosol forcings used by the models and, in some models, from an overestimate of the response to increasing greenhouse gas and other anthropogenic forcing (the latter dominated by the effects of aerosols). *{WGI 2.4.3, Box 9.2, 9.4.1, 10.3.1.1}*

For the longer period from 1951 to 2012, simulated surface warming trends are consistent with the observed trend (*very high confidence*) (Box 1.1, Figure 1c). Furthermore, the independent estimates of radiative forcing, of surface warming and of observed heat storage (the latter available since 1970) combine to give a heat budget for the Earth that is consistent with the assessed *likely* range of equilibrium climate sensitivity (1.5–4.5 °C)[21]. The record of observed climate change has thus allowed characterization of the basic properties of the climate system that have implications for future warming, including the equilibrium climate sensitivity and the transient climate response (see Topic 2). *{WGI Box 9.2, 10.8.1, 10.8.2, Box 12.2, Box 13.1}*



Box 1.1, Figure 1 | Trends in the global mean surface temperature over the periods from 1998 to 2012 **(a)**, 1984 to 1998 **(b)**, and 1951 to 2012 **(c)**, from observations (red) and the 114 available simulations with current-generation climate models (grey bars). The height of each grey bar indicates how often a trend of a certain magnitude (in °C per decade) occurs among the 114 simulations. The width of the red-hatched area indicates the statistical uncertainty that arises from constructing a global average from individual station data. This observational uncertainty differs from the one quoted in the text of Section 1.1.1; there, an estimate of natural internal variability is also included. Here, by contrast, the magnitude of natural internal variability is characterised by the spread of the model ensemble. *{based on WGI Box 9.2, Figure 1}*

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[21] The connection between the heat budget and equilibrium climate sensitivity, which is the long-term surface warming under an assumed doubling of the atmospheric CO_2 concentration, arises because a warmer surface causes enhanced radiation to space which counteracts the increase in the Earth's heat content. How much the radiation to space increases for a given increase in surface temperature depends on the same feedback processes (e.g., cloud feedback, water vapour feedback) that determine equilibrium climate sensitivity.

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high confidence that it did not exceed 10 m above present. During the last interglacial period, the Greenland ice sheet *very likely* contributed between 1.4 and 4.3 m to the higher global mean sea level, implying with *medium confidence* an additional contribution from the Antarctic ice sheet. This change in sea level occurred in the context of different orbital forcing and with high-latitude surface temperature, averaged over several thousand years, at least 2°C warmer than present (*high confidence*). *{WGI SPM B.4, 5.3.4, 5.6.2, 13.2.1}*

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1.2 Past and recent drivers of climate change

Anthropogenic greenhouse gas emissions have increased since the pre-industrial era driven largely by economic and population growth. From 2000 to 2010 emissions were the highest in history. Historical emissions have driven atmospheric concentrations of carbon dioxide, methane and nitrous oxide to levels that are unprecedented in at least the last 800,000 years, leading to an uptake of energy by the climate system.

Natural and anthropogenic substances and processes that alter the Earth's energy budget are physical drivers of climate change. Radiative forcing quantifies the perturbation of energy into the Earth system caused by these drivers. Radiative forcings larger than zero lead to a near-surface warming, and radiative forcings smaller than zero lead to a cooling. Radiative forcing is estimated based on in-situ and remote observations, properties of GHGs and aerosols, and calculations using numerical models. The radiative forcing over the 1750–2011 period is shown in Figure 1.4 in major groupings. The 'Other Anthropogenic' group is principally comprised of cooling effects from aerosol changes, with smaller contributions from ozone changes, land use reflectance changes and other minor terms. *{WGI SPM C, 8.1, 8.5.1}*

1.2.1 Natural and anthropogenic radiative forcings

Atmospheric concentrations of GHGs are at levels that are unprecedented in at least 800,000 years. Concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have all shown large increases since 1750 (40%, 150% and 20%, respectively) (Figure 1.3). CO_2 concentrations are increasing at the fastest observed decadal rate of change (2.0 ± 0.1 ppm/yr) for 2002–2011. After almost one decade of stable CH_4 concentrations since the late 1990s, atmospheric measurements have shown renewed increases since 2007. N_2O concentrations have steadily increased at a rate of 0.73 ± 0.03 ppb/yr over the last three decades. *{WGI SPM B5, 2.2.1, 6.1.2, 6.1.3, 6.3}*

The total anthropogenic radiative forcing over 1750–2011 is calculated to be a warming effect of 2.3 [1.1 to 3.3] W/m² (Figure 1.4), and it has increased more rapidly since 1970 than during prior decades. Carbon dioxide is the largest single contributor to radiative forcing over 1750–2011 and its trend since 1970. The total anthropogenic radiative forcing estimate for 2011 is substantially higher (43%) than the estimate reported in the IPCC

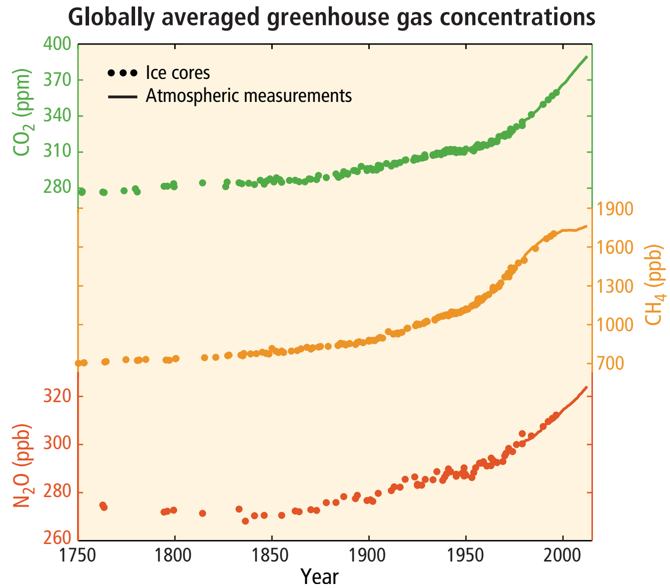

Figure 1.3 | Observed changes in atmospheric greenhouse gas concentrations. Atmospheric concentrations of carbon dioxide (CO_2, green), methane (CH_4, orange), and nitrous oxide (N_2O, red). Data from ice cores (symbols) and direct atmospheric measurements (lines) are overlaid. *{WGI 2.2, 6.2, 6.3, Figure 6.11}*

Fourth Assessment Report (AR4) for the year 2005. This is caused by a combination of continued growth in most GHG concentrations and an improved estimate of radiative forcing from aerosols. *{WGI SPM C, 8.5.1}*

The radiative forcing from aerosols, which includes cloud adjustments, is better understood and indicates a weaker cooling effect than in AR4. The aerosol radiative forcing over 1750–2011 is estimated as –0.9 [–1.9 to –0.1] W/m² (*medium confidence*). Radiative forcing from aerosols has two competing components: a dominant cooling effect from most aerosols and their cloud adjustments and a partially offsetting warming contribution from black carbon absorption of solar radiation. There is *high confidence* that the global mean total aerosol radiative forcing has counteracted a substantial portion of radiative forcing from well-mixed GHGs. Aerosols continue to contribute the largest uncertainty to the total radiative forcing estimate. *{WGI SPM C, 7.5, 8.3, 8.5.1}*

Changes in solar irradiance and volcanic aerosols cause natural radiative forcing (Figure 1.4). The radiative forcing from stratospheric volcanic aerosols can have a large cooling effect on the climate system for some years after major volcanic eruptions. Changes in total solar irradiance are calculated to have contributed only around 2% of the total radiative forcing in 2011, relative to 1750. *{WGI SPM C, Figure SPM.5, 8.4}*

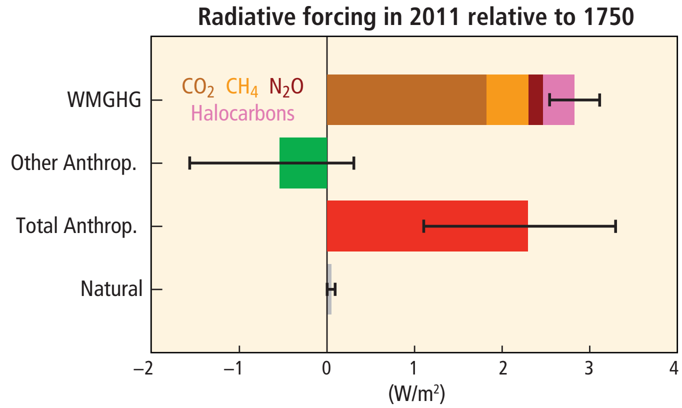

Figure 1.4 | Radiative forcing of climate change during the industrial era (1750–2011). Bars show radiative forcing from well-mixed greenhouse gases (WMGHG), other anthropogenic forcings, total anthropogenic forcings and natural forcings. The error bars indicate the 5 to 95% uncertainty. Other anthropogenic forcings include aerosol, land use surface reflectance and ozone changes. Natural forcings include solar and volcanic effects. The total anthropogenic radiative forcing for 2011 relative to 1750 is 2.3 W/m^2 (uncertainty range 1.1 to 3.3 W/m^2). This corresponds to a CO_2-equivalent concentration (see Glossary) of 430 ppm (uncertainty range 340 to 520 ppm). *{Data from WGI 7.5 and Table 8.6}*

1.2.2 Human activities affecting emission drivers

About half of the cumulative anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years (*high confidence*). Cumulative anthropogenic CO_2 emissions of 2040 ± 310 $GtCO_2$ were added to the atmosphere between 1750 and 2011. Since 1970, cumulative CO_2 emissions from fossil fuel combustion, cement production and flaring have tripled, and cumulative CO_2 emissions from forestry and other land use (FOLU)[22] have increased by about 40% (Figure 1.5)[23]. In 2011, annual CO_2 emissions from fossil fuel combustion, cement production and flaring were 34.8 ± 2.9 $GtCO_2$/yr. For 2002–2011, average annual emissions from FOLU were 3.3 ± 2.9 $GtCO_2$/yr. *{WGI 6.3.1, 6.3.2, WGIII SPM.3}*

About 40% of these anthropogenic CO_2 emissions have remained in the atmosphere (880 ± 35 $GtCO_2$) since 1750. The rest was removed from the atmosphere by sinks, and stored in natural carbon cycle reservoirs. Sinks from ocean uptake and vegetation with soils account, in roughly equal measures, for the remainder of the cumulative CO_2 emissions. The ocean has absorbed about 30% of the emitted anthropogenic CO_2, causing ocean acidification. *{WGI 3.8.1, 6.3.1}*

Total annual anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010 (*high confidence*). Despite a growing number of climate change mitigation policies, annual GHG emissions grew on average by 1.0 $GtCO_2$-eq (2.2%) per year, from 2000 to 2010, compared to 0.4 $GtCO_2$-eq (1.3%) per year, from 1970 to 2000 (Figure 1.6)[24]. Total anthropogenic GHG emissions from 2000 to 2010 were the highest in human history and reached 49 (±4.5) $GtCO_2$-eq/yr in 2010. The global economic crisis of 2007/2008 reduced emissions only temporarily. *{WGIII SPM.3, 1.3, 5.2, 13.3, 15.2.2, Box TS.5, Figure 15.1}*

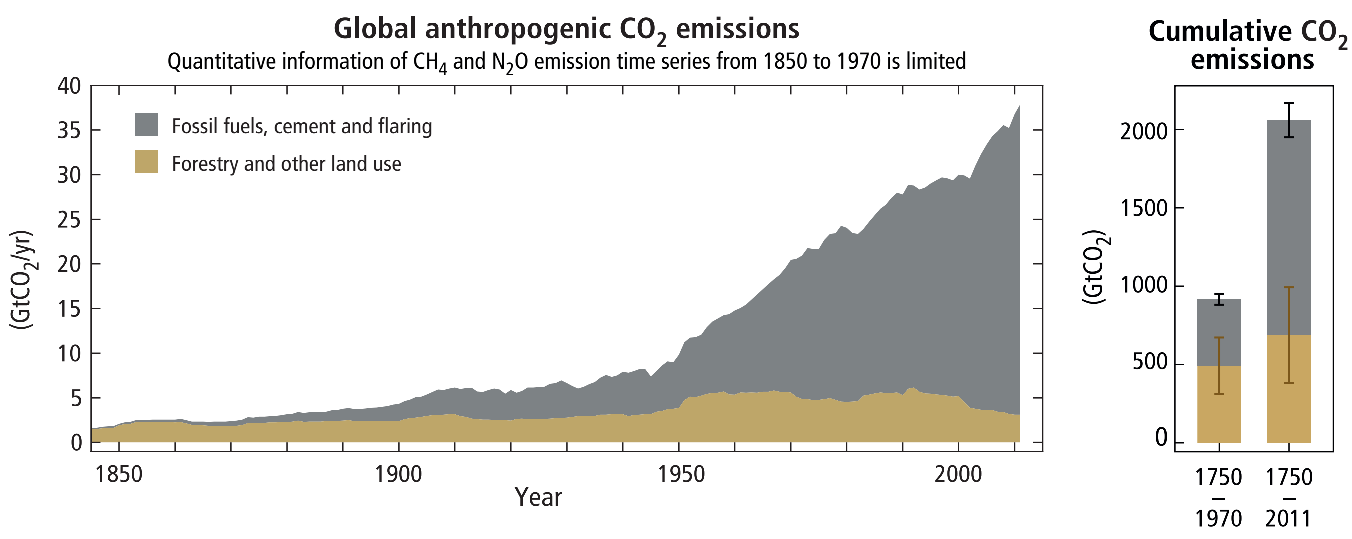

Figure 1.5 | Annual global anthropogenic carbon dioxide (CO_2) emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$/yr) from fossil fuel combustion, cement production and flaring, and forestry and other land use (FOLU), 1750–2011. Cumulative emissions and their uncertainties are shown as bars and whiskers, respectively, on the right-hand side. The global effects of the accumulation of methane (CH_4) and nitrous oxide (N_2O) emissions are shown in Figure 1.3. Greenhouse gas emission data from 1970 to 2010 are shown in Figure 1.6. *{modified from WGI Figure TS.4 and WGIII Figure TS.2}*

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[22] Forestry and other land use (FOLU)—also referred to as LULUCF (land use, land use change and forestry)—is the subset of agriculture, forestry and other land use (AFOLU) emissions and removals of GHGs related to direct human-induced LULUCF activities, excluding agricultural emissions and removals *(see WGIII AR5 Glossary).*

[23] Numbers from WGI 6.3 converted into $GtCO_2$ units. Small differences in cumulative emissions from Working Group III *{WGIII SPM.3, TS.2.1}* are due to different approaches to rounding, different end years and the use of different data sets for emissions from FOLU. Estimates remain extremely close, given their uncertainties.

[24] CO_2-equivalent emission is a common scale for comparing emissions of different GHGs. Throughout the SYR, when historical emissions of GHGs are provided in $GtCO_2$-eq, they are weighted by Global Warming Potentials with a 100-year time horizon (GWP_{100}), taken from the IPCC Second Assessment Report unless otherwise stated. A unit abbreviation of $GtCO_2$-eq is used. *{Box 3.2, Glossary}*

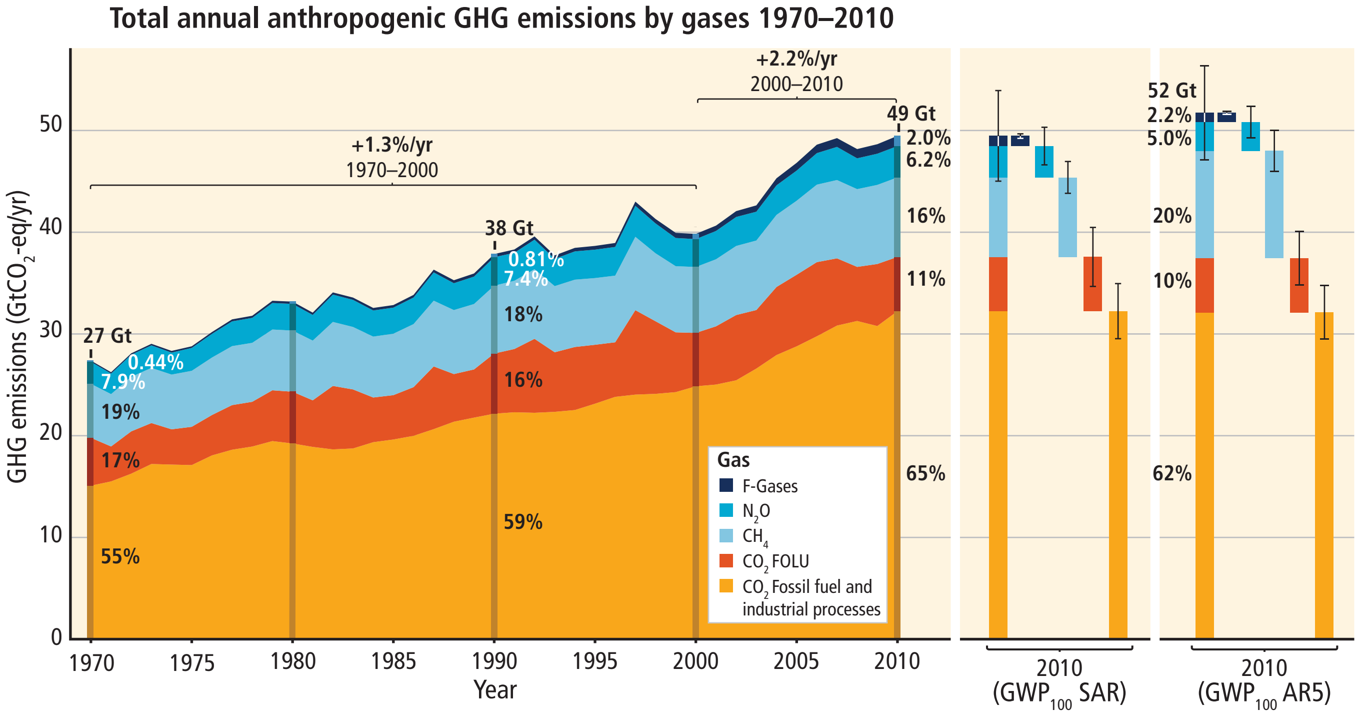

Figure 1.6 | Total annual anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$-eq/yr) for the period 1970 to 2010, by gases: CO_2 from fossil fuel combustion and industrial processes; CO_2 from Forestry and Other Land Use (FOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases covered under the Kyoto Protocol (F-gases). Right hand side shows 2010 emissions, using alternatively CO_2-equivalent emission weightings based on IPCC Second Assessment Report (SAR) and AR5 values. Unless otherwise stated, CO_2-equivalent emissions in this report include the basket of Kyoto gases (CO_2, CH_4, N_2O as well as F-gases) calculated based on 100-year Global Warming Potential (GWP_{100}) values from the SAR (see Glossary). Using the most recent GWP_{100} values from the AR5 (right-hand bars) would result in higher total annual GHG emissions (52 $GtCO_2$-eq/yr) from an increased contribution of methane, but does not change the long-term trend significantly. Other metric choices would change the contributions of different gases (see Box 3.2). The 2010 values are shown again broken down into their components with the associated uncertainties (90% confidence interval) indicated by the error bars. Global CO_2 emissions from fossil fuel combustion are known with an 8% uncertainty margin (90% confidence interval). There are very large uncertainties (of the order of ±50%) attached to the CO_2 emissions from FOLU. Uncertainty about the global emissions of CH_4, N_2O and the F-gases has been estimated at 20%, 60% and 20%, respectively. 2010 was the most recent year for which emission statistics on all gases as well as assessments of uncertainties were essentially complete at the time of data cut off for this report. The uncertainty estimates only account for uncertainty in emissions, not in the GWPs (as given in WGI 8.7). *{WGIII Figure SPM.1}*

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% to the total GHG emission increase between 1970 and 2010, with a contribution of similar percentage over the 2000–2010 period (*high confidence*). Fossil-fuel-related CO_2 emissions reached 32 (±2.7) $GtCO_2$/yr, in 2010, and grew further by about 3% between 2010 and 2011, and by about 1 to 2% between 2011 and 2012. CO_2 remains the major anthropogenic GHG, accounting for 76% of total anthropogenic GHG emissions in 2010. Of the total, 16% comes from CH_4, 6.2% from N_2O, and 2.0% from fluorinated gases (F-gases) (Figure 1.6)[25]. Annually, since 1970, about 25% of anthropogenic GHG emissions have been in the form of non-CO_2 gases[26]. *{WGIII SPM.3, 1.2, 5.2}*

Total annual anthropogenic GHG emissions have increased by about 10 $GtCO_2$-eq between 2000 and 2010. This increase directly came from the energy (47%), industry (30%), transport (11%) and building (3%) sectors (*medium confidence*). Accounting for indirect emissions raises the contributions by the building and industry sectors (*high confidence*). Since 2000, GHG emissions have been growing in all sectors, except in agriculture, forestry and other land use (AFOLU)[22]. In 2010, 35% of GHG emissions were released by the energy sector, 24% (net emissions) from AFOLU, 21% by industry, 14% by transport and 6.4% by the building sector. When emissions from electricity and heat production are attributed to the sectors that use the final energy (i.e., indirect emissions), the shares of the industry and building sectors in global GHG emissions are increased to 31% and 19%, respectively (Figure 1.7). *{WGIII SPM.3, 7.3, 8.1, 9.2, 10.3, 11.2}* See also Box 3.2 for contributions from various sectors, based on metrics other than 100-year Global Warming Potential (GWP_{100}).

Globally, economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to that of the previous three decades, while the contribution of economic growth has risen sharply (*high confidence*). Between 2000 and

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[25] Using the most recent 100-year Global Warming Potential (GWP_{100}) values from the AR5 *{WGI 8.7}* instead of GWP_{100} values from the IPCC Second Assessment Report, global GHG emission totals would be slightly higher (52 $GtCO_2$-eq/yr) and non-CO_2 emission shares would be 20% for CH_4, 5% for N_2O and 2.2% for F-gases.

[26] For this report, data on non-CO_2 GHGs, including F-gases, were taken from the Electronic Data Gathering, Analysis, and Retrieval (EDGAR) database *{WGIII Annex II.9}*, which covers substances included in the Kyoto Protocol in its first commitment period.

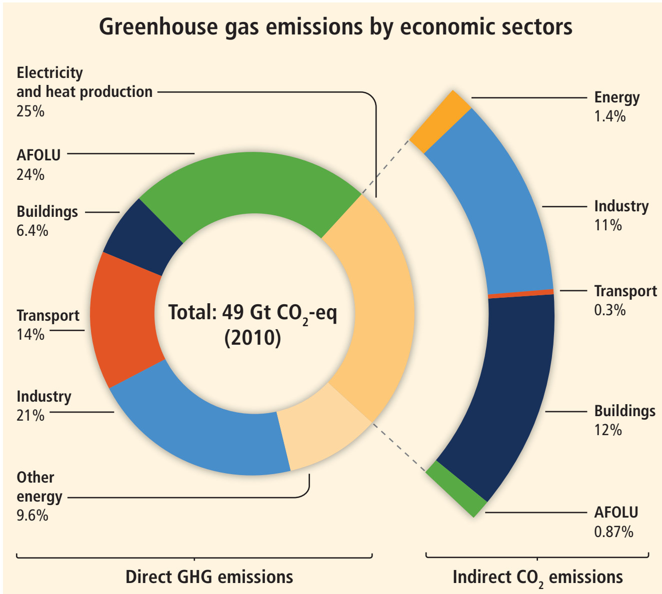


Figure 1.7 | Total anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$-eq/yr) from economic sectors in 2010. The circle shows the shares of direct GHG emissions (in % of total anthropogenic GHG emissions) from five economic sectors in 2010. The pull-out shows how shares of indirect CO_2 emissions (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. 'Other energy' refers to all GHG emission sources in the energy sector as defined in WGIII Annex II, other than electricity and heat production *{WGIII Annex II.9.1}*. The emission data on agriculture, forestry and other land use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from the sub-sectors of forestry and other land use (FOLU) as described in Chapter 11 of the WGIII report. Emissions are converted into CO_2-equivalents based on 100-year Global Warming Potential (GWP_{100}), taken from the IPCC Second Assessment Report (SAR). Sector definitions are provided in WGIII Annex II.9. *{WGIII Figure SPM.2}*

2010, both drivers outpaced emission reductions from improvements in energy intensity of gross domestic product (GDP) (Figure 1.8). Increased use of coal relative to other energy sources has reversed the long-standing trend in gradual decarbonization (i.e., reducing the carbon intensity of energy) of the world's energy supply. *{WGIII SPM.3, TS.2.2, 1.3, 5.3, 7.2, 7.3, 14.3}*

1.3 Attribution of climate changes and impacts

The evidence for human influence on the climate system has grown since AR4. Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, and in global mean sea level rise; and it is *extremely likely* to have been the dominant cause of the observed warming since the mid-20th century. In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate.

The causes of observed changes in the climate system, as well as in any natural or human system impacted by climate, are established following a consistent set of methods. Detection addresses the question of whether climate or a natural or human system affected by climate has actually changed in a statistical sense, while attribution evaluates the relative contributions of multiple causal factors to an observed change

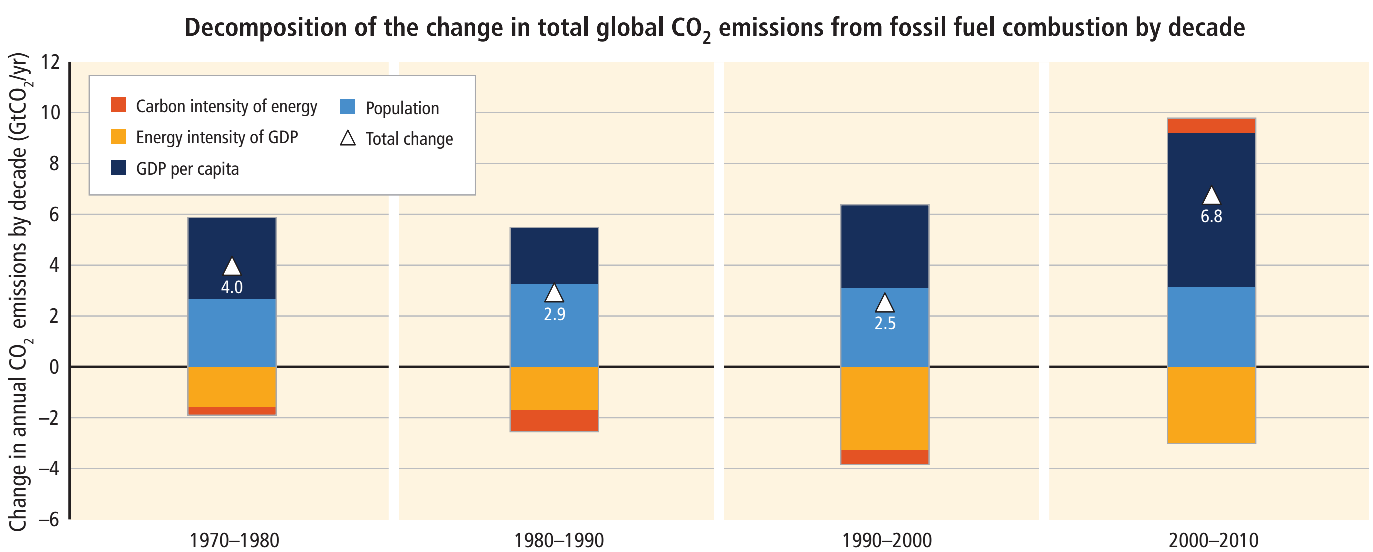


Figure 1.8 | Decomposition of the change in total annual carbon dioxide (CO_2) emissions from fossil fuel combustion by decade and four driving factors: population, income (gross domestic product, GDP) per capita, energy intensity of GDP and carbon intensity of energy. The bar segments show the changes associated with each individual factor, holding the respective other factors constant. Total emission changes are indicated by a triangle. The change in emissions over each decade is measured in gigatonnes of CO_2 per year ($GtCO_2$/yr); income is converted into common units, using purchasing power parities. *{WGIII SPM.3}*

or event with an assignment of statistical confidence[27]. Attribution of climate change to causes quantifies the links between observed climate change and human activity, as well as other, natural, climate drivers. In contrast, attribution of observed impacts to climate change considers the links between observed changes in natural or human systems and observed climate change, regardless of its cause. Results from studies attributing climate change to causes provide estimates of the magnitude of warming in response to changes in radiative forcing and hence support projections of future climate change (Topic 2). Results from studies attributing impacts to climate change provide strong indications for the sensitivity of natural or human systems to future climate change. *{WGI 10.8, WGII SPM A-1, WGI/II/III/SYR Glossaries}*

1.3.1 Attribution of climate changes to human and natural influences on the climate system

It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together (Figure 1.9). The best estimate of the human induced contribution to warming is similar to the observed warming over this period. GHGs contributed a global mean surface warming *likely* to be in the range of 0.5°C to 1.3°C over the period 1951 to 2010, with further contributions from other anthropogenic forcings, including the cooling effect of aerosols, from natural forcings, and from natural internal variability (see Figure 1.9).

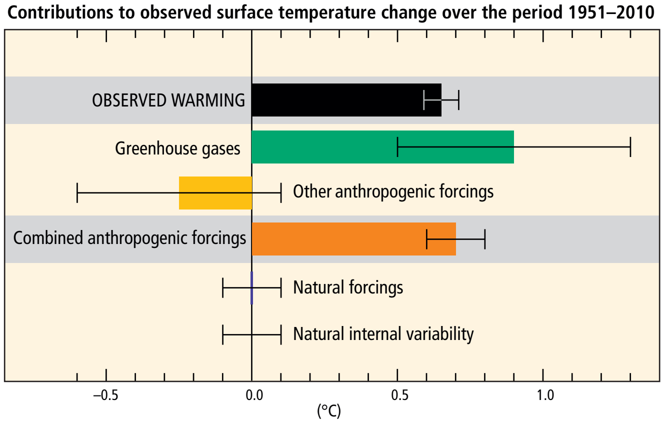


Figure 1.9 | Assessed *likely* ranges (whiskers) and their mid-points (bars) for warming trends over the 1951–2010 period from well-mixed greenhouse gases, other anthropogenic forcings (including the cooling effect of aerosols and the effect of land use change), combined anthropogenic forcings, natural forcings, and natural internal climate variability (which is the element of climate variability that arises spontaneously within the climate system, even in the absence of forcings). The observed surface temperature change is shown in black, with the 5 to 95% uncertainty range due to observational uncertainty. The attributed warming ranges (colours) are based on observations combined with climate model simulations, in order to estimate the contribution by an individual external forcing to the observed warming. The contribution from the combined anthropogenic forcings can be estimated with less uncertainty than the separate contributions from greenhouse gases and other anthropogenic forcings separately. This is because these two contributions partially compensate, resulting in a signal that is better constrained by observations. *{Based on Figure WGI TS.10}*

Together these assessed contributions are consistent with the observed warming of approximately 0.6°C to 0.7°C over this period. *{WGI SPM D.3, 10.3.1}*

It is *very likely* that anthropogenic influence, particularly GHGs and stratospheric ozone depletion, has led to a detectable observed pattern of tropospheric warming and a corresponding cooling in the lower stratosphere since 1961. *{WGI SPM D.3, 2.4.4, 9.4.1, 10.3.1}*

Over every continental region except Antarctica, anthropogenic forcings have *likely* made a substantial contribution to surface temperature increases since the mid-20th century (Figure 1.10). For Antarctica, large observational uncertainties result in *low confidence* that anthropogenic forcings have contributed to the observed warming averaged over available stations. In contrast, it is *likely* that there has been an anthropogenic contribution to the very substantial Arctic warming since the mid-20th century. Human influence has *likely* contributed to temperature increases in many sub-continental regions. *{WGI SPM D.3, TS.4.8, 10.3.1}*

Anthropogenic influences have *very likely* contributed to Arctic sea ice loss since 1979 (Figure 1.10). There is *low confidence* in the scientific understanding of the small observed increase in Antarctic sea ice extent due to the incomplete and competing scientific explanations for the causes of change and *low confidence* in estimates of natural internal variability in that region. *{WGI SPM D.3, 10.5.1, Figure 10.16}*

Anthropogenic influences *likely* contributed to the retreat of glaciers since the 1960s and to the increased surface melting of the Greenland ice sheet since 1993. Due to a low level of scientific understanding, however, there is *low confidence* in attributing the causes of the observed loss of mass from the Antarctic ice sheet over the past two decades. It is *likely* that there has been an anthropogenic contribution to observed reductions in Northern Hemisphere spring snow cover since 1970. *{WGI 4.3.3, 10.5.2, 10.5.3}*

It is *likely* that anthropogenic influences have affected the global water cycle since 1960. Anthropogenic influences have contributed to observed increases in atmospheric moisture content (*medium confidence*), to global-scale changes in precipitation patterns over land (*medium confidence*), to intensification of heavy precipitation over land regions where data are sufficient (*medium confidence*) (see 1.4) and to changes in surface and subsurface ocean salinity (*very likely*). *{WGI SPM D.3, 2.5.1, 2.6.2, 3.3.2, 3.3.3, 7.6.2, 10.3.2, 10.4.2, 10.6}*

It is *very likely* that anthropogenic forcings have made a substantial contribution to increases in global upper ocean heat content (0–700 m) observed since the 1970s (Figure 1.10). There is evidence for human influence in some individual ocean basins**.** It is *very likely* that there is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s. This is based on the *high confidence* in an anthropogenic influence on the two largest contributions to sea level rise: thermal expansion and glacier mass loss. Oceanic

[27] Definitions were taken from the Good Practice Guidance Paper on Detection and Attribution, the agreed product of the IPCC Expert Meeting on Detection and Attribution Related to Anthropogenic Climate Change; see Glossary.

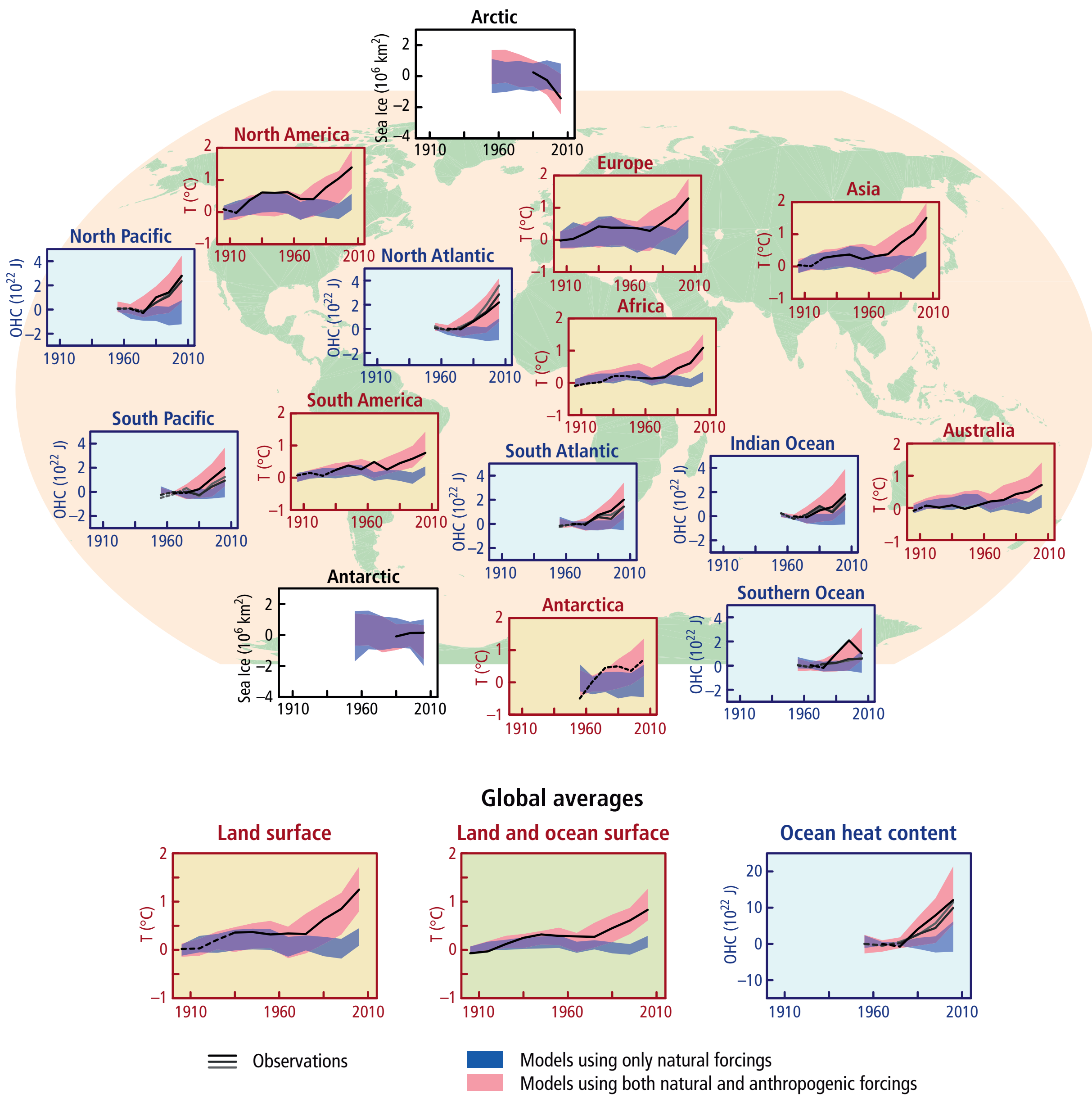


Figure 1.10 | Comparison of observed and simulated change in continental surface temperatures on land (yellow panels), Arctic and Antarctic September sea ice extent (white panels), and upper ocean heat content in the major ocean basins (blue panels). Global average changes are also given. Anomalies are given relative to 1880–1919 for surface temperatures, to 1960–1980 for ocean heat content, and to 1979–1999 for sea ice. All time series are decadal averages, plotted at the centre of the decade. For temperature panels, observations are dashed lines if the spatial coverage of areas being examined is below 50%. For ocean heat content and sea ice panels, the solid lines are where the coverage of data is good and higher in quality, and the dashed lines are where the data coverage is only adequate, and, thus, uncertainty is larger (note that different lines indicate different data sets; for details, see WGI Figure SPM.6). Model results shown are Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble ranges, with shaded bands indicating the 5 to 95% confidence intervals. *{WGI Figure SPM 6; for detail, see WGI Figure TS.12}*

uptake of anthropogenic CO_2 has resulted in gradual acidification of ocean surface waters (*high confidence*). *{WGI SPM D.3, 3.2.3, 3.8.2, 10.4.1, 10.4.3, 10.4.4, 10.5.2, 13.3, Box 3.2, TS.4.4, WGII 6.1.1.2, Box CC-OA}*

1.3.2 Observed impacts attributed to climate change

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate. Evidence of observed climate change impacts is strongest and most comprehensive for natural systems. Some impacts on human systems have also been attributed to climate change, with a major or minor contribution of climate change distinguishable from other influences (Figure 1.11). Impacts on human systems are often geographically heterogeneous because they depend not only on changes in climate variables but also on social and economic factors. Hence, the changes are more easily observed at local levels, while attribution can remain difficult. *{WGII SPM A-1, SPM A-3, 18.1, 18.3–18.6}*

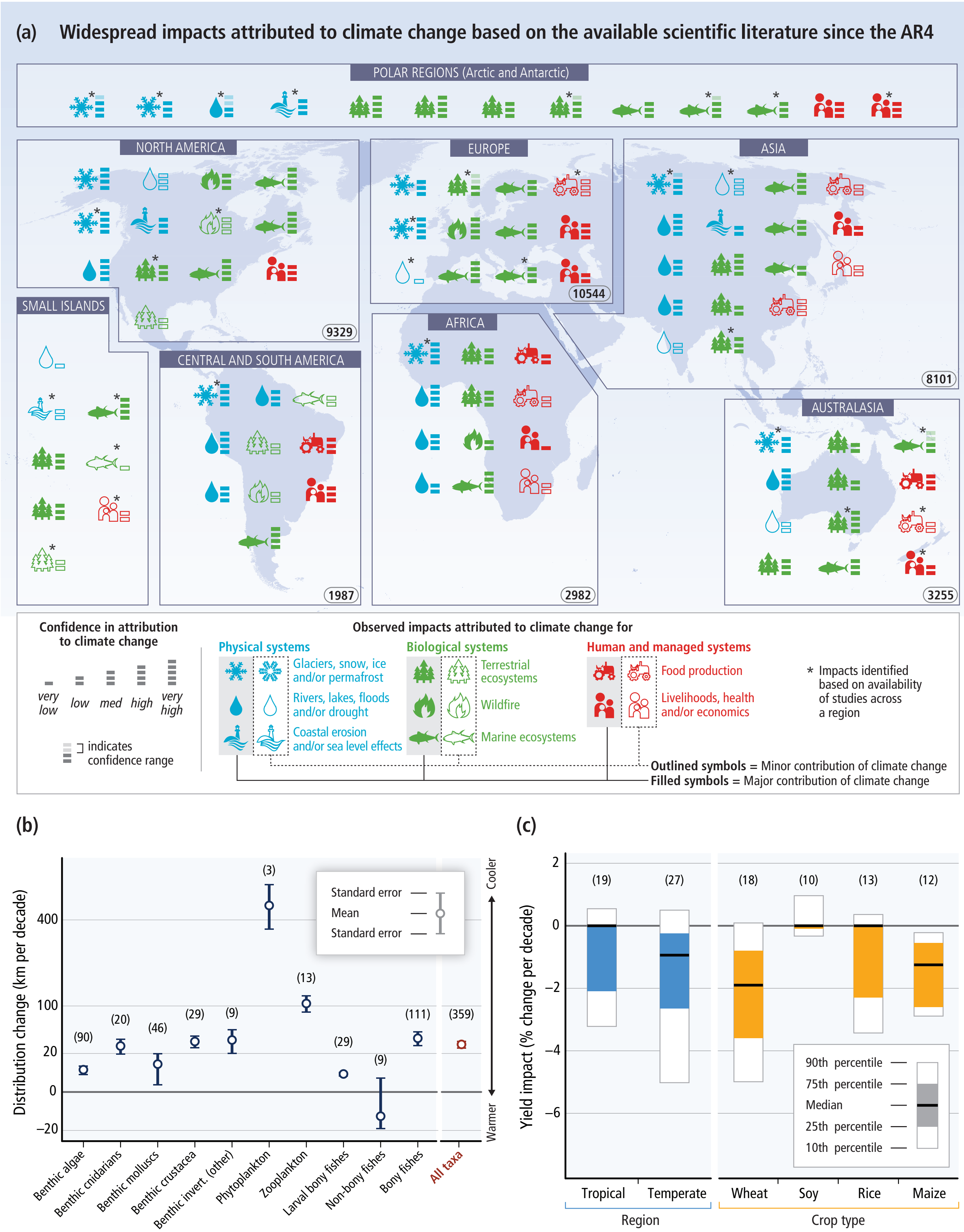

(a) Widespread impacts attributed to climate change based on the available scientific literature since the AR4
POLAR REGIONS (Arctic and Antarctic)
NORTH AMERICA
9329
EUROPE
10544
ASIA
8101
SMALL ISLANDS
CENTRAL AND SOUTH AMERICA
1987
AFRICA
2982
AUSTRALASIA
3255
Confidence in attribution to climate change
very low
low
med
high
very high
indicates confidence range
Observed impacts attributed to climate change for
Physical systems
Glaciers, snow, ice and/or permafrost
Rivers, lakes, floods and/or drought
Coastal erosion and/or sea level effects
Biological systems
Terrestrial ecosystems
Wildfire
Marine ecosystems
Human and managed systems
Food production
Livelihoods, health and/or economics
* Impacts identified based on availability of studies across a region
Outlined symbols = Minor contribution of climate change
Filled symbols = Major contribution of climate change
(b)
Distribution change (km per decade)
400
100
20
0
−20
(90)
(20)
(46)
(29)
(9)
(3)
(13)
(29)
(9)
(111)
(359)
Standard error
Mean
Standard error
Cooler
Warmer
Benthic algae
Benthic cnidarians
Benthic molluscs
Benthic crustacea
Benthic invert. (other)
Phytoplankton
Zooplankton
Larval bony fishes
Non-bony fishes
Bony fishes
All taxa
(c)
Yield impact (% change per decade)
2
0
−2
−4
−6
(19)
(27)
(18)
(10)
(13)
(12)
90th percentile
75th percentile
Median
25th percentile
10th percentile
Tropical
Temperate
Region
Wheat
Soy
Rice
Maize
Crop type

Figure 1.11 | Widespread impacts in a changing world: **(a)** Based on the available scientific literature since the IPCC Fourth Assessment Report (AR4), there are substantially more impacts in recent decades now attributed to climate change. Attribution requires defined scientific evidence on the role of climate change. Absence from the map of additional impacts attributed to climate change does not imply that such impacts have not occurred. The publications supporting attributed impacts reflect a growing knowledge base, but publications are still limited for many regions, systems and processes, highlighting gaps in data and studies. Symbols indicate categories of attributed impacts, the relative contribution of climate change (major or minor) to the observed impact and confidence in attribution. Each symbol refers to one or more entries in WGII Table SPM.A1, grouping related regional-scale impacts. Numbers in ovals indicate regional totals of climate change publications from 2001 to 2010, based on the Scopus bibliographic database for publications in English with individual countries mentioned in title, abstract or key words (as of July 2011). These numbers provide an overall measure of the available scientific literature on climate change across regions; they do not indicate the number of publications supporting attribution of climate change impacts in each region. Studies for polar regions and small islands are grouped with neighbouring continental regions. The inclusion of publications for assessment of attribution followed IPCC scientific evidence criteria defined in WGII Chapter 18. Publications considered in the attribution analyses come from a broader range of literature assessed in the WGII AR5. See WGII Table SPM.A1 for descriptions of the attributed impacts. **(b)** Average rates of change in distribution (km per decade) for marine taxonomic groups based on observations over 1900–2010. Positive distribution changes are consistent with warming (moving into previously cooler waters, generally poleward). The number of responses analysed is given for each category. **(c)** Summary of estimated impacts of observed climate changes on yields over 1960–2013 for four major crops in temperate and tropical regions, with the number of data points analysed given within parentheses for each category. *{WGII Figure SPM.2, Box TS.1 Figure 1}*

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*). Glaciers continue to shrink almost worldwide due to climate change (*high confidence*), affecting runoff and water resources downstream (*medium confidence*). Climate change is causing permafrost warming and thawing in high-latitude regions and in high-elevation regions (*high confidence*). *{WGII SPM A-1}*

Many terrestrial, freshwater and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to ongoing climate change (*high confidence*). While only a few recent species extinctions have been attributed as yet to climate change (*high confidence*), natural global climate change at rates slower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years (*high confidence*). Increased tree mortality, observed in many places worldwide, has been attributed to climate change in some regions. Increases in the frequency or intensity of ecosystem disturbances such as droughts, windstorms, fires and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). Numerous observations over the last decades in all ocean basins show changes in abundance, distribution shifts poleward and/or to deeper, cooler waters for marine fishes, invertebrates and phytoplankton (*very high confidence*), and altered ecosystem composition (*high confidence*), tracking climate trends. Some warm-water corals and their reefs have responded to warming with species replacement, bleaching, and decreased coral cover causing habitat loss (*high confidence*). Some impacts of ocean acidification on marine organisms have been attributed to human influence, from the thinning of pteropod and foraminiferan shells (*medium confidence*) to the declining growth rates of corals (*low confidence*). Oxygen minimum zones are progressively expanding in the tropical Pacific, Atlantic and Indian Oceans, due to reduced ventilation and O_2 solubility in warmer, more stratified oceans, and are constraining fish habitat (*medium confidence*). *{WGII SPM A-1, Table SPM.A1, TS A-1, 6.3.2.5, 6.3.3, 18.3–18.4, 30.5.1.1, Box CC-OA, Box CC-CR}*

Assessment of many studies covering a wide range of regions and crops shows that negative impacts of climate change on crop yields have been more common than positive impacts (*high confidence*). The smaller number of studies showing positive impacts relate mainly to high-latitude regions, though it is not yet clear whether the balance of impacts has been negative or positive in these regions (*high confidence*). Climate change has negatively affected wheat and maize yields for many regions and in the global aggregate (*medium confidence*). Effects on rice and soybean yield have been smaller in major production regions and globally, with a median change of zero across all available data which are fewer for soy compared to the other crops (see Figure 1.11c). Observed impacts relate mainly to production aspects of food security rather than access or other components of food security. Since AR4, several periods of rapid food and cereal price increases following climate extremes in key producing regions indicate a sensitivity of current markets to climate extremes among other factors (*medium confidence*). *{WGII SPM A-1}*

At present the worldwide burden of human ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. However, there has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (*medium confidence*). Local changes in temperature and rainfall have altered the distribution of some water-borne illnesses and disease vectors (*medium confidence*). *{WGII SPM A-1}*

'Cascading' impacts of climate change can now be attributed along chains of evidence from physical climate through to intermediate systems and then to people (Figure 1.12). The changes in climate feeding into the cascade, in some cases, are linked to human drivers (e.g., a decreasing amount of water in spring snowpack in western North America), while, in other cases, assessments of the causes of observed climate change leading into the cascade are not available. In all cases, confidence in detection and attribution to observed climate change decreases for effects further down each impact chain. *{WGII 18.6.3}*

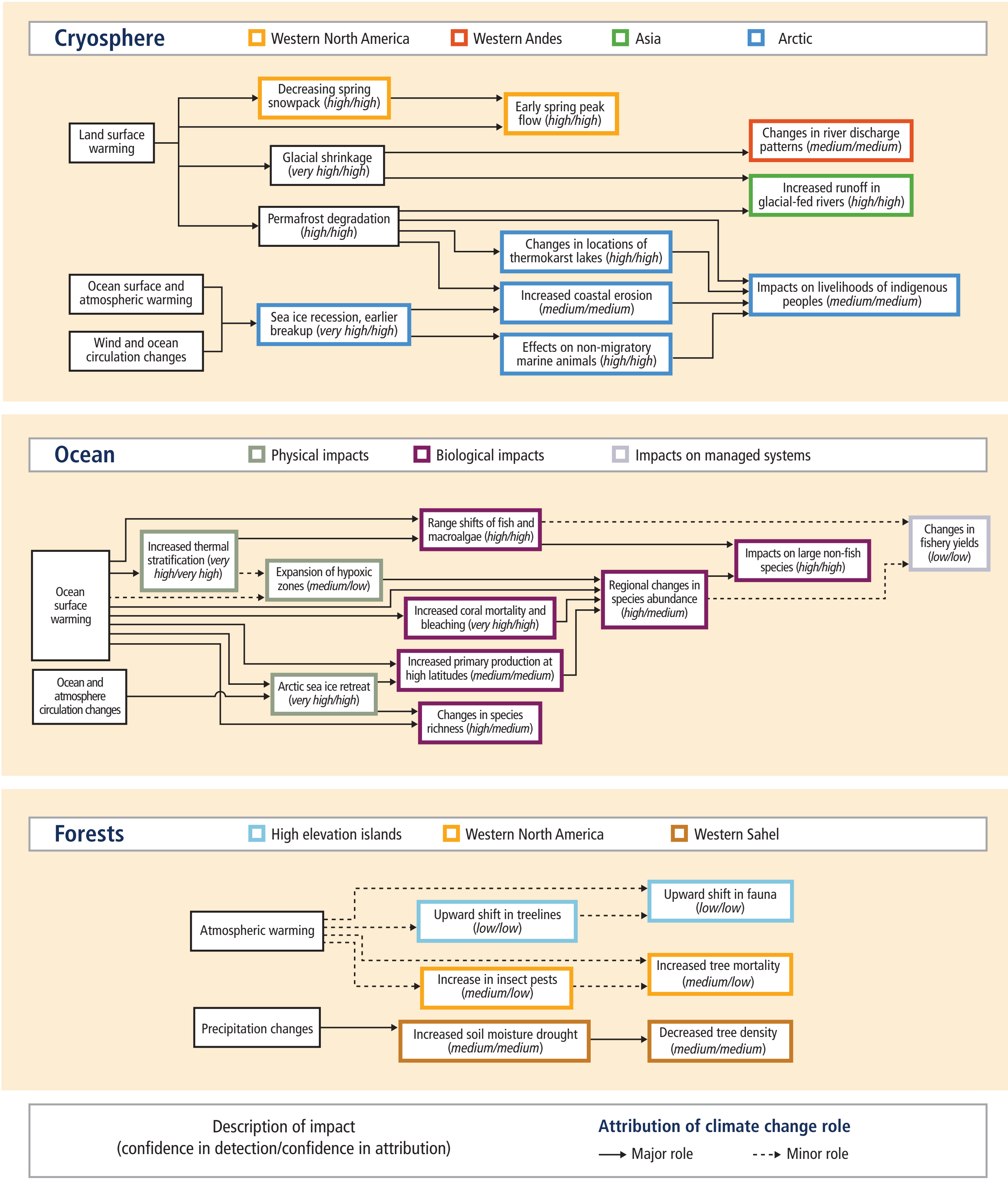


Figure 1.12 | Major systems where new evidence indicates interconnected, 'cascading' impacts from recent climate change through several natural and human subsystems. Bracketed text indicates confidence in the detection of a climate change effect and the attribution of observed impacts to climate change. The role of climate change can be major (solid arrow) or minor (dashed arrow). Initial evidence indicates that ocean acidification is following similar trends with respect to impact on human systems as ocean warming. *{WGII Figure 18-4}*

1.4 Extreme events

Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels and an increase in the number of heavy precipitation events in a number of regions.

It is *very likely* that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. It is *likely* that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. It is *very likely* that human influence has contributed to the observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century. It is *likely* that human influence has more than doubled the probability of occurrence of heat waves in some locations. *{WGI SPM B.1, SPM D.3, Table SPM.1, FAQ 2.2, 2.6.1, 10.6}*

There is *medium confidence* that the observed warming has increased heat-related human mortality and decreased cold-related human mortality in some regions. Extreme heat events currently result in increases in mortality and morbidity in North America (*very high confidence*), and in Europe with impacts that vary according to people's age, location and socio-economic factors (*high confidence*). *{WGII SPM A-1, 11.4.1, Table 23-1, 26.6.1.2}*

There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency and intensity of heavy precipitation events has *likely* increased in North America and Europe. In other continents, *confidence* in trends is at most *medium.* It is *very likely* that global near-surface and tropospheric air specific humidity has increased since the 1970s. In land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century. *{WGI SPM B-1, 2.5.1, 2.5.4–2.5.5, 2.6.2, 10.6, Table SPM.1, FAQ 2.2, SREX Table 3-1, 3.2}*

There is *low confidence* that anthropogenic climate change has affected the frequency and magnitude of fluvial floods on a global scale. The strength of the evidence is limited mainly by a lack of long-term records from unmanaged catchments. Moreover, floods are strongly influenced by many human activities impacting catchments, making the attribution of detected changes to climate change difficult. However, recent detection of increasing trends in extreme precipitation and discharges in some catchments implies greater risks of flooding on a regional scale (*medium confidence*). Costs related to flood damage, worldwide, have been increasing since the 1970s, although this is partly due to the increasing exposure of people and assets. *{WGI 2.6.2, WGII 3.2.7, SREX SPM B}*

There is *low confidence* in observed global-scale trends in droughts, due to lack of direct observations, dependencies of inferred trends on the choice of the definition for drought, and due to geographical inconsistencies in drought trends. There is also *low confidence* in the attribution of changes in drought over global land areas since the mid-20th century, due to the same observational uncertainties and difficulties in distinguishing decadal scale variability in drought from long-term trends. *{WGI Table SPM.1, 2.6.2.3, 10.6, Figure 2.33, WGII 3.ES, 3.2.7}*

There is *low confidence* that long-term changes in tropical cyclone activity are robust, and there is *low confidence* in the attribution of global changes to any particular cause. However, it is *virtually certain* that intense tropical cyclone activity has increased in the North Atlantic since 1970. *{WGI Table SPM.1, 2.6.3, 10.6}*

It is *likely* that extreme sea levels (for example, as experienced in storm surges) have increased since 1970, being mainly the result of mean sea level rise. Due to a shortage of studies and the difficulty of distinguishing any such impacts from other modifications to coastal systems, limited evidence is available on the impacts of sea level rise. *{WGI 3.7.4–3.7.6, Figure 3.15, WGII 5.3.3.2, 18.3}*

Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (*very high confidence*). Impacts of such climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, human morbidity and mortality and consequences for mental health and human well-being. For countries at all levels of development, these impacts are consistent with a significant lack of preparedness for current climate variability in some sectors. *{WGII SPM A-1, 3.2, 4.2-3, 8.1, 9.3, 10.7, 11.3, 11.7, 13.2, 14.1, 18.6, 22.2.3, 22.3, 23.3.1.2, 24.4.1, 25.6-8, 26.6-7, 30.5,Table 18-3, Table 23-1, Figure 26-2, Box 4-3, Box 4-4, Box 25-5, Box 25-6, Box 25-8, Box CC-CR}*

Direct and insured losses from weather-related disasters have increased substantially in recent decades, both globally and regionally. Increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters (*high confidence*). *{WGII 10.7.3, SREX SPM B, 4.5.3.3}*

1.5 Exposure and vulnerability

The character and severity of impacts from climate change and extreme events emerge from risk that depends not only on climate-related hazards but also on exposure (people and assets at risk) and vulnerability (susceptibility to harm) of human and natural systems.

Exposure and vulnerability are influenced by a wide range of social, economic and cultural factors and processes that have been incompletely considered to date and that make quantitative assessments of their future trends difficult (*high confidence*). These factors include wealth and its distribution across society, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures and institutions to resolve conflict. *{WGII SPM A-3, SREX SPM B}*

Differences in vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities often produced by uneven development processes (*very high confidence*). These differences shape differential risks from climate change. People who are socially, economically, culturally, politically, institutionally or otherwise marginalized are especially vulnerable to climate change and also to some adaptation and mitigation responses (*medium evidence, high agreement*). This heightened vulnerability is rarely due to a single cause. Rather, it is the product of intersecting social processes that result in inequalities in socio-economic status and income, as well as in exposure. Such social processes include, for example, discrimination on the basis of gender, class, ethnicity, age and (dis)ability. *{WGII SPM A-1, Figure SPM.1, 8.1–8.2, 9.3–9.4, 10.9, 11.1, 11.3–11.5, 12.2–12.5, 13.1–13.3, 14.1–14.3, 18.4, 19.6, 23.5, 25.8, 26.6, 26.8, 28.4, Box CC-GC}*

Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (*high confidence*). Climate-related hazards affect poor people's lives directly through impacts on livelihoods, reductions in crop yields or the destruction of homes, and indirectly through, for example, increased food prices and food insecurity. Observed positive effects for poor and marginalized people, which are limited and often indirect, include examples such as diversification of social networks and of agricultural practices. *{WGII SPM A-1, 8.2–8.3, 9.3, 11.3, 13.1–13.3, 22.3, 24.4, 26.8}*

Violent conflict increases vulnerability to climate change (*medium evidence, high agreement*). Large-scale violent conflict harms assets that facilitate adaptation, including infrastructure, institutions, natural resources, social capital and livelihood opportunities. *{WGII SPM A-1, 12.5, 19.2, 19.6}*

1.6 Human responses to climate change: adaptation and mitigation

Adaptation and mitigation experience is accumulating across regions and scales, even while global anthropogenic greenhouse gas emissions have continued to increase.

Throughout history, people and societies have adjusted to and coped with climate, climate variability and extremes, with varying degrees of success. In today's changing climate, accumulating experience with adaptation and mitigation efforts can provide opportunities for learning and refinement (3, 4). *{WGII SPM A-2}*

Adaptation is becoming embedded in some planning processes, with more limited implementation of responses (*high confidence*). Engineered and technological options are commonly implemented adaptive responses, often integrated within existing programmes, such as disaster risk management and water management. There is increasing recognition of the value of social, institutional and ecosystem-based measures and of the extent of constraints to adaptation. *{WGII SPM A-2, 4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 14.1, 14.3–14.4, 15.2–15.5, 17.2–17.3, 21.3, 21.5, 22.4, 23.7, 25.4, 26.8–26.9, 30.6, Box 25-1, Box 25-2, Box 25-9, Box CC-EA}*

Governments at various levels have begun to develop adaptation plans and policies and integrate climate change considerations into broader development plans. Examples of adaptation are now available from all regions of the world (see Topic 4 for details on adaptation options and policies to support their implementation). *{WGII SPM A-2, 22.4, 23.7, 24.4–24.6, 24.9, 25.4, 25.10, 26.7–26.9, 27.3, 28.2, 28.4, 29.3, 29.6, 30.6, Table 25-2, Table 29-3, Figure 29-1, Box 5-1, Box 23-3, Box 25-1, Box 25-2, Box 25-9, Box CC-TC}*

Global increases in anthropogenic emissions and climate impacts have occurred, even while mitigation activities have taken place in many parts of the world. Though various mitigation initiatives between the sub-national and global scales have been developed or implemented, a full assessment of their impact may be premature. *{WGIII SPM.3, SPM.5}*

2 Future Climate Changes, Risks and Impacts

Topic 2: Future Climate Changes, Risk and Impacts

Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks.

Topic 2 assesses projections of future climate change and the resulting risks and impacts. Factors that determine future climate change, including scenarios for future greenhouse gas (GHG) emissions, are outlined in Section 2.1. Descriptions of the methods and tools used to make projections of climate, impacts and risks, and their development since the IPCC Fourth Assessment Report (AR4), are provided in Boxes 2.1 to 2.3. Details of projected changes in the climate system, including the associated uncertainty and the degree of expert confidence in the projections are provided in Section 2.2. The future impacts of climate change on natural and human systems and associated risks are assessed in Section 2.3. Topic 2 concludes with an assessment of irreversible changes, abrupt changes and changes beyond 2100 in Section 2.4.

2.1 Key drivers of future climate and the basis on which projections are made

Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Projections of greenhouse gas emissions vary over a wide range, depending on both socio-economic development and climate policy.

Climate models are mathematical representations of processes important in the Earth's climate system. Results from a hierarchy of climate models are considered in this report; ranging from simple idealized models, to models of intermediate complexity, to comprehensive General Circulation Models (GCMs), including Earth System Models (ESMs) that also simulate the carbon cycle. The GCMs simulate many climate aspects, including the temperature of the atmosphere and the oceans, precipitation, winds, clouds, ocean currents and sea-ice extent. The models are extensively tested against historical observations (Box 2.1). *{WGI 1.5.2, 9.1.2, 9.2, 9.8.1}*

In order to obtain climate change projections, the climate models use information described in scenarios of GHG and air pollutant emissions and land use patterns. Scenarios are generated by a range of approaches, from simple idealised experiments to Integrated Assessment Models (IAMs, see Glossary). Key factors driving changes in anthropogenic GHG emissions are economic and population growth, lifestyle and behavioural changes, associated changes in energy use and land use, technology and climate policy, which are fundamentally uncertain. *{WGI 11.3, 12.4, WGIII 5, 6, 6.1}*

The standard set of scenarios used in the AR5 is called Representative Concentration Pathways (RCPs, Box 2.2). *{WGI Box SPM.1}*

Box 2.1 | Advances, Confidence and Uncertainty in Modelling the Earth's Climate System

Improvements in climate models since the IPCC Fourth Assessment Report (AR4) are evident in simulations of continental-scale surface temperature, large-scale precipitation, the monsoon, Arctic sea ice, ocean heat content, some extreme events, the carbon cycle, atmospheric chemistry and aerosols, the effects of stratospheric ozone and the El Niño-Southern Oscillation. Climate models reproduce the observed continental-scale surface temperature patterns and multi-decadal trends, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (*very high confidence*). The simulation of large-scale patterns of precipitation has improved somewhat since the AR4, although models continue to perform less well for precipitation than for surface temperature. *Confidence* in the representation of processes involving clouds and aerosols remains *low*. *{WGI SPM D.1, 7.2.3,* 7.3.3, *7.6.2, 9.4, 9.5, 9.8, 10.3.1}*

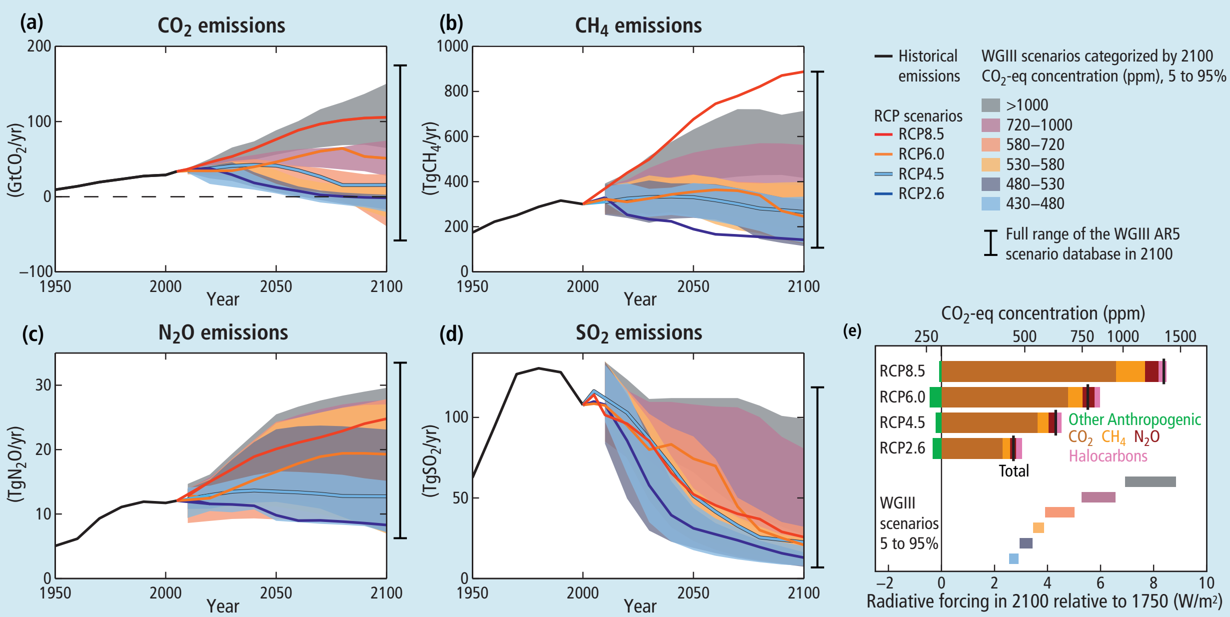
The ability to simulate ocean thermal expansion, glaciers and ice sheets, and thus sea level, has improved since the AR4, but significant challenges remain in representing the dynamics of the Greenland and Antarctic ice sheets. This, together with advances in scientific understanding and capability, has resulted in improved sea level projections in this report, compared with the AR4. *{WGI SPM E.6, 9.1.3, 9.2, 9.4.2, 9.6, 9.8, 13.1, 13.4, 13.5}*

There is overall consistency between the projections from climate models in AR4 and AR5 for large-scale patterns of change and the magnitude of the uncertainty has not changed significantly, but new experiments and studies have led to a more complete and rigorous characterization of the uncertainty in long-term projections. *{WGI 12.4}*

Box 2.2 | The Representative Concentration Pathways

The Representative Concentration Pathways (RCPs) describe four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs have been developed using Integrated Assessment Models (IAMs) as input to a wide range of climate model simulations to project their consequences for the climate system. These climate projections, in turn, are used for impacts and adaptation assessment. The RCPs are consistent with the wide range of scenarios in the mitigation literature assessed by WGIII[28]. The scenarios are used to assess the costs associated with emission reductions consistent with particular concentration pathways. The RCPs represent the range of GHG emissions in the wider literature well (Box 2.2, Figure 1); they include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5. RCP2.6 is representative of a scenario that aims to keep global warming *likely* below 2°C above pre-industrial temperatures. The majority of models indicate that scenarios meeting forcing levels similar to RCP2.6 are characterized by substantial net negative emissions[29] by 2100, on average around 2 $GtCO_2$/yr. The land use scenarios of RCPs, together, show a wide range of possible futures, ranging from a net reforestation to further deforestation, consistent with projections in the full scenario literature. For air pollutants such as sulfur dioxide (SO_2), the RCP scenarios assume a consistent decrease in emissions as a consequence of assumed air pollution control and GHG mitigation policy (Box 2.2, Figure 1). Importantly, these future scenarios do not account for possible changes in natural forcings (e.g., volcanic eruptions) (see Box 1.1). *{WGI Box SPM.1, 6.4, 8.5.3, 12.3, Annex II, WGII 19, 21, WGIII 6.3.2, 6.3.6}*

The RCPs cover a wider range than the scenarios from the Special Report on Emissions Scenarios (SRES) used in previous assessments, as they also represent scenarios with climate policy. In terms of overall forcing, RCP8.5 is broadly comparable to the SRES A2/A1FI scenario, RCP6.0 to B2 and RCP4.5 to B1. For RCP2.6, there is no equivalent scenario in SRES. As a result, the differences in the magnitude of AR4 and AR5 climate projections are largely due to the inclusion of the wider range of emissions assessed. *{WGI TS Box TS.6, 12.4.9}*



Box 2.2, Figure 1 | Emission scenarios and the resulting radiative forcing levels for the Representative Concentration Pathways (RCPs, lines) and the associated scenarios categories used in WGIII (coloured areas, see Table 3.1). Panels a to d show the emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulfur dioxide (SO_2). Panel e shows future radiative forcing levels for the RCPs calculated using the simple carbon cycle climate model, Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), for the RCPs (per forcing agent) and for the WGIII scenario categories (total) *{WGI 8.2.2, 8.5.3, Figure 8.2, Annex II, WGIII Table SPM.1, Table 6.3}*. The WGIII scenario categories summarize the wide range of emission scenarios published in the scientific literature and are defined based on total CO_2-equivalent concentrations (in ppm) in 2100 (Table 3.1). The vertical lines to the right of the panels (panel a–d) indicate the full range of the WGIII AR5 scenario database.

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28 Roughly 300 baseline scenarios and 900 mitigation scenarios are categorized by CO_2-equivalent concentration (CO_2-eq) by 2100. The CO_2-eq includes the forcing due to all GHGs (including halogenated gases and tropospheric ozone), aerosols and albedo change (see Glossary).

29 Net negative emissions can be achieved when more GHGs are sequestered than are released into the atmosphere (e.g., by using bio-energy in combination with carbon dioxide capture and storage).

The methods used to estimate future impacts and risks resulting from climate change are described in Box 2.3. Modelled future impacts assessed in this report are generally based on climate-model projections using the RCPs, and in some cases, the older Special Report on Emissions Scenarios (SRES). *{WGI Box SPM.1, WGII 1.1, 1.3, 2.2–2.3, 19.6, 20.2, 21.3, 21.5, 26.2, Box CC-RC}*

Risk of climate-related impacts results from the interaction between climate-related hazards (including hazardous events and trends) and the vulnerability and exposure of human and natural systems. Alternative development paths influence risk by changing the likelihood of climatic events and trends, through their effects on GHGs, pollutants and land use, and by altering vulnerability and exposure. *{WGII SPM, 19.2.4, Figure 19-1, Box 19-2}*

Experiments, observations and models used to estimate future impacts and risks have improved since the AR4, with increasing understanding across sectors and regions. For example, an improved knowledge base has enabled expanded assessment of risks for human security and livelihoods and for the oceans. For some aspects of climate change and climate change impacts, uncertainty about future outcomes has narrowed. For others, uncertainty will persist. Some of the persistent uncertainties are grounded in the mechanisms that control the magnitude and pace of climate change. Others emerge from potentially complex interactions between the changing climate and the underlying vulnerability and exposure of people, societies and ecosystems. The combination of persistent uncertainty in key mechanisms plus the prospect of complex interactions motivates a focus on risk in this report. Because risk involves both probability and consequence, it is important to consider the full range of possible outcomes, including low-probability, high-consequence impacts that are difficult to simulate. *{WGII 2.1–2.4, 3.6, 4.3, 11.3, 12.6, 19.2, 19.6, 21.3–21.5, 22.4, 25.3–25.4, 25.11, 26.2}*

2.2 Projected changes in the climate system

Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is *very likely* that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise.

The projected changes in Section 2.2 are for 2081–2100 relative to 1986–2005, unless otherwise indicated.

2.2.1 Air temperature

The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is similar for the four RCPs, and will *likely* be in the range 0.3°C to 0.7°C (*medium confidence*)[30]. This range assumes no major volcanic eruptions or changes in some natural sources (e.g., methane (CH_4) and nitrous oxide (N_2O)), or unexpected changes in total solar irradiance. Future climate will depend on

Box 2.3 | Models and Methods for Estimating Climate Change Risks, Vulnerability and Impacts

Future climate-related risks, vulnerabilities and impacts are estimated in the AR5 through experiments, analogies and models, as in previous assessments. 'Experiments' involve deliberately changing one or more climate-system factors affecting a subject of interest to reflect anticipated future conditions, while holding the other factors affecting the subject constant. 'Analogies' make use of existing variations and are used when controlled experiments are impractical due to ethical constraints, the large area or long time required or high system complexity. Two types of analogies are used in projections of climate and impacts. Spatial analogies identify another part of the world currently experiencing similar conditions to those anticipated to be experienced in the future. Temporal analogies use changes in the past, sometimes inferred from paleo-ecological data, to make inferences about changes in the future. 'Models' are typically numerical simulations of real-world systems, calibrated and validated using observations from experiments or analogies, and then run using input data representing future climate. Models can also include largely descriptive narratives of possible futures, such as those used in scenario construction. Quantitative and descriptive models are often used together. Impacts are modelled, among other things, for water resources, biodiversity and ecosystem services on land, inland waters, the oceans and ice bodies, as well as for urban infrastructure, agricultural productivity, health, economic growth and poverty. *{WGII 2.2.1, 2.4.2, 3.4.1, 4.2.2, 5.4.1, 6.5, 7.3.1, 11.3.6, 13.2.2}*

Risks are evaluated based on the interaction of projected changes in the Earth system with the many dimensions of vulnerability in societies and ecosystems. The data are seldom sufficient to allow direct estimation of probabilities of a given outcome; therefore, expert judgment using specific criteria (large magnitude, high probability or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation) is used to integrate the diverse information sources relating to the severity of consequences and the likelihood of occurrence into a risk evaluation, considering exposure and vulnerability in the context of specific hazards. *{WGII 11.3, 19.2, 21.1, 21.3–21.5, 25.3–25.4, 25.11, 26.2}*

[30] The 1986–2005 period was approximately 0.61 [0.55 to 0.67] °C warmer than the period 1850–1900. *{WGI SPM E, 2.4.3}*

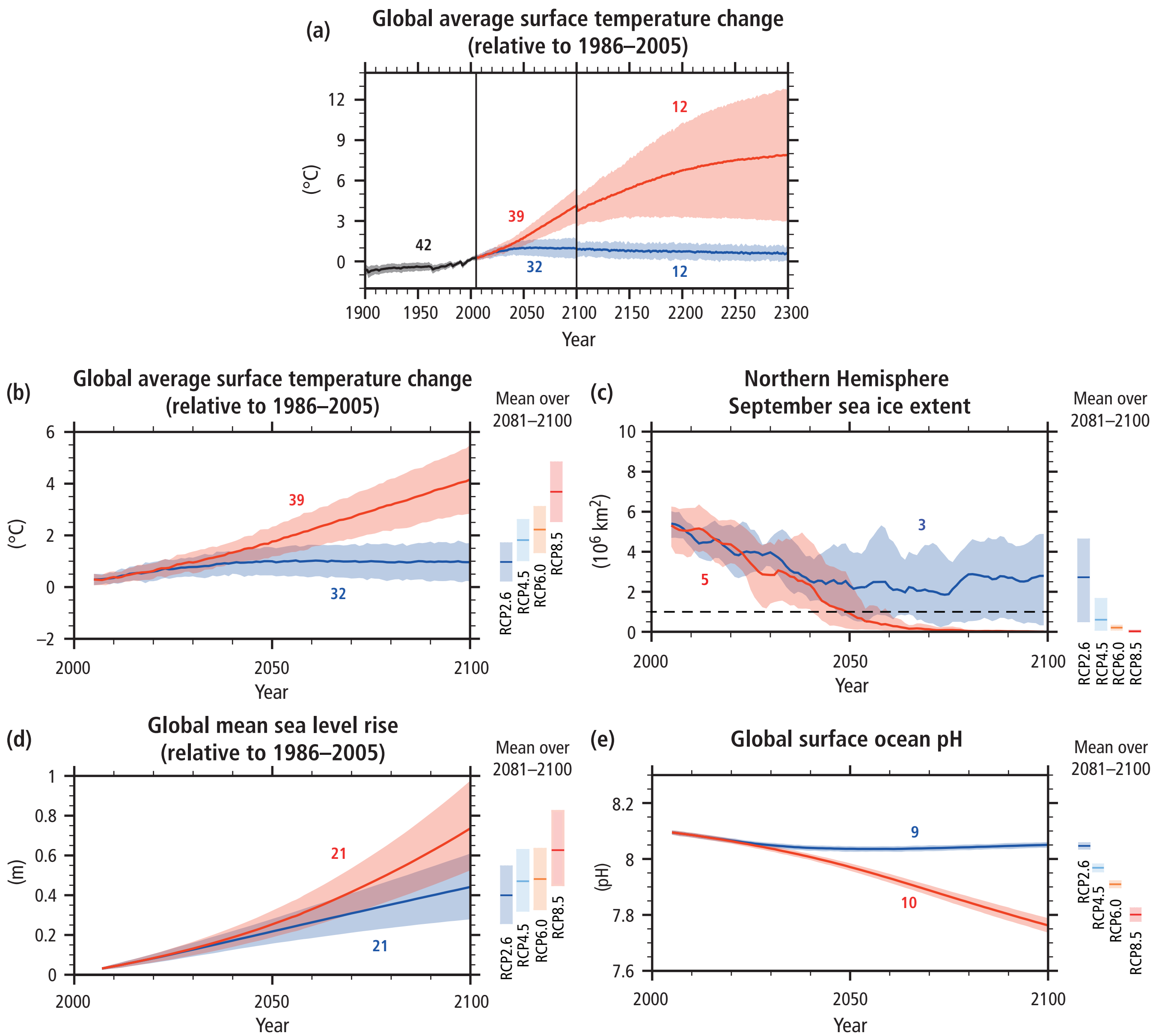

Figure 2.1 | **(a)** Time series of global annual change in mean surface temperature for the 1900–2300 period (relative to 1986–2005) from Coupled Model Intercomparison Project Phase 5 (CMIP5) concentration-driven experiments. Projections are shown for the multi-model mean (solid lines) and the 5 to 95% range across the distribution of individual models (shading). Grey lines and shading represent the CMIP5 historical simulations. Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning. **(b)** Same as (a) but for the 2006–2100 period (relative to 1986–2005). **(c)** Change in Northern Hemisphere September sea-ice extent (5 year running mean). The dashed line represents nearly ice-free conditions (i.e., when September sea-ice extent is less than 10^6 km^2 for at least five consecutive years). **(d)** Change in global mean sea level. **(e)** Change in ocean surface pH. For all panels, time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The number of CMIP5 models used to calculate the multi-model mean is indicated. The mean and associated uncertainties averaged over the 2081–2100 period are given for all RCP scenarios as coloured vertical bars on the right hand side of panels (b) to (e). For sea-ice extent (c), the projected mean and uncertainty (minimum–maximum range) is only given for the subset of models that most closely reproduce the climatological mean state and the 1979–2012 trend in the Arctic sea ice. For sea level (d), based on current understanding (from observations, physical understanding and modelling), only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. However, there is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century. *{WGI Figure SPM.7, Figure SPM.9, Figure 12.5, 6.4.4, 12.4.1, 13.4.4, 13.5.1}*

committed warming caused by past anthropogenic emissions, as well as future anthropogenic emissions and natural climate variability. By the mid-21st century, the magnitude of the projected climate change is substantially affected by the choice of emissions scenarios. Climate change continues to diverge among the scenarios through to 2100 and beyond (Table 2.1, Figure 2.1). The ranges provided for particular RCPs (Table 2.1), and those given below in Section 2.2, primarily arise from differences in the sensitivity of climate models to the imposed forcing. *{WGI SPM E.1, 11.3.2, 12.4.1}*

Table 2.1 | Projected change in global mean surface temperature and global mean sea level rise for the mid- and late 21st century, relative to the 1986–2005 period. *{WGI Table SPM.2, 12.4.1, 13.5.1, Table 12.2, Table 13.5}*

		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range [c]**	**Mean**	***Likely* range [c]**
Global Mean Surface Temperature Change (°C) [a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range [d]**	**Mean**	***Likely* range [d]**
Global Mean Sea Level Rise (m) [b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Notes:

[a] Based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble; changes calculated with respect to the 1986–2005 period. Using Hadley Centre Climatic Research Unit Gridded Surface Temperature Data Set 4 (HadCRUT4) and its uncertainty estimate (5 to 95% confidence interval), the observed warming from 1850–1900 to the reference period 1986–2005 is 0.61 [0.55 to 0.67] °C. *Likely* ranges have not been assessed here with respect to earlier reference periods because methods are not generally available in the literature for combining the uncertainties in models and observations. Adding projected and observed changes does not account for potential effects of model biases compared to observations, and for natural internal variability during the observational reference period. *{WGI 2.4.3, 11.2.2, 12.4.1, Table 12.2, Table 12.3}*

[b] Based on 21 CMIP5 models; changes calculated with respect to the 1986–2005 period. Based on current understanding (from observations, physical understanding and modelling), only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

[c] Calculated from projections as 5 to 95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean surface temperature change in 2046–2065, *confidence* is *medium*, because the relative importance of natural internal variability, and uncertainty in non-greenhouse gas forcing and response, are larger than for the 2081–2100 period. The *likely* ranges for 2046–2065 do not take into account the possible influence of factors that lead to the assessed range for near term (2016–2035) change in global mean surface temperature that is lower than the 5 to 95% model range, because the influence of these factors on longer term projections has not been quantified due to insufficient scientific understanding. *{WGI 11.3.1}*

[d] Calculated from projections as 5 to 95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean sea level rise *confidence* is *medium* for both time horizons.

Relative to 1850–1900, global surface temperature change for the end of the 21st century (2081–2100) is projected to *likely* exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (*high confidence*). Warming is *likely* to exceed 2°C for RCP6.0 and RCP8.5 (*high confidence*), *more likely than not* to exceed 2°C for RCP4.5 (*medium confidence*), but *unlikely* to exceed 2°C for RCP2.6 (*medium confidence*). *{WGI SPM E.1, 12.4.1, Table 12.3}*

The Arctic region will continue to warm more rapidly than the global mean (Figure 2.2) (*very high confidence*). The mean warming over land will be larger than over the ocean (*very high confidence*) and larger than global average warming (Figure 2.2). *{WGI SPM E.1, 11.3.2, 12.4.3, 14.8.2}*

It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases. It is *very likely* that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur. *{WGI SPM E.1, 12.4.3}*

2.2.2 Water cycle

Changes in precipitation in a warming world will not be uniform. The high latitudes and the equatorial Pacific are *likely* to experience an increase in annual mean precipitation by the end of this century under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will *likely* decrease, while in many mid-latitude wet regions, mean precipitation will *likely* increase under the RCP8.5 scenario (Figure 2.2). *{WGI SPM E.2, 7.6.2, 12.4.5, 14.3.1, 14.3.5}*

Extreme precipitation events over most mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent as global mean surface temperature increases. *{WGI SPM E.2, 7.6.2, 12.4.5}*

Globally, in all RCPs, it is *likely* that the area encompassed by monsoon systems will increase and monsoon precipitation is *likely* to intensify and El Niño-Southern Oscillation (ENSO) related precipitation variability on regional scales will *likely* intensify. *{WGI SPM E.2, 14.2, 14.4}*

2.2.3 Ocean, cryosphere and sea level

The global ocean will continue to warm during the 21st century. The strongest ocean warming is projected for the surface in tropical and Northern Hemisphere subtropical regions. At greater depth the warming will be most pronounced in the Southern Ocean (*high confidence*). *{WGI SPM E.4, 6.4.5, 12.4.7}*

It is *very likely* that the Atlantic Meridional Overturning Circulation (AMOC) will weaken over the 21st century, with best estimates and model ranges for the reduction of 11% (1 to 24%) for

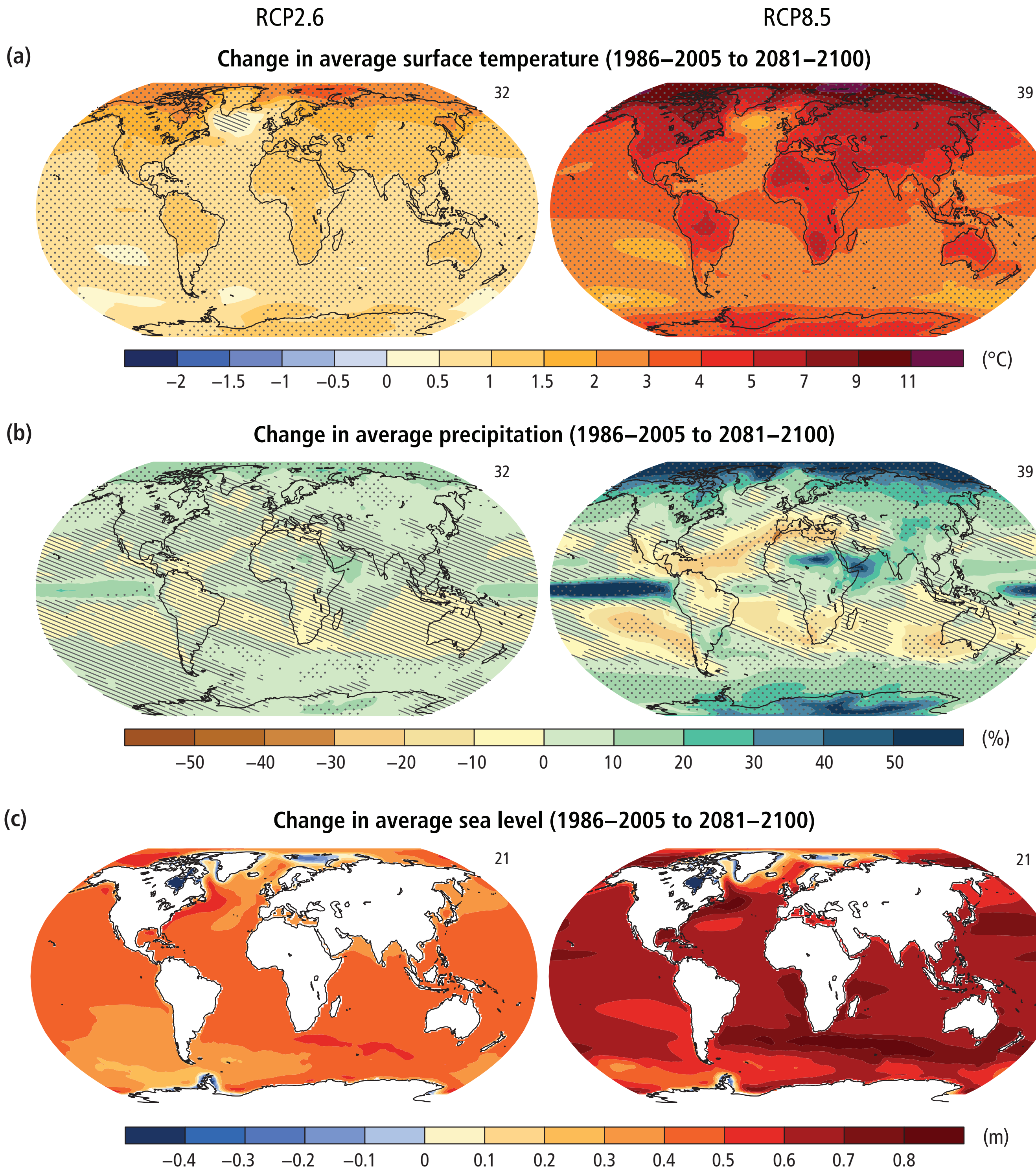

Figure 2.2 | Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean projections (i.e., the average of the model projections available) for the 2081–2100 period under the RCP2.6 (left) and RCP8.5 (right) scenarios for **(a)** change in annual mean surface temperature and **(b)** change in annual mean precipitation, in percentages, and **(c)** change in average sea level. Changes are shown relative to the 1986–2005 period. The number of CMIP5 models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (dots) on (a) and (b) indicates regions where the projected change is large compared to natural internal variability (i.e., greater than two standard deviations of internal variability in 20-year means) and where 90% of the models agree on the sign of change. Hatching (diagonal lines) on (a) and (b) shows regions where the projected change is less than one standard deviation of natural internal variability in 20-year means. *{WGI Figure SPM.8, Figure 13.20, Box 12.1}*

the RCP2.6 scenario, 34% (12 to 54%) for the RCP8.5. Nevertheless, it is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century. *{WGI SPM E.4, 12.4.7.2}*

Year-round reductions in Arctic sea ice are projected for all RCP scenarios. The subset of models that most closely reproduce the observations[31] project that a nearly ice-free Arctic Ocean[32] in September is *likely* for RCP8.5 before mid-century (*medium confidence*) (Figure 2.1). In the Antarctic, a decrease in sea ice extent and volume is projected with *low confidence*. *{WGI SPM E.5, 12.4.6.1}*

The area of Northern Hemisphere spring snow cover is *likely* to decrease by 7% for RCP2.6 and by 25% in RCP8.5 by the end of the 21st century for the multi-model average (*medium confidence*). *{WGI SPM E.5, 12.4.6}*

It is *virtually certain* that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases. The area of permafrost near the surface (upper 3.5 m) is *likely* to decrease by 37% (RCP2.6) to 81% (RCP8.5) for the multi-model average (*medium confidence*). *{WGI SPM E.5, 12.4.6}*

The global glacier volume, excluding glaciers on the periphery of Antarctica (and excluding the Greenland and Antarctic ice sheets), is projected to decrease by 15 to 55% for RCP2.6 and by 35 to 85% for RCP8.5 (*medium confidence*). *{WGI SPM E.5, 13.4.2, 13.5.1}*

Global mean sea level will continue to rise during the 21st century (Table 2.1, Figure 2.1). There has been significant improvement in understanding and projection of sea level change since the AR4. Under all RCP scenarios, the rate of sea level rise will *very likely* exceed the observed rate of 2.0 [1.7–2.3] mm/yr during 1971–2010, with the rate of rise for RCP8.5 during 2081–2100 of 8 to 16 mm/yr (*medium confidence*). *{WGI SPM B4, SPM E.6, 13.5.1}*

Sea level rise will not be uniform across regions. By the end of the 21st century, it is *very likely* that sea level will rise in more than about 95% of the ocean area. Sea level rise depends on the pathway of CO_2 emissions, not only on the cumulative total; reducing emissions earlier rather than later, for the same cumulative total, leads to a larger mitigation of sea level rise. About 70% of the coastlines worldwide are projected to experience sea level change within ±20% of the global mean (Figure 2.2). It is *very likely* that there will be a significant increase in the occurrence of future sea level extremes in some regions by 2100. *{WGI SPM E.6, TS 5.7.1, 12.4.1, 13.4.1, 13.5.1, 13.6.5, 13.7.2, Table 13.5}*

2.2.4 Carbon cycle and biogeochemistry

Ocean uptake of anthropogenic CO_2 will continue under all four RCPs through to 2100, with higher uptake for higher concentration pathways (*very high confidence*). The future evolution of the land carbon uptake is less certain. A majority of models projects a continued land carbon uptake under all RCPs, but some models simulate a land carbon loss due to the combined effect of climate change and land use change. *{WGI SPM E.7, 6.4.2, 6.4.3}*

Based on Earth System Models, there is *high confidence* that the feedback between climate change and the carbon cycle will amplify global warming. Climate change will partially offset increases in land and ocean carbon sinks caused by rising atmospheric CO_2. As a result more of the emitted anthropogenic CO_2 will remain in the atmosphere, reinforcing the warming. *{WGI SPM E.7, 6.4.2, 6.4.3}*

Earth System Models project a global increase in ocean acidification for all RCP scenarios by the end of the 21st century, with a slow recovery after mid-century under RCP2.6. The decrease in surface ocean pH is in the range of 0.06 to 0.07 (15 to 17% increase in acidity) for RCP2.6, 0.14 to 0.15 (38 to 41%) for RCP4.5, 0.20 to 0.21 (58 to 62%) for RCP6.0, and 0.30 to 0.32 (100 to 109%) for RCP8.5 (Figure 2.1). *{WGI SPM E.7, 6.4.4}*

It is *very likely* that the dissolved oxygen content of the ocean will decrease by a few percent during the 21st century in response to surface warming, predominantly in the subsurface mid-latitude oceans. There is no consensus on the future volume of low oxygen waters in the open ocean because of large uncertainties in potential biogeochemical effects and in the evolution of tropical ocean dynamics. *{WGI TS 5.6, 6.4.5, WGII TS B-2, 6.1}*

2.2.5 Climate system responses

Climate system properties that determine the response to external forcing have been estimated both from climate models and from analysis of past and recent climate change. The equilibrium climate sensitivity (ECS)[33] is *likely* in the range 1.5°C to 4.5°C, *extremely unlikely* less than 1°C, and *very unlikely* greater than 6°C. *{WGI SPM D.2, TS TFE.6, 10.8.1, 10.8.2, 12.5.4, Box 12.2}*

Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Multiple lines of evidence indicate a strong and consistent near-linear relationship across all scenarios considered between net cumulative CO_2 emissions (including the impact of CO_2 removal) and projected global temperature change to the year 2100 (Figure 2.3). Past emissions and observed warming support this relationship within uncertainties. Any given level of warming is associated with a range of cumulative CO_2 emissions (depending on non-CO_2 drivers), and therefore, for example, higher emissions in earlier decades imply lower emissions later. *{WGI SPM E.8, TS TFE.8, 12.5.4}*

The global mean peak surface temperature change per trillion tonnes of carbon (1000 GtC) emitted as CO_2 is *likely* in the range of 0.8°C to 2.5°C. This quantity, called the transient climate response to cumulative carbon emissions (TCRE), is supported by both modelling and observational evidence and applies to cumulative emissions up to about 2000 GtC. *{WGI SPM D.2, TS TFE.6, 12.5.4, Box 12.2}*

[31] Climatological mean state and the 1979–2012 trend in Arctic sea-ice extent.

[32] When sea-ice extent is less than one million km^2 for at least five consecutive years.

[33] Defined as the equilibrium global average surface warming following a doubling of CO_2 concentration (relative to pre-industrial).

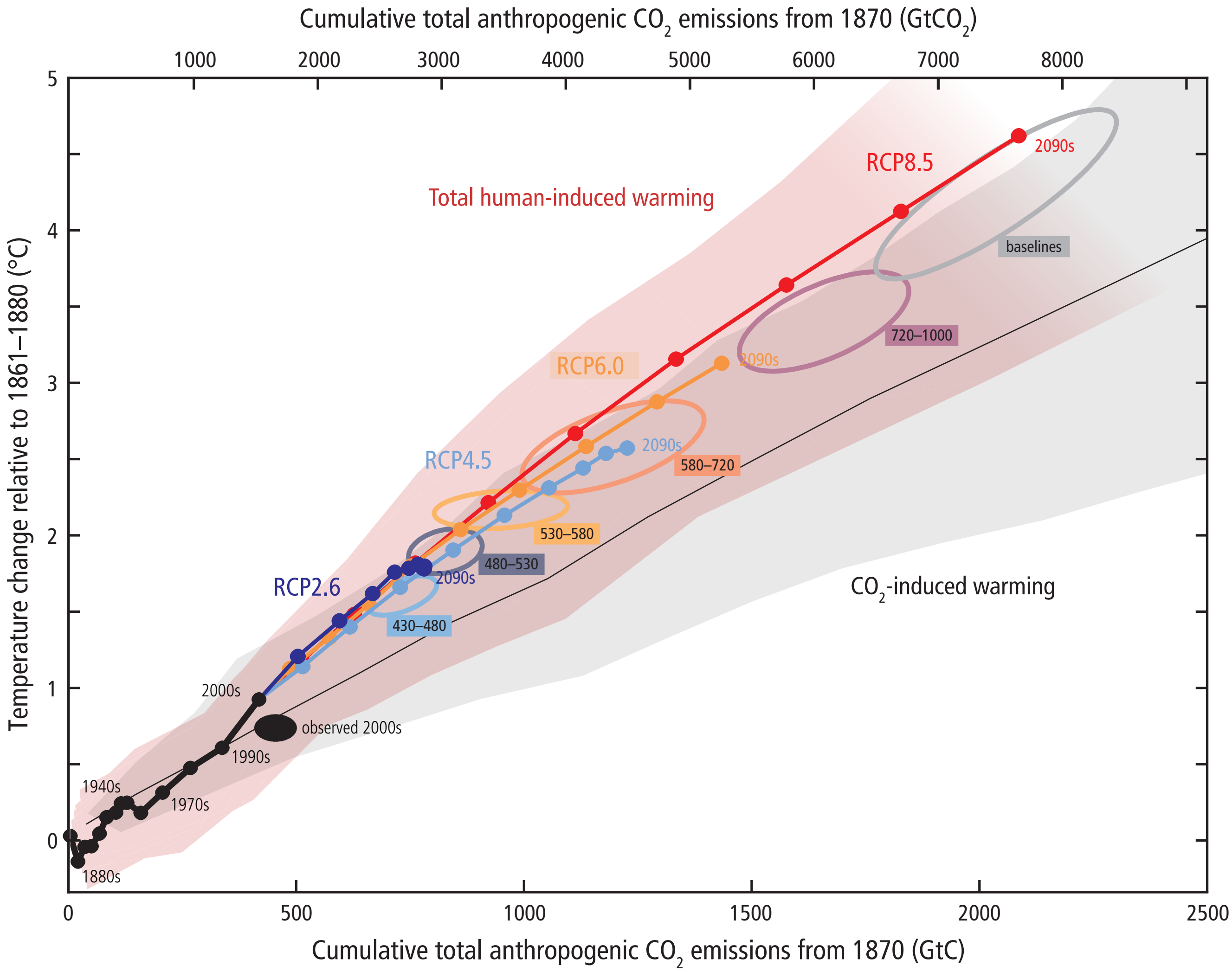

Figure 2.3 | Global mean surface temperature increase as a function of cumulative total global carbon dioxide (CO_2) emissions from various lines of evidence. Multi-model results from a hierarchy of climate carbon-cycle models for each Representative Concentration Pathway (RCP) until 2100 are shown (coloured lines). Model results over the historical period (1860 to 2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. Dots indicate decadal averages, with selected decades labelled. Ellipses show total anthropogenic warming in 2100 versus cumulative CO_2 emissions from 1870 to 2100 from a simple climate model (median climate response) under the scenario categories used in WGIII. Temperature values are always given relative to the 1861–1880 period, and emissions are cumulative since 1870. Black filled ellipse shows observed emissions to 2005 and observed temperatures in the decade 2000–2009 with associated uncertainties. *{WGI SPM E.8, TS TFE.8, Figure 1, TS.SM.10, 12.5.4, Figure 12.45, WGIII Table SPM.1, Table 6.3}*

Warming caused by CO_2 emissions is effectively irreversible over multi-century timescales unless measures are taken to remove CO_2 from the atmosphere. Ensuring CO_2-induced warming remains *likely* less than 2°C requires cumulative CO_2 emissions from all anthropogenic sources to remain below about 3650 $GtCO_2$ (1000 GtC), over half of which were already emitted by 2011. *{WGI SPM E.8, TS TFE.8, 12.5.2, 12.5.3, 12.5.4}*

Multi-model results show that limiting total human-induced warming (accounting for both CO_2 and other human influences on climate) to less than 2°C relative to the period 1861–1880 with a probability of >66% would require total CO_2 emissions from all anthropogenic sources since 1870 to be limited to about 2900 $GtCO_2$ when accounting for non-CO_2 forcing as in the RCP2.6 scenario, with a range of 2550 to 3150 $GtCO_2$ arising from variations in non-CO_2 climate drivers across the scenarios considered by WGIII (Table 2.2). About 1900 [1650 to 2150] $GtCO_2$ were emitted by 2011, leaving about 1000 $GtCO_2$ to be consistent with this temperature goal. Estimated total fossil carbon reserves exceed this remaining amount by a factor of 4 to 7, with resources much larger still. *{WGI SPM E.8, TS TFE.8, Figure 1, TS.SM.10, 12.5.4, Figure 12.45, WGIII Table SPM.1, Table 6.3, Table 7.2}*

Table 2.2 | Cumulative carbon dioxide (CO_2) emission consistent with limiting warming to less than stated temperature limits at different levels of probability, based on different lines of evidence. *{WGI 12.5.4, WGIII 6}*

Cumulative CO_2 emissions from 1870 in $GtCO_2$									
Net anthropogenic warming [a]	<1.5°C			<2°C			<3°C		
Fraction of simulations meeting goal [b]	66%	50%	33%	66%	50%	33%	66%	50%	33%
Complex models, RCP scenarios only [c]	2250	2250	2550	2900	3000	3300	4200	4500	4850
Simple model, WGIII scenarios [d]	No data	2300 to 2350	2400 to 2950	2550 to 3150	2900 to 3200	2950 to 3800	n.a. [e]	4150 to 5750	5250 to 6000
Cumulative CO_2 emissions from 2011 in $GtCO_2$									
Complex models, RCP scenarios only [c]	400	550	850	1000	1300	1500	2400	2800	3250
Simple model, WGIII scenarios [d]	No data	550 to 600	600 to 1150	750 to 1400	1150 to 1400	1150 to 2050	n.a. [e]	2350 to 4000	3500 to 4250
Total fossil carbon available in 2011 [f]: 3670 to 7100 $GtCO_2$ (reserves) and 31300 to 50050 $GtCO_2$ (resources)									

Notes:

[a] Warming due to CO_2 and non-CO_2 drivers. Temperature values are given relative to the 1861–1880 base period.

[b] Note that the 66% range in this table should not be equated to the likelihood statements in Table SPM.1 and Table 3.1 and WGIII Table SPM.1. The assessment in these latter tables is not only based on the probabilities calculated for the full ensemble of scenarios in WGIII using a single climate model, but also the assessment in WGI of the uncertainty of the temperature projections not covered by climate models.

[c] Cumulative CO_2 emissions at the time the temperature threshold is exceeded that are required for 66%, 50% or 33% of the Coupled Model Intercomparison Project Phase 5 (CMIP5) complex models Earth System Model (ESM) and Earth System Models of Intermediate Complexity (EMIC) simulations, assuming non-CO_2 forcing follows the RCP8.5 scenario. Similar cumulative emissions are implied by other RCP scenarios. For most scenario–threshold combinations, emissions and warming continue after the threshold is exceeded. Nevertheless, because of the cumulative nature of CO_2 emissions, these figures provide an indication of the cumulative CO_2 emissions implied by the CMIP5 model simulations under RCP-like scenarios. Values are rounded to the nearest 50.

[d] Cumulative CO_2 emissions at the time of peak warming from WGIII scenarios for which a fraction of greater than 66% (66 to 100%), greater than 50% (50 to 66%) or greater than 33% (33 to 50%) of climate simulations keep global mean temperature increase to below the stated threshold. Ranges indicate the variation in cumulative CO_2 emissions arising from differences in non-CO_2 drivers across the WGIII scenarios. The fraction of climate simulations for each scenario is derived from a 600-member parameter ensemble of a simple carbon-cycle climate model, Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), in a probabilistic mode. Parameter and scenario uncertainty are explored in this ensemble. Structural uncertainties cannot be explored with a single model set-up. Ranges show the impact of scenario uncertainty, with 80% of scenarios giving cumulative CO_2 emissions within the stated range for the given fraction of simulations. Simple model estimates are constrained by observed changes over the past century, do not account for uncertainty in model structure and may omit some feedback processes: they are hence slightly higher than the CMIP5 complex models estimates. Values are rounded to the nearest 50.

[e] The numerical results for the cumulative CO_2 emissions for staying below 3°C with greater than 66% (66 to 100%) is greatly influenced by a large number of scenarios that would also meet the 2°C objective and therefore not comparable with numbers provided for the other temperature threshold.

[f] Reserves are quantities able to be recovered under existing economic and operating conditions; resources are those where economic extraction is potentially feasible. *{WGIII Table 7.2}*

2.3 Future risks and impacts caused by a changing climate

Climate change will amplify existing risks and create new risks for natural and human systems. Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Increasing magnitudes of warming increase the likelihood of severe, pervasive and irreversible impacts for people, species and ecosystems. Continued high emissions would lead to mostly negative impacts for biodiversity, ecosystem services and economic development and amplify risks for livelihoods and for food and human security.

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Rising rates and magnitudes of warming and other changes in the climate system, accompanied by ocean acidification, increase the risk of severe, pervasive, and in some cases, irreversible detrimental impacts. Future climate change will amplify existing climate-related risks and create new risks. *{WGII SPM B, Figure SPM.1}*

Key risks are potentially severe impacts relevant to understanding dangerous anthropogenic interference with the climate system. Risks are considered key due to high hazard or high vulnerability of societies and systems exposed, or both. Their identification is based on large magnitude or high probability of impacts; irreversibility or timing of impacts; persistent vulnerability or exposure; or limited potential to reduce risks. Some risks are particularly relevant for individual regions (Figure 2.4), while others are global (Table 2.3). For risk assessment it is important to evaluate the widest possible range of impacts, including low-probability outcomes with large consequences. Risk levels often increase with temperature (Box 2.4) and are sometimes more directly linked to other dimensions of climate change, such as the rate of warming, as well as the magnitudes and rates of ocean acidification and sea level rise (Figure 2.5). *{WGII SPM A-3, SPM B-1}*

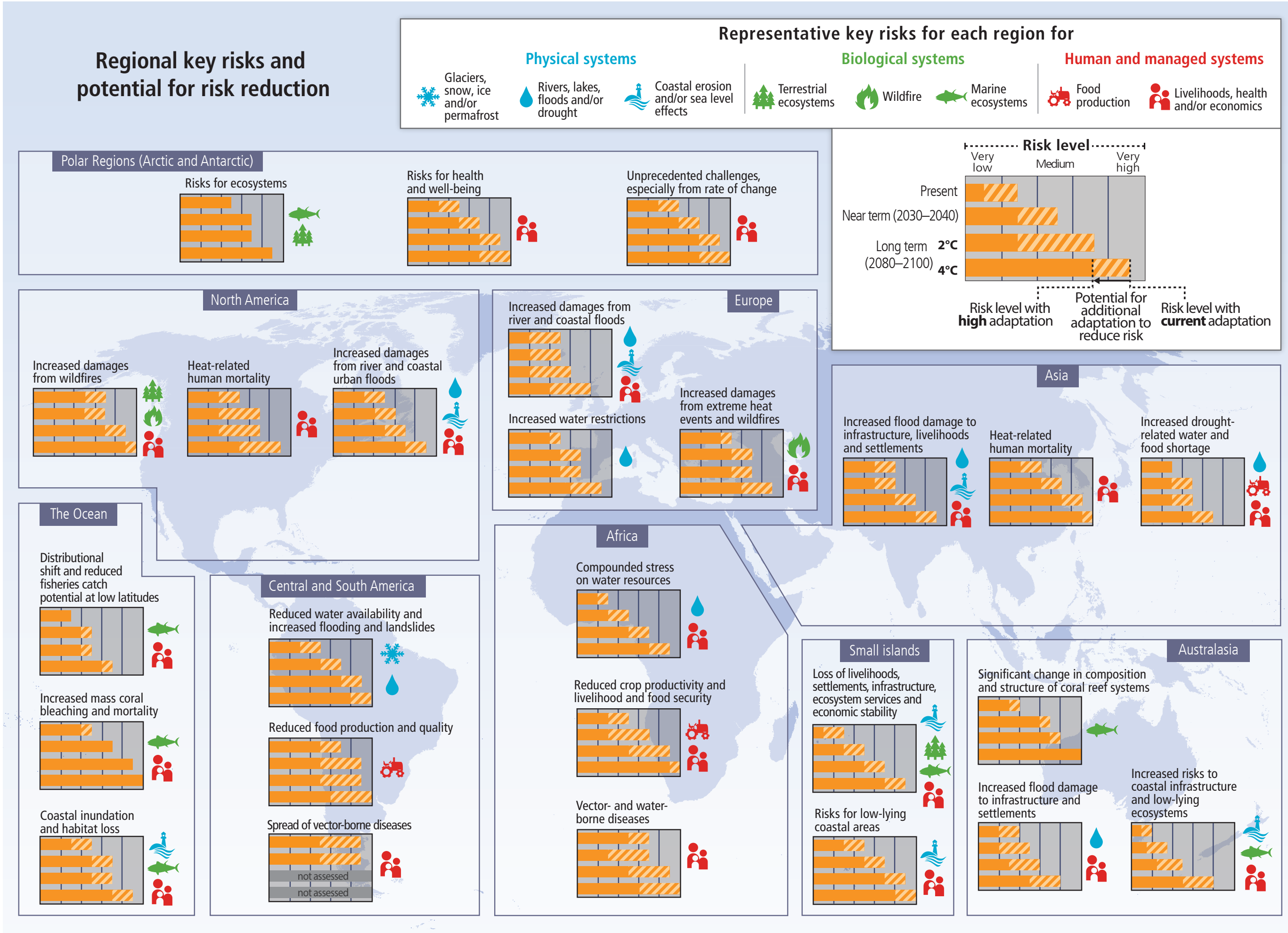

Figure 2.4 | Representative key risks for each region, including the potential for risk reduction through adaptation and mitigation, as well as limits to adaptation. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Risk levels are assessed as very low, low, medium, high or very high for three timeframes: the present, near term (here, for 2030–2040) and long term (here, for 2080–2100). In the near term, projected levels of global mean temperature increase do not diverge substantially across different emission scenarios. For the long term, risk levels are presented for two possible futures (2°C and 4°C global mean temperature increase above pre-industrial levels). For each time frame, risk levels are indicated for a continuation of current adaptation and assuming high levels of current or future adaptation. Risk levels are not necessarily comparable, especially across regions. *{WGII SPM Assessment Box SPM.2 Table 1}*

Key risks that span sectors and regions include the following (*high confidence*) *{WGII SPM B-1}*:

1. Risk of severe ill-health and disrupted livelihoods resulting from storm surges, sea level rise and coastal flooding; inland flooding in some urban regions; and periods of extreme heat.

2. Systemic risks due to extreme weather events leading to break-down of infrastructure networks and critical services.

3. Risk of food and water insecurity and loss of rural livelihoods and income, particularly for poorer populations.

4. Risk of loss of ecosystems, biodiversity and ecosystem goods, functions and services.

The overall risks of future climate change impacts can be reduced by limiting the rate and magnitude of climate change, including ocean acidification. Some risks are considerable even at 1°C global mean temperature increase above pre-industrial levels. Many global risks are high to very high for global temperature increases of 4°C or more (see Box 2.4). These risks include severe and wide-spread impacts on unique and threatened systems, the extinction of many species, large risks to food security and compromised normal human activities, including growing food or working outdoors in some areas for parts of the year, due to the combination of high temperature and humidity (*high confidence*). The precise levels of climate change sufficient to trigger abrupt and irreversible change remain uncertain, but the risk associated with crossing such thresholds in the earth system or in interlinked human and natural systems increases with rising temperature (*medium confidence*). *{WGII SPM B-1}*

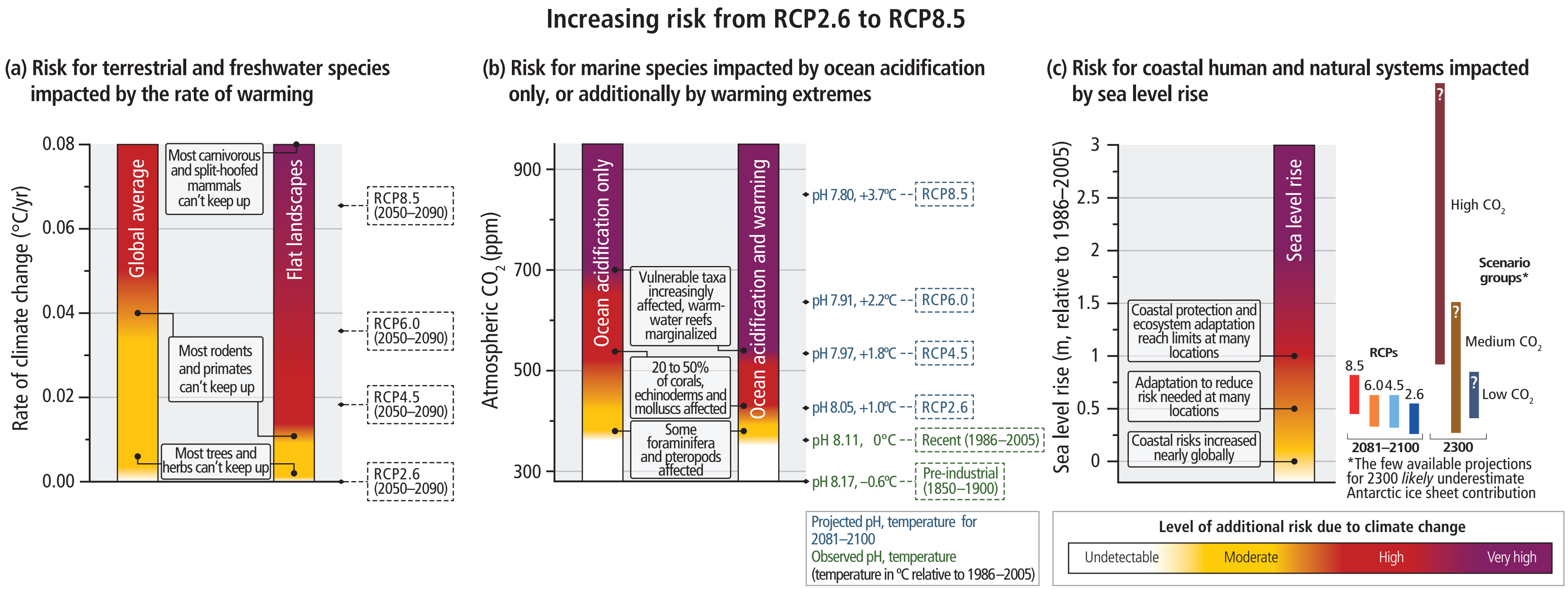

Figure 2.5 | The risks of: **(a)** disruption of the community composition of terrestrial and freshwater ecosystems due to the rate of warming; **(b)** marine organisms impacted by ocean acidification (OA) or warming extremes combined with OA; and **(c)** coastal human and natural systems impacted by sea level rise. The risk level criteria are consistent with those used in Box 2.4 and their calibration is illustrated by the annotations to each panel. **(a)** At high rates of warming, major groups of terrestrial and freshwater species are unable to move fast enough to stay within the spatially shifting climate envelopes to which they are adapted. The median observed or modelled speeds at which species populations move (km/decade) are compared against the speed at which climate envelopes move across the landscape, given the projected climate change rates for each Representative Concentration Pathway (RCP) over the 2050–2090 period. The results are presented for the average of all landscapes, globally, as well as for flat landscapes, where the climate envelope moves especially fast. **(b)** Sensitivity to ocean acidification is high in marine organisms building a calcium carbonate shell. The risks from OA increase with warming because OA lowers the tolerated levels of heat exposure, as seen in corals and crustaceans. **(c)** The height of a 50-year flood event has already increased in many coastal locations. A 10- to more than 100-fold increase in the frequency of floods in many places would result from a 0.5 m rise in sea level in the absence of adaptation. Local adaptation capacity (and, in particular, protection) reaches its limits for ecosystems and human systems in many places under a 1 m sea level rise. (2.2.4, Table 2.1, Figure 2.8) *{WGI 3.7.5, 3.8, 6.4.4, Figure 13.25, WGII Figure SPM.5, Figure 4-5, Figure 6-10, Box CC-OA, 4.4.2.5, 5.2, 5.3–5.5, 5.4.4, 5.5.6, 6.3}*

Adaptation can substantially reduce the risks of climate change impacts, but greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). The potential for adaptation, as well as constraints and limits to adaptation, varies among sectors, regions, communities and ecosystems. The scope for adaptation changes over time and is closely linked to socio-economic development pathways and circumstances. See Figure 2.4 and Table 2.3, along with Topics 3 and 4. *{WGII SPM B, SPM C, TS B, TS C}*

2.3.1 Ecosystems and their services in the oceans, along coasts, on land and in freshwater

Risks of harmful impacts on ecosystems and human systems increase with the rates and magnitudes of warming, ocean acidification, sea level rise and other dimensions of climate change (*high confidence*). Future risk is indicated to be high by the observation that natural global climate change at rates lower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years on land and in the oceans (*high confidence*). Many plant and animal species will be unable to adapt locally or move fast enough during the 21st century to track suitable climates under mid- and high range rates of climate change (RCP4.5, RCP6.0 and RCP8.5) (*medium confidence*) (Figure 2.5a). Coral reefs and polar ecosystems are highly vulnerable. *{WGII SPM A-1, SPM B-2, 4.3–4, 5.4, 6.1, 6.3, 6.5, 25.6, 26.4, 29.4, Box CC-CR, Box CC-MB, Box CC-RF}*

A large fraction of terrestrial, freshwater and marine species faces increased extinction risk due to climate change during and beyond the 21st century, especially as climate change interacts with other stressors (*high confidence*). Extinction risk is increased relative to pre-industrial and present periods, under all RCP scenarios, as a result of both the magnitude and rate of climate change (*high confidence*). Extinctions will be driven by several climate-associated drivers (warming, sea-ice loss, variations in precipitation, reduced river flows, ocean acidification and lowered ocean oxygen levels) and the interactions among these drivers and their interaction with simultaneous habitat modification, over-exploitation of stocks, pollution, eutrophication and invasive species (*high confidence*). *{WGII SPM B-2, 4.3–4.4, 6.1, 6.3, 6.5, 25.6, 26.4, Box CC-RF, Box CC-MB}*

Global marine species redistribution and marine biodiversity reduction in sensitive regions, under climate change, will challenge the sustained provision of fisheries productivity and other ecosystem services, especially at low latitudes (*high confidence*). By the mid-21st century, under 2°C global warming relative to pre-industrial temperatures, shifts in the geographical range of marine species will cause species richness and fisheries catch potential to increase, on average, at mid and high latitudes (*high confidence*) and to decrease at tropical latitudes and in semi-enclosed seas (Figure 2.6a) (*medium confidence*). The progressive expansion of Oxygen Minimum Zones and anoxic 'dead zones' in the oceans will further constrain fish habitats (*medium confidence*). Open-ocean net primary production is projected to redistribute and to decrease globally, by 2100, under all RCP scenarios (*medium confidence*). Climate change adds to the threats of over-fishing and other non-climatic stressors (*high confidence*). *{WGII SPM B-2, 6.3–6.5, 7.4, 25.6, 28.3, 29.3, 30.6–30.7, Box CC-MB, Box CC-PP}*

Marine ecosystems, especially coral reefs and polar ecosystems, are at risk from ocean acidification (*medium* to *high confidence*). Ocean acidification has impacts on the physiology, behaviour and population dynamics of organisms. The impacts on individual species and the number of species affected in species groups increase from RCP4.5 to RCP8.5. Highly calcified molluscs, echinoderms and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*) (Figure 2.6b). Ocean acidification acts together with other global changes (e.g., warming, progressively lower oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*), leading to interactive, complex and amplified impacts for species and ecosystems (Figure 2.5b). *{WGII SPM B-2, Figure SPM.6B, 5.4, 6.3.2, 6.3.5, 22.3, 25.6, 28.3, 30.5, Figure 6-10, Box CC-CR, Box CC-OA, Box TS.7}*

Carbon stored in the terrestrial biosphere is susceptible to loss to the atmosphere as a result of climate change, deforestation and ecosystem degradation (*high confidence*). The aspects of climate change with direct effects on stored terrestrial carbon include high temperatures, drought and windstorms; indirect effects include increased risk of fires, pest and disease outbreaks**.** Increased tree mortality and associated forest dieback is projected to occur in many regions over the 21st century (*medium confidence*), posing risks for carbon storage, biodiversity, wood production, water quality, amenity and economic activity. There is a high risk of substantial carbon and methane emissions as a result of permafrost thawing. *{WGII SPM, 4.2–4.3, Figure 4-8, Box 4-2, Box 4-3, Box 4-4}*

Coastal systems and low-lying areas will increasingly experience submergence, flooding and erosion throughout the 21st century and beyond, due to sea level rise (*very high confidence*). The population and assets projected to be exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development and urbanization (*high confidence*). Climatic and non-climatic drivers affecting coral reefs will erode habitats, increase coastline exposure to waves and storms and degrade environmental features important to fisheries and tourism (*high confidence*). Some low-lying developing countries and small island states are expected to face very high impacts that could have associated damage and adaptation costs of several percentage points of gross domestic product (GDP) (Figure 2.5c). *{WGII 5.3–5.5, 22.3, 24.4, 25.6, 26.3, 26.8, 29.4, Table 26-1, Box 25-1, Box CC-CR}*

2.3.2 Water, food and urban systems, human health, security and livelihoods

The fractions of the global population that will experience water scarcity and be affected by major river floods are projected to increase with the level of warming in the 21st century (*robust evidence, high agreement*). *{WGII 3.4–3.5, 26.3, 29.4, Table 3-2, Box 25-8}*

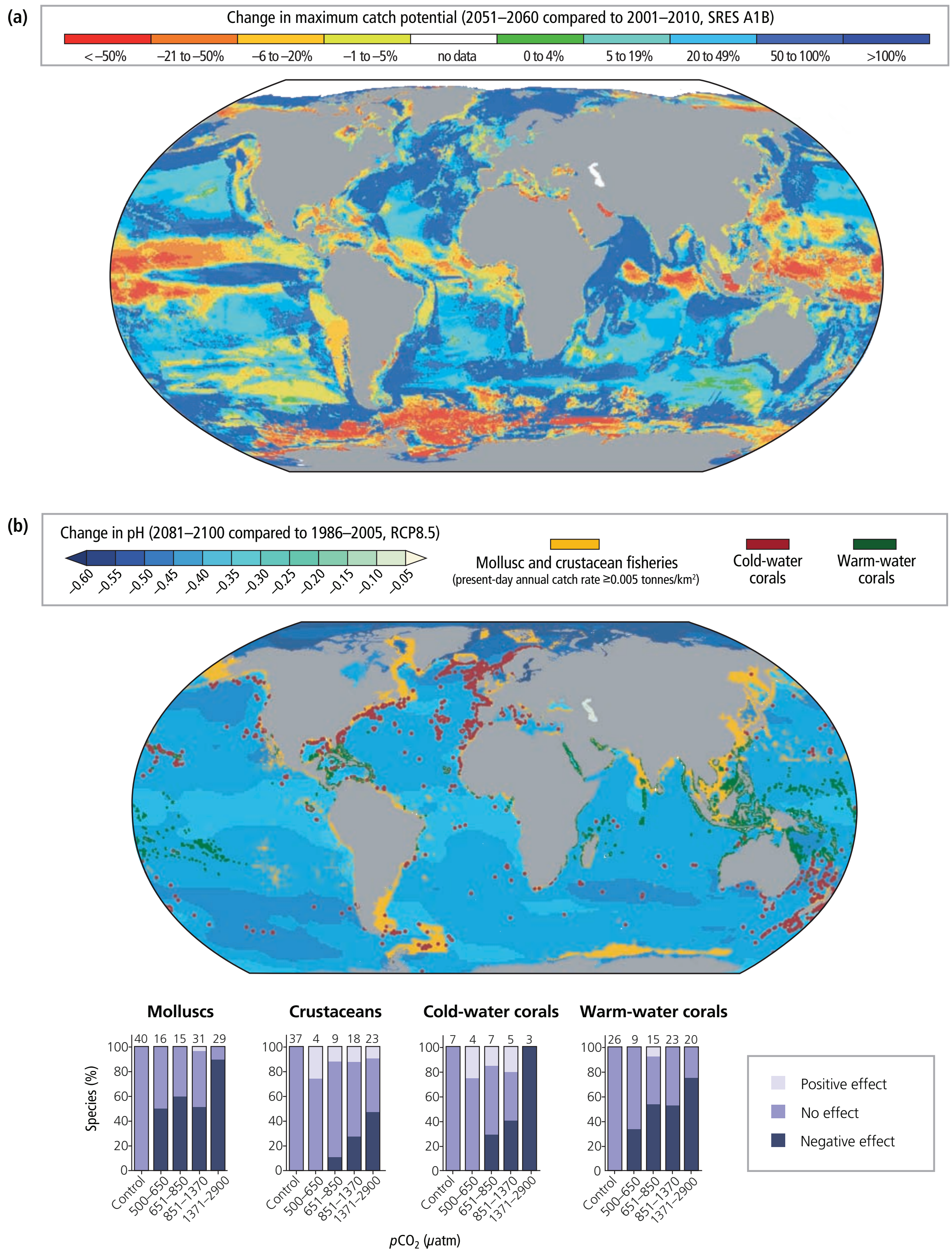

Figure 2.6 | Climate change risks for fisheries. **(a)** Projected global redistribution of maximum catch potential of ~1000 species of exploited fishes and invertebrates, comparing the 10-year averages over 2001–2010 and 2051–2060, using ocean conditions based on a single climate model under a moderate to high warming scenario (2°C warming relative to pre-industrial temperatures), without analysis of potential impacts of overfishing or ocean acidification. **(b)** Marine mollusc and crustacean fisheries (present-day estimated annual catch rates ≥0.005 tonnes/km^2) and known locations of cold- and warm-water corals, depicted on a global map showing the projected distribution of surface ocean acidification by 2100 under RCP8.5. The bottom panel compares the percentage of species sensitive to ocean acidification for corals, molluscs and crustaceans, vulnerable animal phyla with socio-economic relevance (e.g., for coastal protection and fisheries). The number of species analysed across studies is given on top of the bars for each category of elevated CO_2. For 2100, RCP scenarios falling within each pCO_2 category are as follows: RCP4.5 for 500 to 650 μatm, RCP6.0 for 651 to 850 μatm and RCP8.5 for 851 to 1370 μatm. By 2150, RCP8.5 falls within the 1371 to 2900 μatm category. The control category corresponds to 380 μatm (The unit μatm is approximately equivalent to ppm in the atmosphere). *{WGI Figure SPM.8, Box SPM.1, WGII SPM B-2, Figure SPM.6, 6.1, 6.3, 30.5, Figure 6-10 , Figure 6-14}*

Climate change over the 21st century is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions (*robust evidence*, *high agreement*), intensifying competition for water among sectors (*limited evidence*, *medium agreement*). In presently dry regions, the frequency of droughts will *likely* increase by the end of the 21st century under RCP8.5 (*medium confidence*). In contrast, water resources are projected to increase at high latitudes (*robust evidence, high agreement*). The interaction of increased temperature; increased sediment, nutrient and pollutant loadings from heavy rainfall; increased concentrations of pollutants during droughts; and disruption of treatment facilities during floods will reduce raw water quality and pose risks to drinking water quality (*medium evidence, high agreement*). *{WGI 12.4, WGII 3.2, 3.4–3.6, 22.3, 23.9, 25.5, 26.3, Table 3-2, Table 23-3, Box 25-2, Box CC-RF, Box CC-WE}*

All aspects of food security are potentially affected by climate change, including food production, access, use and price stability (*high confidence*). For wheat, rice and maize in tropical and temperate regions, climate change without adaptation is projected to negatively impact production at local temperature increases of 2°C or more above late 20th century levels, although individual locations may benefit (*medium confidence*). Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the 2030–2049 period showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than 25%, compared with the late 20th century. Global temperature increases of ~4°C or more above late 20th century levels, combined with increasing food demand, would pose large risks to food security, both globally and regionally (*high confidence*) (Figure 2.4, 2.7). The relationship between global and regional warming is explained in 2.2.1. *{WGII 6.3–6.5, 7.4–7.5, 9.3, 22.3, 24.4, 25.7, 26.5, Table 7-2, Table 7-3, Figure 7-1, Figure 7-4, Figure 7-5, Figure 7-6, Figure 7-7, Figure 7-8, Box 7-1}*

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). Health impacts include greater likelihood of injury and death due to more intense heat waves and fires, increased risks from foodborne and waterborne diseases and loss of work capacity and reduced labour productivity in vulnerable populations (*high confidence*). Risks of undernutrition in poor regions will increase (*high confidence*). Risks from vector-borne diseases are projected to generally increase with warming, due to the extension of the infection area and season, despite reductions in some areas that become too hot for disease vectors (*medium confidence*). Globally, the magnitude and severity of negative impacts will increasingly outweigh positive impacts (*high confidence*). By 2100 for RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is expected to compromise common human activities, including growing food and working outdoors (*high confidence*). *{WGII SPM B-2, 8.2, 11.3–11.8, 19.3, 22.3, 25.8, 26.6, Figure 25-5, Box CC-HS}*

In urban areas, climate change is projected to increase risks for people, assets, economies and ecosystems, including risks from heat stress, storms and extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, water scarcity, sea level rise and storm surges (*very high confidence*). These risks will be amplified for those lacking essential infrastructure and services or living in exposed areas. *{WGII 3.5, 8.2–8.4, 22.3, 24.4–24.5, 26.8, Table 8-2, Box 25-9, Box CC-HS}*

Rural areas are expected to experience major impacts on water availability and supply, food security, infrastructure and agricultural incomes, including shifts in the production areas of food and non-food crops around the world (*high confidence*). These impacts will disproportionately affect the welfare of the poor in rural areas, such as female-headed households and those with limited access to land, modern agricultural inputs, infrastructure and education. *{WGII 5.4, 9.3, 25.9, 26.8, 28.2, 28.4, Box 25-5}*

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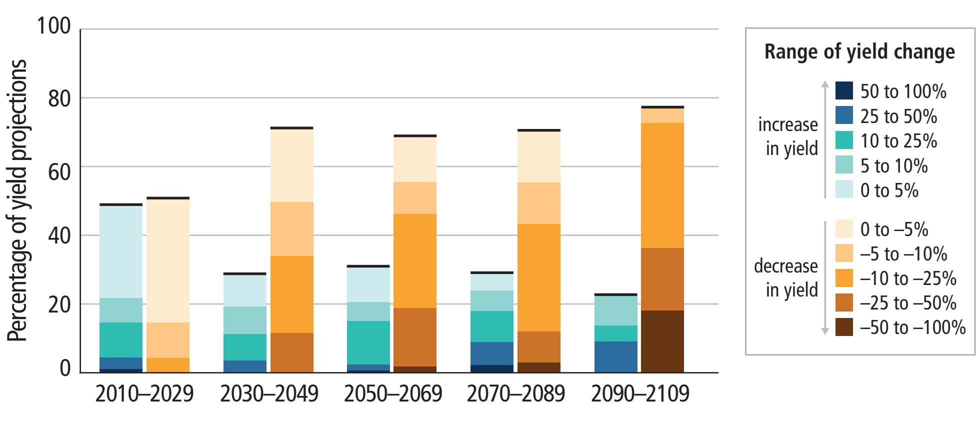
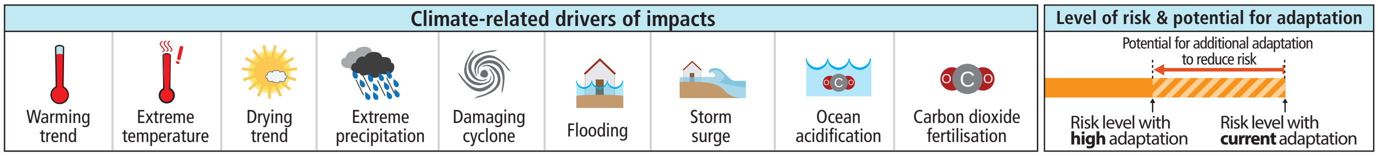


Figure 2.7 | Summary of projected changes in crop yields (mostly wheat, maize, rice and soy) due to climate change over the 21st century. The figure combines 1090 data points from crop model projections, covering different emission scenarios, tropical and temperate regions and adaptation and no-adaptation cases. The projections are sorted into the 20-year periods (horizontal axis) during which their midpoint occurs. Changes in crop yields are relative to late 20th century levels and data for each time period sum to 100%. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. *{WGII Figure SPM.7}*

Table 2.3 | Examples of global key risks for different sectors, including the potential for risk reduction through adaptation and mitigation, as well as limits to adaptation. Each key risk is assessed as very low, low, medium, high or very high. Risk levels are presented for three time frames: present, near term (here, for 2030–2040) and long term (here, for 2080–2100). In the near term, projected levels of global mean temperature increase do not diverge substantially across different emission scenarios. For the long term, risk levels are presented for two possible futures (2°C and 4°C global mean temperature increase above pre-industrial levels). For each time frame, risk levels are indicated for a continuation of current adaptation and assuming high levels of current or future adaptation. Risk levels are not necessarily comparable, especially across regions. Relevant climate variables are indicated by icons. *{WGII Table TS.4}*



Global Risks

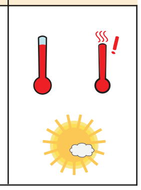
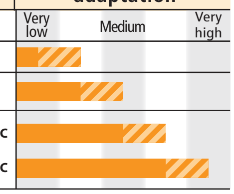
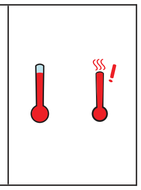
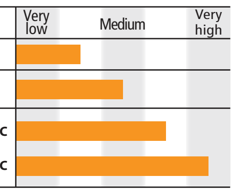
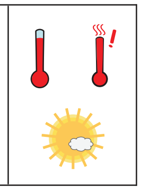
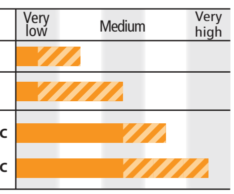
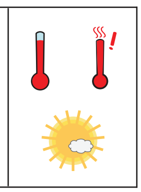
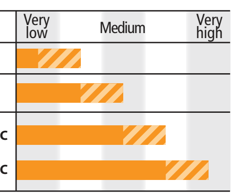
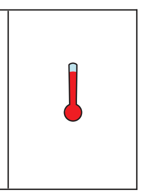
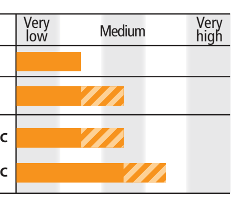
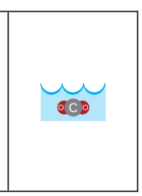
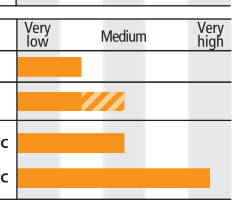
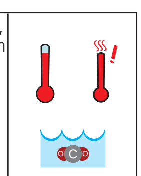
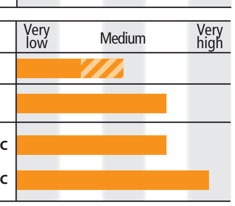
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Reduction in terrestrial carbon sink: Carbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere, resulting from increased fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures (*medium confidence*) *{WGII 4.2, 4.3}*	• Adaptation options include managing land use (including deforestation), fire and other disturbances, and non-climatic stressors.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost, spread of shrubs in tundra and increase in pests and fires in boreal forests (*medium confidence*) *{WGII 4.3, Box 4-4}*	• There are few adaptation options in the Arctic.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Amazon tipping point: Moist Amazon forests could change abruptly to less-carbon-dense, drought- and fire-adapted ecosystems (*low confidence*) *{WGII 4.3, Box 4-3}*	• Policy and market measures can reduce deforestation and fire.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Increased risk of species extinction: A large fraction of the species assessed is vulnerable to extinction due to climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountaintops, islands or small protected areas are especially at risk. Cascading effects through organism interactions, especially those vulnerable to phenological changes, amplify risk (*high confidence*) *{WGII 4.3, 4.4}*	• Adaptation options include reduction of habitat modification and fragmentation, pollution, over-exploitation and invasive species; protected area expansion; assisted dispersal; and *ex situ* conservation.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Global redistribution and decrease of low-latitude fisheries yields, paralleled by a global trend to catches having smaller fishes (*medium confidence*) *{WGII 6.3 to 6.5, 30.5, 30.6}*	• Increasing coastal poverty at low latitudes as fisheries become smaller – partially compensated by the growth of aquaculture and marine spatial planning, as well as enhanced industrialized fishing efforts		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Reduced growth and survival of commercially valuable shellfish and other calcifiers (e.g., reef building corals, calcareous red algae) due to ocean acidification (*high confidence*) *{WGII 5.3, 6.1, 6.3, 6.4, 30.3, Box CC-OA}*	• Evidence for differential resistance and evolutionary adaptation of some species exists, but they are *likely* to be limited at higher CO_2 concentrations and temperatures. • Adaptation options include exploiting more resilient species or protecting habitats with low natural CO_2 levels, as well as reducing other stresses, mainly pollution, and limiting pressures from tourism and fishing.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Marine biodiversity loss with high rate of climate change (*medium confidence*) *{WGII 6.3, 6.4, Table 30-4, Box CC-MB}*	• Adaptation options are limited to reducing other stresses, mainly pollution, and limiting pressures from coastal human activities such as tourism and fishing.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

Table 2.3 *(continued)*

Global Risks				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Negative impacts on average crop yields and increases in yield variability due to climate change (*high confidence*) *{WGII 7.2 to 7.5, Figure 7-5, Box 7-1}*	• Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	Very low · Medium · Very high
Urban risks associated with water supply systems (*high confidence*) *{WGII 8.2, 8.3}*	• Adaptation options include changes to network infrastructure as well as demand-side management to ensure sufficient water supplies and quality, increased capacities to manage reduced freshwater availability, and flood risk reduction.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	Very low · Medium · Very high
Urban risks associated with energy systems (*high confidence*) *{WGII 8.2, 8.4}*	• Most urban centers are energy intensive, with energy-related climate policies focused only on mitigation measures. A few cities have adaptation initiatives underway for critical energy systems. There is potential for non-adapted, centralised energy systems to magnify impacts, leading to national and transboundary consequences from localised extreme events.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	Very low · Medium · Very high
Urban risks associated with housing (*high confidence*) *{WGII 8.3}*	• Poor quality, inappropriately located housing is often most vulnerable to extreme events. Adaptation options include enforcement of building regulations and upgrading. Some city studies show the potential to adapt housing and promote mitigation, adaptation and development goals simultaneously. Rapidly growing cities, or those rebuilding after a disaster, especially have opportunities to increase resilience, but this is rarely realised. Without adaptation, risks of economic losses from extreme events are substantial in cities with high-value infrastructure and housing assets, with broader economic effects possible.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	Very low · Medium · Very high
Displacement associated with extreme events (*high confidence*) *{WGII 12.4}*	• Adaptation to extreme events is well understood, but poorly implemented even under present climate conditions. Displacement and involuntary migration are often temporary. With increasing climate risks, displacement is more likely to involve permanent migration.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	Very low · Medium · Very high
Violent conflict arising from deterioration in resource-dependent livelihoods such as agriculture and pastoralism (*high confidence*) *{WGII 12.5}*	Adaptation options: • Buffering rural incomes against climate shocks, for example through livelihood diversification, income transfers and social safety net provision • Early warning mechanisms to promote effective risk reduction • Well-established strategies for managing violent conflict that are effective but require significant resources, investment and political will		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	Very low · Medium · Very high
Declining work productivity, increasing morbidity (e.g., dehydration, heat stroke and heat exhaustion), and mortality from exposure to heat waves. Particularly at risk are agricultural and construction workers as well as children, homeless people, the elderly, and women who have to walk long hours to collect water (*high confidence*) *{WGII 13.2, Box 13-1}*	• Adaptation options are limited for people who are dependent on agriculture and cannot afford agricultural machinery. • Adaptation options are limited in the construction sector where many poor people work under insecure arrangements. • Adaptation limits may be exceeded in certain areas in a +4°C world.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	Very low · Medium · Very high
Reduced access to water for rural and urban poor people due to water scarcity and increasing competition for water (*high confidence*) *{WGII 13.2, Box 13-1}*	• Adaptation through reducing water use is not an option for the many people already lacking adequate access to safe water. Access to water is subject to various forms of discrimination, for instance due to gender and location. Poor and marginalised water users are unable to compete with water extraction by industries, large-scale agriculture and other powerful users.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	Very low · Medium · Very high

2

Box 2.4 | Reasons For Concern Regarding Climate Change

Five Reasons For Concern (RFCs) have provided a framework for summarizing key risks since the IPCC Third Assessment Report. They illustrate the implications of warming and of adaptation limits for people, economies and ecosystems across sectors and regions. They provide one starting point for evaluating dangerous anthropogenic interference with the climate system. All warming levels in the text of Box 2.4 are relative to the 1986–2005 period. Adding ~0.6°C to these warming levels roughly gives warming relative to the 1850–1900 period, used here as a proxy for pre-industrial times (right-hand scale in Box 2.4, Figure 1). *{WGII Assessment Box SPM.1}*

The five RFCs are associated with:

1. **Unique and threatened systems:** Some ecosystems and cultures are already at risk from climate change (*high confidence*). With additional warming of around 1°C, the number of unique and threatened systems at risk of severe consequences increases. Many systems with limited adaptive capacity, particularly those associated with Arctic sea ice and coral reefs, are subject to very high risks with additional warming of 2°C. In addition to risks resulting from the *magnitude* of warming, terrestrial species are also sensitive to the *rate* of warming, marine species to the rate and degree of ocean acidification and coastal systems to sea level rise (Figure 2.5).

2. **Extreme weather events:** Climate change related risks from extreme events, such as heat waves, heavy precipitation and coastal flooding, are already moderate (*high confidence*). With 1°C additional warming, risks are high (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase progressively with further warming (*high confidence*).

3. **Distribution of impacts:** Risks are unevenly distributed between groups of people and between regions; risks are generally greater for disadvantaged people and communities everywhere. Risks are already moderate because of regional differences in observed climate change impacts, particularly for crop production (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high under additional warming of above 2°C (*medium confidence*).

4. **Global aggregate impacts:** Risks of global aggregate impacts are moderate under additional warming of between 1°C and 2°C, reflecting impacts on both the Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss, with associated loss of ecosystem goods and services, leads to high risks at around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates are available for additional warming of above 3°C.

5. **Large-scale singular events:** With increasing warming, some physical and ecological systems are at risk of abrupt and/or irreversible changes (see Section 2.4). Risks associated with such tipping points are moderate between 0 and 1°C additional warming, since there are signs that both warm-water coral reefs and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase at a steepening rate under an additional warming of 1 to 2°C and become high above 3°C, due to the potential for large and irreversible sea level rise from ice sheet loss. For sustained warming above some threshold greater than ~0.5°C additional warming (*low confidence*) but less than ~3.5°C (*medium confidence*), near-complete loss of the Greenland ice sheet would occur over a millennium or more, eventually contributing up to 7 m to global mean sea level rise.

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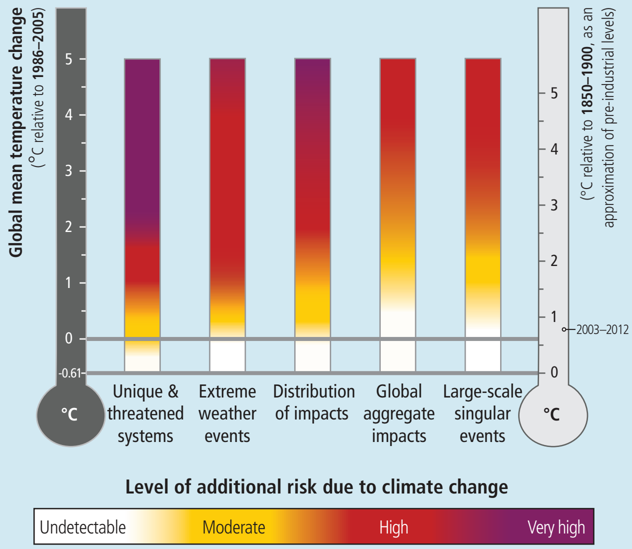
Box 2.4 *(continued)*



Box 2.4, Figure 1 | Risks associated with Reasons For Concern at a global scale are shown for increasing levels of climate change. The colour shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. White indicates no associated impacts are detectable and attributable to climate change. Yellow indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*. Red indicates severe and widespread impacts. Purple, introduced in this assessment, shows that very high risk is indicated by all key risk criteria. *{WGII Assessment Box SPM.1, Figure 19-4}*

Aggregate economic losses accelerate with increasing temperature (*limited evidence, high agreement*), but global economic impacts from climate change are currently difficult to estimate. With recognized limitations, the existing incomplete estimates of global annual economic losses for warming of ~2.5°C above pre-industrial levels are 0.2 to 2.0% of income (*medium evidence, medium agreement*). Changes in population, age structure, income, technology, relative prices, lifestyle, regulation and governance are projected to have relatively larger impacts than climate change, for most economic sectors (*medium evidence, high agreement*). More severe and/or frequent weather hazards are projected to increase disaster-related losses and loss variability, posing challenges for affordable insurance, particularly in developing countries. International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales. (Box 3.1) *{WGII 3.5, 10.2, 10.7, 10.9–10.10, 17.4–17.5, 25.7, 26.7–26.9, Box 25-7}*

From a poverty perspective, climate change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security and prolong existing poverty traps and create new ones, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries (Figure 2.4). *{WGII 8.1, 8.3–8.4, 9.3, 10.9, 13.2–13.4, 22.3, 26.8}*

Climate change is projected to increase displacement of people (*medium evidence, high agreement*). Displacement risk increases when populations that lack the resources for planned migration experience higher exposure to extreme weather events, such as floods and droughts. Expanding opportunities for mobility can reduce vulnerability for such populations. Changes in migration patterns can be responses to both extreme weather events and longer term climate variability and change, and migration can also be an effective adaptation strategy. *{WGII 9.3, 12.4, 19.4, 22.3, 25.9}*

Climate change can indirectly increase risks of violent conflict by amplifying well-documented drivers of these conflicts, such as poverty and economic shocks (*medium confidence*). Multiple lines of evidence relate climate variability to some forms of conflict. *{WGII SPM, 12.5, 13.2, 19.4}*

2.4 Climate change beyond 2100, irreversibility and abrupt changes

Many aspects of climate change and its associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases.

Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions (see Section 2.2.5 for the relationship between CO_2 emissions and global temperature change.). A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial timescale, except in the

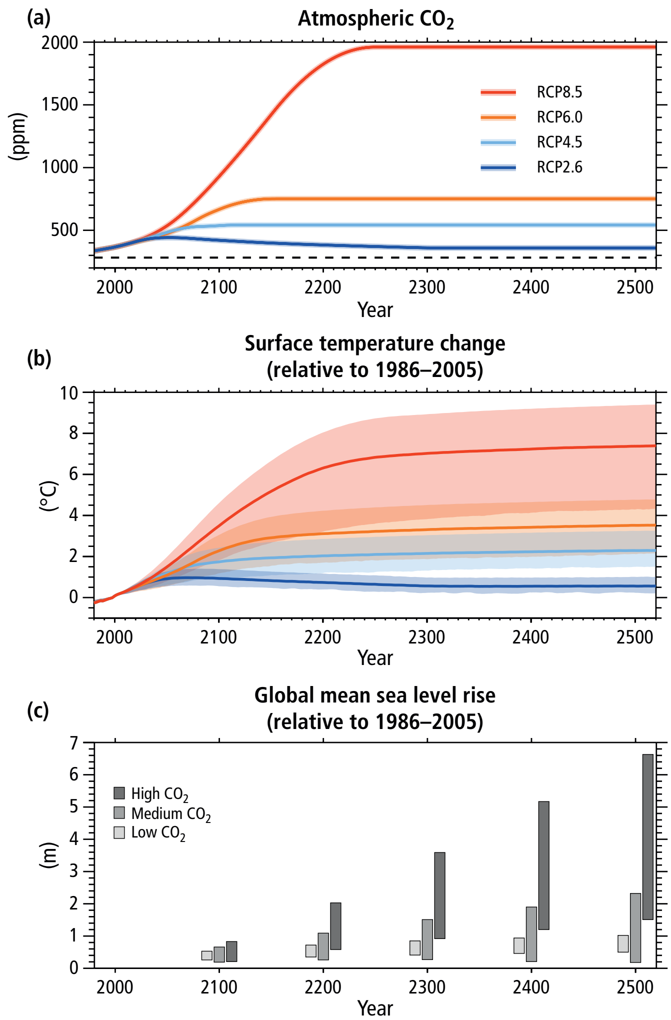


Figure 2.8 | **(a)** Atmospheric carbon dioxide (CO_2) and **(b)** projected global mean surface temperature change as simulated by Earth System Models of Intermediate Complexity (EMICs) for the four Representative Concentration Pathways (RCPs) up to 2300 (relative to 1986–2005) followed by a constant (year 2300 level) radiative forcing. A 10-year smoothing was applied. The dashed line on (a) indicates the pre-industrial CO_2 concentration. **(c)** Sea level change projections grouped into three categories according to the concentration of greenhouse gas (in CO_2-eq) in 2100 (low: concentrations that peak and decline and remain below 500 ppm, as in scenario RCP2.6; medium: 500 to 700 ppm, including RCP4.5; high: concentrations that are above 700 ppm but below 1500 ppm, as in scenario RCP6.0 and RCP8.5). The bars in (c) show the maximum possible spread that can be obtained with the few available model results (and should not be interpreted as uncertainty ranges). These models *likely* underestimate the Antarctica ice sheet contribution, resulting in an underestimation of projected sea level rise beyond 2100. *{WGI Figure 12.43, Figure 13.13, Table 13.8, WGII SPM B-2}*

case of a large net removal of CO_2 from the atmosphere over a sustained period (Figure 2.8a, b). *{WGI SPM E.1, SPM E.8, 12.5.2}*

Stabilization of global average surface temperature does not imply stabilization for all aspects of the climate system. Shifting biomes, re-equilibrating soil carbon, ice sheets, ocean temperatures and associated sea level rise all have their own intrinsic long timescales that will result in ongoing changes for hundreds to thousands of years after global surface temperature has been stabilized. *{WGI SPM E.8, 12.5.2–12.5.4, WGII 4.2}*

Ocean acidification will continue for centuries if CO_2 emissions continue, it will strongly affect marine ecosystems (*high confidence*), and the impact will be exacerbated by rising temperature extremes (Figure 2.5b). ***{WGI 3.8.2, 6.4.4, WGII SPM B-2, 6.3.2, 6.3.5, 30.5, Box CC-OA}***

Global mean sea level rise will continue for many centuries beyond 2100 (*virtually certain*). The few available analyses that go beyond 2100 indicate sea level rise to be less than 1 m above the pre-industrial level by 2300 for GHG concentrations that peak and decline and remain below 500 ppm CO_2-eq, as in scenario RCP2.6. For a radiative forcing that corresponds to a CO_2-eq concentration in 2100 that is above 700 ppm but below 1500 ppm, as in scenario RCP8.5, the projected rise is 1 m to more than 3 m by 2300 (*medium confidence*) (Figure 2.8c). There is *low confidence* in the available models' ability to project solid ice discharge from the Antarctic ice sheet. Hence, these models *likely* underestimate the Antarctica ice sheet contribution, resulting in an underestimation of projected sea level rise beyond 2100. *{WGI SPM E.8, 13.4.4, 13.5.4}*

There is little evidence in global climate models of a tipping point or critical threshold in the transition from a perennially ice-covered to a seasonally ice-free Arctic Ocean, beyond which further sea-ice loss is unstoppable and irreversible. *{WGI 12.5.5}*

There is *low confidence* in assessing the evolution of the Atlantic Meridional Overturning Circulation beyond the 21st century because of the limited number of analyses and equivocal results. However, a collapse beyond the 21st century for large sustained warming cannot be excluded. *{WGI SPM E.4, 12.4.7, 12.5.5}*

Sustained mass loss by ice sheets would cause larger sea level rise, and part of the mass loss might be irreversible. There is *high confidence* that sustained global mean warming greater than a threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) of global warming with respect to pre-industrial temperatures. Abrupt and irreversible ice loss from a potential instability of marine-based sectors of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment. *{WGI SPM E.8, 5.6.2, 5.8.1, 13.4.3, 13.5.4}*

Within the 21st century, magnitudes and rates of climate change associated with medium to high emission scenarios (RCP4.5, RCP6.0 and RCP8.5) pose a high risk of abrupt and irreversible regional-scale change in the composition, structure and function of marine, terrestrial and freshwater ecosystems, including wetlands (*medium confidence*), as well as warm water coral reefs (*high confidence*). Examples that could substantially amplify climate change are the boreal-tundra Arctic system (*medium confidence*) and the Amazon forest (*low confidence*). *{WGII 4.3.3.1, Box 4.3, Box 4.4, 5.4.2.4, 6.3.1–6.3.4, 6.4.2, 30.5.3–30.5.6, Box CC-CR, Box CC-MB}*

A reduction in permafrost extent is *virtually certain* with continued rise in global temperatures. Current permafrost areas are projected to become a net emitter of carbon (CO_2 and CH_4) with a loss of 180 to 920 $GtCO_2$ (50 to 250 GtC) under RCP8.5 over the 21st century (*low confidence*). *{WGI TFE.5, 6.4.3.4, 12.5.5, WGII 4.3.3.4}*

3 Future Pathways for Adaptation, Mitigation and Sustainable Development

Topic 3: Future Pathways for Adaption, Mitigation and Sustainable Development

Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. Substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development.

Adaptation and mitigation are two complementary strategies for responding to climate change. Adaptation is the process of adjustment to actual or expected climate and its effects in order to either lessen or avoid harm or exploit beneficial opportunities. Mitigation is the process of reducing emissions or enhancing sinks of greenhouse gases (GHGs), so as to limit future climate change. Both adaptation and mitigation can reduce and manage the risks of climate change impacts. Yet adaptation and mitigation can also create other risks, as well as benefits. Strategic responses to climate change involve consideration of climate-related risks along with the risks and co-benefits of adaptation and mitigation actions. *{WGII SPM A-3, SPM C, Glossary, WGIII SPM.2, 4.1, 5.1, Glossary}*

Mitigation, adaptation and climate impacts can all result in transformations to and changes in systems. Depending on the rate and magnitude of change and the vulnerability and exposure of human and natural systems, climate change will alter ecosystems, food systems, infrastructure, coastal, urban and rural areas, human health and livelihoods. Adaptive responses to a changing climate require actions that range from incremental changes to more fundamental, transformational changes[34]. Mitigation can involve fundamental changes in the way that human societies produce and use energy services and land. *{WGII B, C, TS C, Box TS.8, Glossary, WGIII SPM.4}*

Topic 3 of this report examines the factors that influence the assessment of mitigation and adaptation strategies. It considers the benefits, risks, incremental changes and potential transformations from different combinations of mitigation, adaptation and residual climate-related impacts. It considers how responses in the coming decades will influence options for limiting long-term climate change and opportunities for adapting to it. Finally, it considers factors—including uncertainty, ethical considerations and links to other societal goals—that may influence choices about mitigation and adaptation. Topic 4 then assesses the prospects for mitigation and adaptation on the basis of current knowledge of tools, options and policies.

3.1 Foundations of decision-making about climate change

Effective decision-making to limit climate change and its effects can be informed by a wide range of analytical approaches for evaluating expected risks and benefits, recognizing the importance of governance, ethical dimensions, equity, value judgments, economic assessments and diverse perceptions and responses to risk and uncertainty.

Sustainable development and equity provide a basis for assessing climate policies. Limiting the effects of climate change is necessary to achieve sustainable development and equity, including poverty eradication. Countries' past and future contributions to the accumulation of GHGs in the atmosphere are different, and countries also face varying challenges and circumstances and have different capacities to address mitigation and adaptation. Mitigation and adaptation raise issues of equity, justice and fairness and are necessary to achieve sustainable development and poverty eradication. Many of those most vulnerable to climate change have contributed and contribute little to GHG emissions. Delaying mitigation shifts burdens from the present to the future, and insufficient adaptation responses to emerging impacts are already eroding the basis for sustainable development. Both adaptation and mitigation can have distributional effects locally, nationally and internationally, depending on who pays and who benefits. The process of decision-making about climate change, and the degree to which it respects the rights and views of all those affected, is also a concern of justice. *{WGII 2.2, 2.3, 13.3, 13.4, 17.3, 20.2, 20.5, WGIII SPM.2, 3.3, 3.10, 4.1.2, 4.2, 4.3, 4.5, 4.6, 4.8}*

Effective mitigation will not be achieved if individual agents advance their own interests independently. Climate change has the characteristics of a collective action problem at the global scale, because most GHGs accumulate over time and mix globally, and emissions by any agent (e.g., individual, community, company, country) affect other agents. Cooperative responses, including international cooperation, are therefore required to effectively mitigate GHG emissions and address other climate change issues. The effectiveness of adaptation can be enhanced through complementary actions across levels, including international cooperation. The evidence suggests that outcomes seen as equitable can lead to more effective cooperation. *{WGII 20.3.1, WGIII SPM.2, TS.1, 1.2, 2.6, 3.2, 4.2, 13.2, 13.3}*

Decision-making about climate change involves valuation and mediation among diverse values and may be aided by the analytic methods of several normative disciplines. Ethics analyses the different values involved and the relations between them. Recent political philosophy has investigated the question of responsibility for the effects of emissions. Economics and decision analysis provide

[34] Transformation is used in this report to refer to a change in the fundamental attributes of a system (see Glossary). Transformations can occur at multiple levels; at the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. *{WGII SPM C-2, 2–13, 20.5, WGIII SPM, 6–12}*

quantitative methods of valuation which can be used for estimating the social cost of carbon (see Box 3.1), in cost–benefit and cost-effectiveness analyses, for optimization in integrated models and elsewhere. Economic methods can reflect ethical principles, and take account of non-marketed goods, equity, behavioural biases, ancillary benefits and costs and the differing values of money to different people. They are, however, subject to well-documented limitations. *{WGII 2.2, 2.3, WGIII SPM.2, Box TS.2, 2.4, 2.5, 2.6, 3.2–3.6, 3.9.4}*

Analytical methods of valuation cannot identify a single best balance between mitigation, adaptation and residual climate impacts. Important reasons for this are that climate change involves extremely complex natural and social processes, there is extensive disagreement about the values concerned, and climate change impacts and mitigation approaches have important distributional effects. Nevertheless, information on the consequences of emissions pathways to alternative climate goals and risk levels can be a useful input into decision-making processes. Evaluating responses to climate change involves assessment of the widest possible range of impacts, including low-probability outcomes with large consequences. *{WGII 1.1.4, 2.3, 2.4, 17.3, 19.6, 19.7, WGIII 2.5, 2.6, 3.4, 3.7, Box 3-9}*

Effective decision-making and risk management in the complex environment of climate change may be iterative: strategies can often be adjusted as new information and understanding develops during implementation. However, adaptation and mitigation choices in the near term will affect the risks of climate change throughout the 21st century and beyond, and prospects for climate-resilient pathways for sustainable development depend on what is achieved through mitigation. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if mitigation is delayed too long. Decision-making about climate change is influenced by how individuals and organizations perceive risks and uncertainties and take them into account. They sometimes use simplified decision rules, overestimate or underestimate risks and are biased towards the status quo. They differ in their degree of risk aversion and the relative importance placed on near-term versus long-term ramifications of specific actions. Formalized analytical methods for decision-making under uncertainty can account accurately for risk, and focus attention on both short- and long-term consequences. *{WGII SPM A-3, SPM C-2, 2.1–2.4, 3.6, 14.1–14.3, 15.2–15.4, 17.1–17.3, 17.5, 20.2, 20.3, 20.6, WGIII SPM.2, 2.4, 2.5, 5.5, 16.4}*

3.2 Climate change risks reduced by adaptation and mitigation

Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*). Mitigation involves some level of co-benefits and of risks due to adverse side effects, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change, increasing the benefits from near-term mitigation efforts.

The risks of climate change, adaptation and mitigation differ in nature, timescale, magnitude and persistence (*high confidence*). Risks from adaptation include maladaptation and negative ancillary impacts. Risks from mitigation include possible adverse side effects of large-scale deployment of low-carbon technology options and economic costs. Climate change risks may persist for millennia and can involve very high risk of severe impacts and the presence of significant irreversibilities combined with limited adaptive capacity. In contrast, the stringency of climate policies can be adjusted much more quickly in response to observed consequences and costs and create lower risks of irreversible consequences (3.3, 3.4, 4.3). *{WGI SPM E.8, 12.4, 12.5.2, 13.5, WGII 4.2, 17.2, 19.6, WGIII TS.3.1.4, Table TS.4, Table TS.5, Table TS.6, Table TS.7, Table TS.8, 2.5, 6.6}*

Mitigation and adaptation are complementary approaches for reducing risks of climate change impacts. They interact with one another and reduce risks over different timescales (*high confidence*). Benefits from adaptation can already be realized in addressing current risks and can be realized in the future for addressing emerging risks. Adaptation has the potential to reduce climate change impacts over the next few decades, while mitigation has relatively little influence on climate outcomes over this timescale. Near-term and longer-term mitigation and adaptation, as well as development pathways, will determine the risks of climate change beyond mid-century. The potential for adaptation differs across sectors and will be limited by institutional and capacity constraints, increasing the long-term benefits of mitigation (*high confidence*). The level of mitigation will influence the rate and magnitude of climate change, and greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*) (3.3). *{WGI 11.3, 12.4, WGII SPM A-3, SPM B-2, SPM C-2, 1.1.4.4, 2.5, 16.3–16.6, 17.3, 19.2, 20.2.3, 20.3, 20.6}*

3

Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread and irreversible impacts globally (*high confidence*) (Topic 2 and Figure 3.1a). Estimates of warming in 2100 without additional climate mitigation efforts are from 3.7°C to 4.8°C compared with pre-industrial levels (median climate response); the range is 2.5°C to 7.8°C when using the 5th to 95th percentile range of the median climate response (Figure 3.1). The risks associated with temperatures at or above 4°C include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, consequential constraints on common human activities, increased likelihood of triggering tipping points (critical thresholds) and limited potential for adaptation in some cases (*high confidence*). Some risks of climate change, such as risks to unique and threatened systems and risks associated with extreme weather events, are moderate to high at temperatures 1°C to 2°C above pre-industrial levels. *{WGII SPM B-1, SPM C-2, WGIII SPM.3}*

Substantial cuts in GHG emissions over the next few decades can substantially reduce risks of climate change by limiting warming in the second half of the 21st century and beyond (*high confidence*). Global mean surface warming is largely determined by cumulative emissions, which are, in turn, linked to emissions over different timescales (Figure 3.1). Limiting risks across Reasons For Concern would imply a limit for cumulative emissions of CO_2.

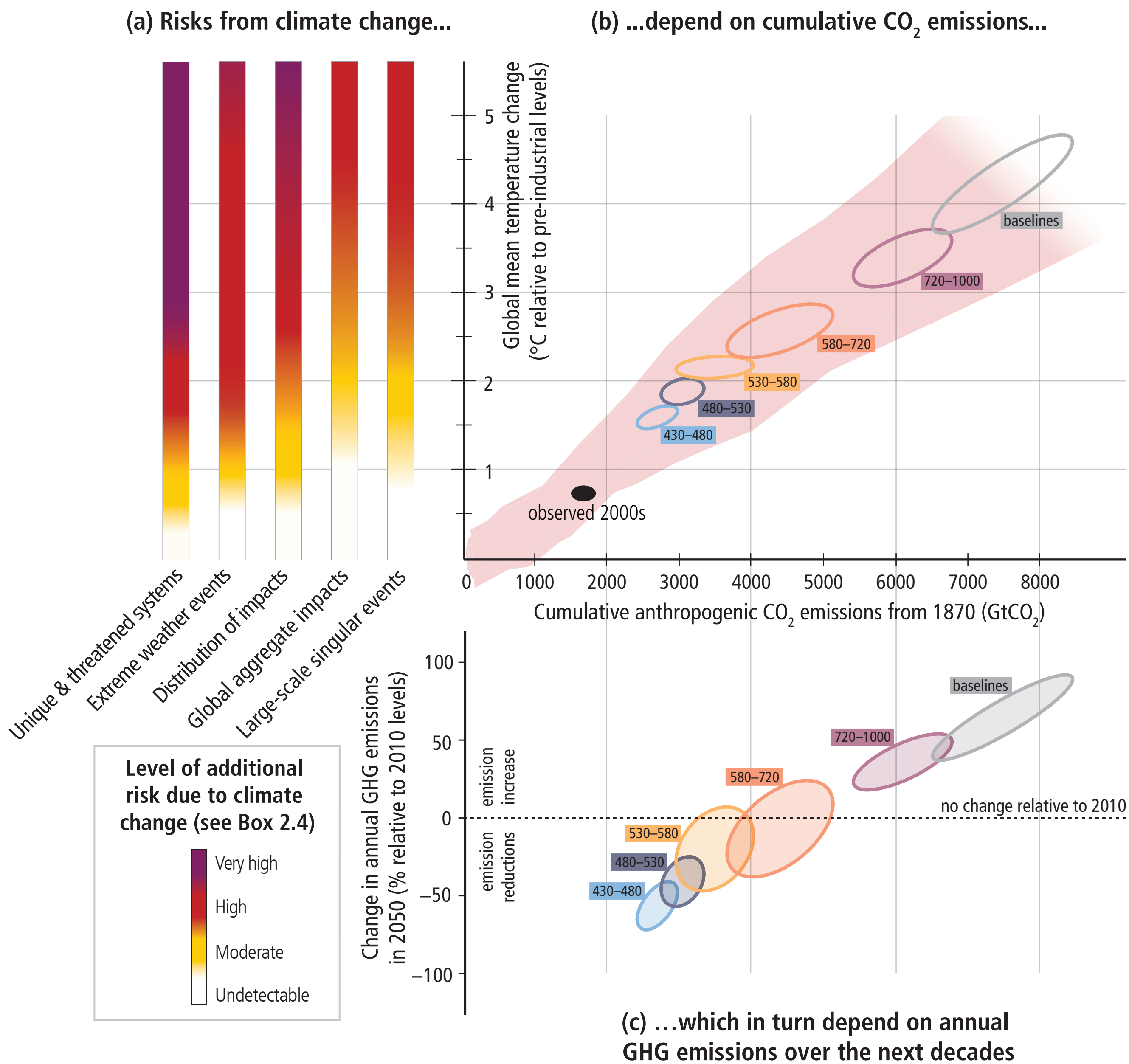


Figure 3.1 | The relationship between risks from climate change, temperature change, cumulative carbon dioxide (CO_2) emissions and changes in annual greenhouse gas (GHG) emissions by 2050. Limiting risks across Reasons For Concern **(a)** would imply a limit for cumulative emissions of CO_2 **(b)**, which would constrain annual emissions over the next few decades **(c)**. **Panel a** reproduces the five Reasons For Concern (Box 2.4). **Panel b** links temperature changes to cumulative CO_2 emissions (in $GtCO_2$), from 1870. They are based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (pink plume) and on a simple climate model (median climate response in 2100) for the baselines and five mitigation scenario categories (six ellipses). Details are provided in Figure 2.3. **Panel c** shows the relationship between the cumulative CO_2 emissions (in $GtCO_2$) of the scenario categories and their associated change in annual GHG emissions by 2050, expressed in percentage change (in percent $GtCO_2$-eq per year) relative to 2010. The ellipses correspond to the same scenario categories as in Panel b, and are built with a similar method (see details in Figure 2.3).

Such a limit would require that global net emissions of CO_2 eventually decrease to zero (Figure 3.1a,b) (*high confidence*). Reducing risks of climate change through mitigation would involve substantial cuts in GHG emissions over the next few decades (Figure 3.1c). But some risks from residual damages are unavoidable, even with mitigation and adaptation (*very high confidence*). A subset of relevant climate change risks has been estimated using aggregate economic indicators. Such economic estimates have important limitations and are therefore a useful but insufficient basis for decision-making on long-term mitigation targets (see Box 3.1). *{WGII 19.7.1, WGIII SPM.3, Figure 3.1}*

Mitigation involves some level of co-benefits and risks, but these risks do not involve the same possibility of severe, widespread and irreversible impacts as risks from climate change (*high confidence*). Scenarios that are *likely* to limit warming to below 2°C or even 3°C compared with pre-industrial temperatures involve large-scale changes in energy systems and potentially land use over the coming decades (3.4). Associated risks include those linked to large-scale deployment of technology options for producing low-carbon energy, the potential for high aggregate economic costs of mitigation and impacts on vulnerable countries and industries. Other risks and co-benefits are associated with human health, food security, energy security, poverty reduction, biodiversity conservation, water availability, income distribution, efficiency of taxation systems, labour supply and employment, urban sprawl, fossil fuel export revenues and the economic growth of developing countries (Table 4.5). *{WGIII SPM.4.1, SPM.4.2, TS.3.1.4, Table TS.4, Table TS.5, Table TS.6, Table TS.7, Table TS.8, 6.6}*

Inertia in the economic and climate systems and the possibility of irreversible impacts from climate change increase the benefits of near-term mitigation efforts (*high confidence*). The actions taken today affect the options available in the future to reduce emissions, limit temperature change and adapt to climate change. Near-term choices can create, amplify or limit significant elements of lock-in that are important for decision-making. Lock-ins and irreversibilities occur in the climate system due to large inertia in some of its components such as heat transfer from the ocean surface to depth leading to continued ocean warming for centuries regardless of emission scenario and the irreversibility of a large fraction of anthropogenic climate change resulting from CO_2 emissions on a multi-century to millennial timescale unless CO_2 were to be removed from the atmosphere through large-scale human interventions over a sustained period (see also Box 3.3). Irreversibilities in socio-economic and biological systems also result from infrastructure development and long-lived products and from climate change impacts, such as species extinction. The larger potential for irreversibility and pervasive impacts from climate change risks than from mitigation risks increases the benefit of short-term mitigation efforts. Delays in additional mitigation or constraints on technological options limit the mitigation options and increase the long-term mitigation costs as well as other risks that would be incurred in the medium to long term to hold climate change impacts at a given level (Table WGIII SPM.2, blue segment). *{WGI SPM E-8, WGII SPM B-2, 2.1, 19.7, 20.3, Box 20-4, WGIII SPM.4.1, SPM.4.2.1, 3.6, 6.4, 6.6, 6.9}*

3.3 Characteristics of adaptation pathways

Adaptation can reduce the risks of climate change impacts, but there are limits to its effectiveness, especially with greater magnitudes and rates of climate change. Taking a longer-term perspective, in the context of sustainable development, increases the likelihood that more immediate adaptation actions will also enhance future options and preparedness.

Adaptation can contribute to the well-being of current and future populations, the security of assets and the maintenance of ecosystem goods, functions and services now and in the future. Adaptation is place- and context-specific, with no single approach for reducing risks appropriate across all settings (*high confidence*). Effective risk reduction and adaptation strategies consider vulnerability and exposure and their linkages with socio-economic processes, sustainable development, and climate change. Adaptation research since the IPCC Fourth Assessment Report (AR4) has evolved from a dominant consideration of engineering and technological adaptation pathways to include more ecosystem-based, institutional and social measures. A previous focus on cost–benefit analysis, optimization and efficiency approaches has broadened with the development of multi-metric evaluations that include risk and uncertainty dimensions integrated within wider policy and ethical frameworks to assess trade-offs and constraints. The range of specific adaptation measures has also expanded (4.2, 4.4.2.1), as have the links to sustainable development (3.5). There are many studies on local and sectoral adaptation costs and benefits, but few global analyses and *very low confidence*

Box 3.1 | The Limits of the Economic Assessment of Climate Change Risks

A subset of climate change risks and impacts are often measured using aggregate economic indicators, such as gross domestic product (GDP) or aggregate income. Estimates, however, are partial and affected by important conceptual and empirical limitations. These incomplete estimates of global annual economic losses for temperature increases of ~2.5°C above pre-industrial levels are between 0.2 and 2.0% of income (*medium evidence, medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence, high agreement*). Estimates of the incremental aggregate economic impact of emitting one more tonne of carbon dioxide (the social cost of carbon) are derived from these studies and lie between a few dollars and several hundreds of dollars per tonne of carbon in 2000 to 2015 (*robust evidence, medium agreement*). These impact estimates are incomplete and depend on a large number of assumptions, many of which are disputable. Many estimates do not account for the possibility of large-scale singular events and irreversibility, tipping points and other important factors, especially those that are difficult to monetize, such as loss of biodiversity. Estimates of aggregate costs mask significant differences in impacts across sectors, regions, countries and communities, and they therefore depend on ethical considerations, especially on the aggregation of losses across and within countries (*high confidence*). Estimates of global aggregate economic losses exist only for limited warming levels. These levels are exceeded in scenarios for the 21st century unless additional mitigation action is implemented, leading to additional economic costs. The total economic effects at different temperature levels would include mitigation costs, co-benefits of mitigation, adverse side effects of mitigation, adaptation costs and climate damages. As a result, mitigation cost and climate damage estimates at any given temperature level cannot be compared to evaluate the costs and benefits of mitigation. Very little is known about the economic cost of warming above 3°C relative to the current temperature level. Accurately estimating climate change risks (and thus the benefits of mitigation) takes into account the full range of possible impacts of climate change, including those with high consequences but a low probability of occurrence. The benefits of mitigation may otherwise be underestimated (*high confidence*). Some limitations of current estimates may be unavoidable, even with more knowledge, such as issues with aggregating impacts over time and across individuals when values are heterogeneous. In view of these limitations, it is outside the scope of science to identify a single best climate change target and climate policy (3.1, 3.4). *{WGII SPM B-2, 10.9.2, 10.9.4, 13.2, 17.2–17.3, 18.4, 19.6, WGIII 3.6}* in their results. *{WGII SPM C-1, Table SPM.1, 14.1, 14.ES, 15.2, 15.5, 17.2, 17.ES}*

Adaptation planning and implementation at all levels of governance are contingent on societal values, objectives and risk perceptions (*high confidence*). Recognition of diverse interests, circumstances, social-cultural contexts and expectations can benefit decision-making processes. Indigenous, local and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change, but these have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge into practices increases the effectiveness of adaptation as do effective decision support, engagement and policy processes (4.4.2). *{WGII SPM C-1}*

Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (*high confidence*). National governments can coordinate adaptation efforts of local and sub-national governments, for example by protecting vulnerable groups, by supporting economic diversification and by providing information, policy and legal frameworks and financial support (*robust evidence, high agreement*). Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households and civil society and in managing risk information and financing (*medium evidence, high agreement*). *{WGII SPM C-1}*

A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability (*high confidence*), but some near-term responses to climate change may also limit future choices. Integration of adaptation into planning, including policy design, and decision-making can promote synergies with development and disaster risk reduction. However, poor planning or implementation, overemphasizing short-term outcomes or failing to sufficiently anticipate consequences can result in maladaptation, increasing the vulnerability or exposure of the target group in the future or the vulnerability of other people, places or sectors (*medium evidence, high agreement*). For example, enhanced protection of exposed assets can lock in dependence on further protection measures. Appropriate adaptation options can be better assessed by including co-benefits and mitigation implications (3.5 and 4.2). *{WGII SPM C-1}*

Numerous interacting constraints can impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: limited financial and human resources; limited integration or coordination of governance; uncertainties about projected impacts; different perceptions of risks; competing values; absence of key adaptation leaders and advocates; and limited tools to monitor adaptation effectiveness. Other constraints include insufficient research, monitoring and observation and the financial and other resources to maintain them. Underestimating the complexity of adaptation as a social process can create unrealistic expectations about achieving intended adaptation outcomes (see Sections 4.1 and 4.2 for details in relation to implementation). *{WGII SPM C-1}*

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available. Value-based judgments of what constitutes an intolerable risk may differ. Limits to adaptation emerge from the interaction among climate change and biophysical and/or socio-economic constraints. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. In some parts of the world, insufficient responses to emerging impacts are already eroding the basis for sustainable development. For most regions and sectors, empirical evidence is not sufficient to quantify magnitudes of climate change that would constitute a future adaptation limit. Furthermore, economic development, technology and cultural norms and values can change over time to enhance or reduce the capacity of systems to avoid limits. As a consequence, some limits are 'soft' in that they may be alleviated over time. Other limits are 'hard' in that there are no reasonable prospects for avoiding intolerable risks. *{WGII SPM C-2, TS}*

Transformations in economic, social, technological and political decisions and actions can enhance adaptation and promote sustainable development (*high confidence*). Restricting adaptation responses to incremental changes to existing systems and structures without considering transformational change may increase costs and losses and miss opportunities. For example, enhancing infrastructure to protect other built assets can be expensive and ultimately not defray increasing costs and risks, whereas options such as relocation or using ecosystem services to adapt may provide a range of benefits now and in the future. Transformational adaptation can include introduction of new technologies or practices, formation of new financial structures or systems of governance, adaptation at greater scales or magnitudes and shifts in the location of activities. Planning and implementation of transformational adaptation could reflect strengthened, altered or aligned paradigms and consequently may place new and increased demands on governance structures to reconcile different goals and visions for the future and to address possible equity and ethical implications: transformational adaptation pathways are enhanced by iterative learning, deliberative processes, and innovation. At the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. *{WGII SPM C-2, 1.1, 2.5, 5.5, 8.4, 14.1, 14.3, 16.2-7, 20.3.3, 20.5, 25.10, Table 14-4, Table 16-3, Box 16.1, Box 16.4, Box 25.1}*

Building adaptive capacity is crucial for effective selection and implementation of adaptation options (*robust evidence, high agreement*). Successful adaptation requires not only identifying adaptation options and assessing their costs and benefits, but also increasing the adaptive capacity of human and natural systems (*medium evidence, high agreement*). This can involve complex governance challenges and new institutions and institutional arrangements. (4.2) *{WGII 8.1, 12.3, 14.1-3, 16.2, 16.3, 16.5, 16.8}*

Significant co-benefits, synergies and trade-offs exist between mitigation and adaptation and among different adaptation responses; interactions occur both within and across regions (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use and biodiversity, but tools to understand and manage these interactions remain limited. Examples of actions with co-benefits include (i) improved energy efficiency and cleaner energy sources, leading to reduced emissions of health-damaging, climate-altering air pollutants; (ii) reduced energy and water consumption in urban areas through greening cities and recycling water; (iii) sustainable agriculture and forestry; and (iv) protection of ecosystems for carbon storage and other ecosystem services. *{WGII SPM C-1}*

3.4 Characteristics of mitigation pathways

There are multiple mitigation pathways that are *likely* to limit warming to below 2°C relative to pre-industrial levels. These pathways would require substantial emissions reductions over the next few decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century. Implementing such reductions poses substantial technological, economic, social and institutional challenges, which increase with delays in additional mitigation and if key technologies are not available. Limiting warming to lower or higher levels involves similar challenges but on different timescales.

Without additional efforts to reduce GHG emissions beyond those in place today, global emission growth is expected to persist driven by growth in global population and economic activities (*high confidence*) (Figure 3.2). Global GHG emissions under most scenarios without additional mitigation (baseline scenarios) are between about 75 $GtCO_2$-eq/yr and almost 140 $GtCO_2$-eq/yr in 2100[35] which is approximately between the 2100 emission levels in the RCP6.0 and RCP8.5 pathways (Figure 3.2)[36]. Baseline scenarios exceed 450 ppm CO_2-eq by 2030 and reach CO_2-eq concentration levels between about 750 ppm CO_2-eq and more than 1300 ppm CO_2-eq by 2100. Global mean surface temperature increases in 2100 range from about 3.7°C to 4.8°C above the average for 1850–1900 for a median climate response. They range from 2.5°C to 7.8°C when including climate uncertainty (5th to 95th percentile range)[37]. The future scenarios do not account for possible changes in natural forcings in the climate system (see Box 1.1). *{WGIII SPM.3, SPM.4.1, TS.2.2, TS.3.1, 6.3, Box TS.6}*

Many different combinations of technological, behavioural and policy options can be used to reduce emissions and limit temperature change (*high confidence*). To evaluate possible pathways to long-term climate goals, about 900 mitigation scenarios were collected for this assessment, each of which describes different technological, socio-economic and institutional changes. Emission reductions under these scenarios lead to concentrations in 2100 from 430 ppm CO_2-eq to above 720 ppm CO_2-eq which is comparable to the 2100 forcing levels between RCP2.6 and RCP6.0. Scenarios with concentration levels of below 430 ppm CO_2-eq by 2100 were also assessed. *{WGIII SPM.4.1, TS3.1, 6.1, 6.2, 6.3, Annex II}*

Scenarios leading to CO_2-eq concentrations in 2100 of about 450 ppm or lower are *likely* to maintain warming below 2°C over the 21st century relative to pre-industrial levels (*high confidence*). Mitigation scenarios reaching concentration levels of about 500 ppm CO_2-eq by 2100 are *more likely than not* to limit warming to less than 2°C relative to pre-industrial levels, unless concentration levels temporarily exceed roughly 530 ppm CO_2-eq before 2100. In this case, warming is *about as likely as not* to remain below 2°C relative to pre-industrial levels. Scenarios that exceed about 650 ppm CO_2-eq by 2100 are *unlikely* to limit warming to below 2°C relative to pre-industrial levels. Mitigation scenarios in which warming is *more likely than not* to be less than 1.5°C relative to pre-industrial levels by 2100 are characterized by concentration levels by 2100 of below 430 ppm CO_2-eq. In these scenarios, temperature peaks during the century and subsequently declines (Table 3.1). *{WGIII SPM.4.1, Table SPM.1, TS.3.1, Box TS.6, 6.3}*

Mitigation scenarios reaching about 450 ppm CO_2-eq in 2100 (consistent with a *likely* chance to keep warming below 2°C relative to pre-industrial level) typically involve temporary overshoot[38] of atmospheric concentrations, as do many scenarios reaching about 500 ppm CO_2-eq to about 550 ppm CO_2-eq by 2100 (Table 3.1). Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and afforestation in the second half of the century (*high confidence*). The availability and scale of these and other Carbon Dioxide Removal (CDR) technologies and methods are uncertain, and CDR technologies and methods are, to varying degrees, associated with challenges and risks (see Box 3.3)[39]. CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. *{WGIII SPM.4.1, Table SPM.1, TS.3.1, 6.3, 6.9.1, Figure 6.7, 7.11, 11.13}*

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[35] Unless otherwise noted, scenario ranges cited in Topic 3 and Topic 4 refer to the 10th to 90th percentile ranges (see Table 3.1).

[36] For a discussion on CO2-equivalent (CO2-eq) emissions and concentrations, see Box 3.2 on GHG metrics and mitigation pathways and the Glossary.

[37] The range quoted here is based on the warming results of a simple climate model for the emissions of around 300 baseline scenarios, expressed compared to the 1850–1900 period. The warming results quoted in Section 2.2 are obtained by prescribing future concentrations of GHG in CMIP5 Earth System Models. This results in a mean warming of 1.0°C (5th to 95th percentile range: 0.3°C to 1.7°C) for RCP2.6, and a mean warming of 3.7°C (2.6°C to 4.8°C) for RCP8.5 relative to the period 1986–2005. For the same concentration-driven experiments, the simple climate model approach gives consistent results. The median warming is 0.9°C (0.5°C to 1.6°C) for RCP2.6 and 3.7°C (2.5°C to 5.9°C) for RCP8.5 relative to the period 1986–2005. However, the high-end of the CMIP5 ESMs range is more constrained. In addition, the baseline temperature increase quoted here is wider than that of the concentration-driven RCP8.5 experiments mentioned above as it is based on a wider set of scenarios, includes carbon cycle response uncertainty, and uses a different base year (2.2, 3.4).

[38] In concentration 'overshoot' scenarios, concentrations peak during the century and then decline.

[39] CDR methods have biogeochemical and technological limitations to their potential on the global scale. There is insufficient knowledge to quantify how much CO2 emissions could be partially offset by CDR on a century timescale. CDR methods may carry side effects and long-term consequences on a global scale.

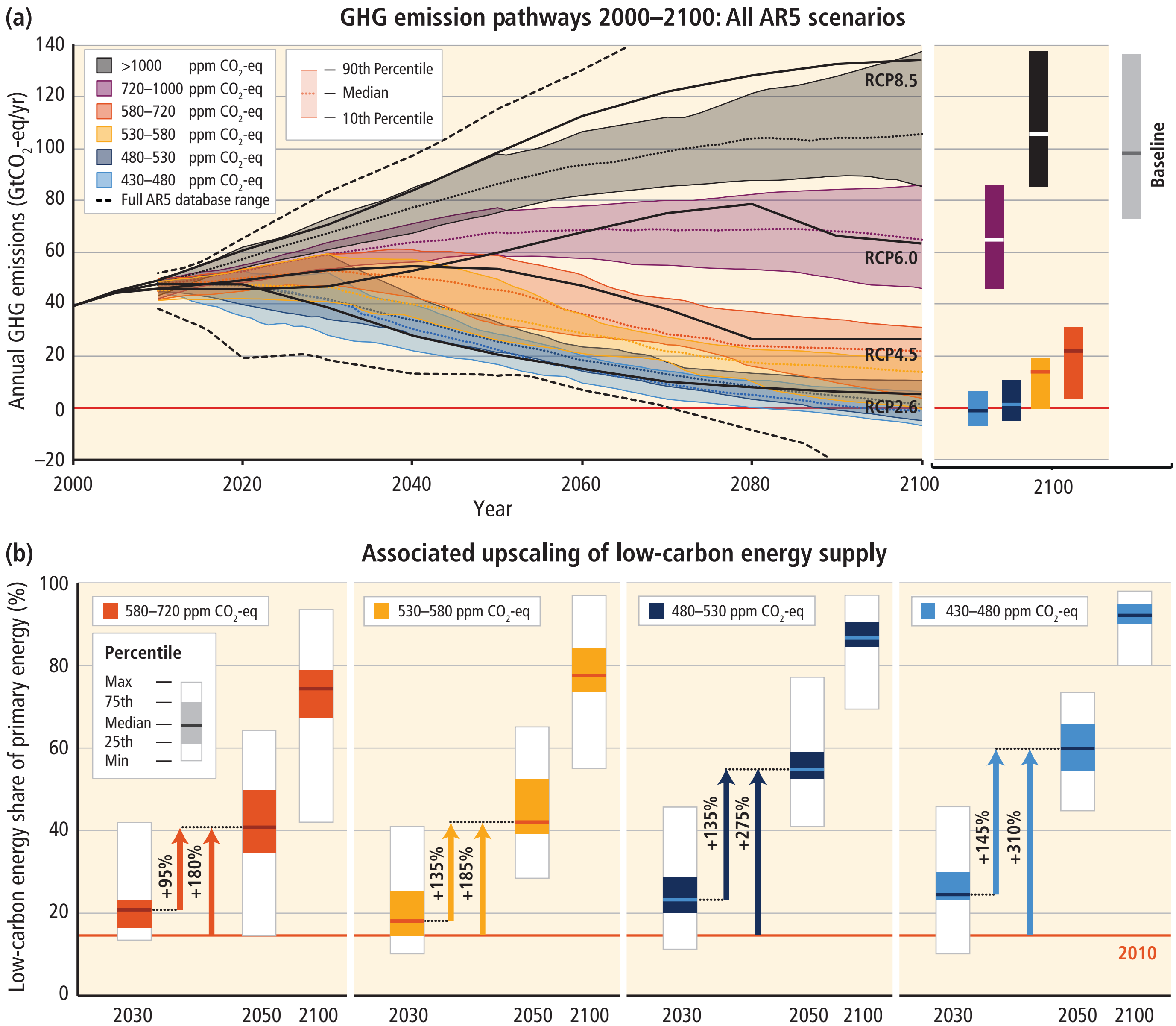

Figure 3.2 | Global greenhouse gas (GHG) emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$-eq/yr) in baseline and mitigation scenarios for different long-term concentration levels **(a)** and associated scale-up requirements of low-carbon energy (% of primary energy) for 2030, 2050 and 2100, compared to 2010 levels, in mitigation scenarios **(b)**. *{WGIII SPM.4, Figure 6.7, Figure 7.16}* [Note: CO_2-eq emissions include the basket of Kyoto gases (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) as well as fluorinated gases) calculated based on 100-year Global Warming Potential (GWP_{100}) values from the IPCC Second Assessment Report.]

Limiting warming with a *likely* chance to less than 2°C relative to pre-industrial levels would require substantial cuts in anthropogenic GHG emissions[40] by mid-century through large-scale changes in energy systems and possibly land use. Limiting warming to higher levels would require similar changes but less quickly. Limiting warming to lower levels would require these changes more quickly (*high confidence*). Scenarios that are *likely* to maintain warming at below 2°C are characterized by a 40 to 70% reduction in GHG emissions by 2050, relative to 2010 levels, and emissions levels near zero or below in 2100 (Figure 3.2, Table 3.1). Scenarios with higher emissions in 2050 are characterized by a greater reliance on CDR technologies beyond mid-century, and vice versa. Scenarios that are *likely* to maintain warming at below 2°C include more rapid improvements in energy efficiency and a tripling to nearly a quadrupling of the share of zero- and low-carbon energy supply from renewable energy, nuclear energy and fossil energy with carbon dioxide capture and storage (CCS) or BECCS by the year 2050 (Figure 3.2b). The scenarios describe a wide range of changes in land use, reflecting

[40] This range differs from the range provided for a similar concentration category in AR4 (50 to 85% lower than in 2000 for CO_2 only). Reasons for this difference include that this report has assessed a substantially larger number of scenarios than in AR4 and looks at all GHGs. In addition, a large proportion of the new scenarios include CDR technologies. Other factors include the use of 2100 concentration levels instead of stabilization levels and the shift in reference year from 2000 to 2010. Scenarios with higher emission levels by 2050 are characterized by a greater reliance on CDR technologies beyond mid-century.

Table 3.1 | Key characteristics of the scenarios collected and assessed for WGIII AR5. For all parameters the 10th to 90th percentile of the scenarios is shown [a].

<table>
<tr><th rowspan="2">CO_2-eq Concentrations in 2100 (ppm CO_2-eq) [f]

Category label (conc. range)</th><th rowspan="2">Subcategories</th><th rowspan="2">Relative position of the RCPs [d]</th><th colspan="2">Change in CO_2-eq emissions compared to 2010 (in %) [c]</th><th colspan="4">Likelihood of staying below a specific temperature level over the 21st century (relative to 1850–1900) [d, e]</th></tr>
<tr><th>2050</th><th>2100</th><th>1.5ºC</th><th>2ºC</th><th>3ºC</th><th>4ºC</th></tr>
<tr><td><430</td><td colspan="8">Only a limited number of individual model studies have explored levels below 430 ppm CO_2-eq [j]</td></tr>
<tr><td>450
(430 to 480)</td><td>Total range [a, g]</td><td>RCP2.6</td><td>–72 to –41</td><td>–118 to –78</td><td>More unlikely than likely</td><td>Likely</td><td rowspan="6">Likely</td><td rowspan="8">Likely</td></tr>
<tr><td rowspan="2">500
(480 to 530)</td><td>No overshoot of 530 ppm CO_2-eq</td><td></td><td>–57 to –42</td><td>–107 to –73</td><td rowspan="6">Unlikely</td><td>More likely than not</td></tr>
<tr><td>Overshoot of 530 ppm CO_2-eq</td><td></td><td>–55 to –25</td><td>–114 to –90</td><td>About as likely as not</td></tr>
<tr><td rowspan="2">550
(530 to 580)</td><td>No overshoot of 580 ppm CO_2-eq</td><td></td><td>–47 to –19</td><td>–81 to –59</td><td rowspan="3">More unlikely than likely [i]</td></tr>
<tr><td>Overshoot of 580 ppm CO_2-eq</td><td></td><td>–16 to 7</td><td>–183 to –86</td></tr>
<tr><td>(580 to 650)</td><td>Total range</td><td rowspan="2">RCP4.5</td><td>–38 to 24</td><td>–134 to –50</td></tr>
<tr><td>(650 to 720)</td><td>Total range</td><td>–11 to 17</td><td>–54 to –21</td><td rowspan="2">Unlikely</td><td>More likely than not</td></tr>
<tr><td>(720 to 1000) [b]</td><td>Total range</td><td>RCP6.0</td><td>18 to 54</td><td>–7 to 72</td><td rowspan="2">Unlikely [h]</td><td>More unlikely than likely</td></tr>
<tr><td>>1000 [b]</td><td>Total range</td><td>RCP8.5</td><td>52 to 95</td><td>74 to 178</td><td>Unlikely [h]</td><td>Unlikely</td><td>More unlikely than likely</td></tr>
</table>

Notes:

[a] The 'total range' for the 430 to 480 ppm CO_2-eq concentrations scenarios corresponds to the range of the 10th to 90th percentile of the subcategory of these scenarios shown in Table 6.3 of the Working Group III report.

[b] Baseline scenarios fall into the >1000 and 720 to 1000 ppm CO_2-eq categories. The latter category also includes mitigation scenarios. The baseline scenarios in the latter category reach a temperature change of 2.5°C to 5.8°C above the average for 1850–1900 in 2100. Together with the baseline scenarios in the >1000 ppm CO_2-eq category, this leads to an overall 2100 temperature range of 2.5°C to 7.8°C (range based on median climate response: 3.7°C to 4.8°C) for baseline scenarios across both concentration categories.

[c] The global 2010 emissions are 31% above the 1990 emissions (consistent with the historic greenhouse gas emission estimates presented in this report). CO_2-eq emissions include the basket of Kyoto gases (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) as well as fluorinated gases).

[d] The assessment here involves a large number of scenarios published in the scientific literature and is thus not limited to the Representative Concentration Pathways (RCPs). To evaluate the CO_2-eq concentration and climate implications of these scenarios, the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) was used in a probabilistic mode. For a comparison between MAGICC model results and the outcomes of the models used in WGI, see WGI 12.4.1.2, 12.4.8 and WGIII 6.3.2.6.

[e] The assessment in this table is based on the probabilities calculated for the full ensemble of scenarios in WGIII using MAGICC and the assessment in WGI of the uncertainty of the temperature projections not covered by climate models. The statements are therefore consistent with the statements in WGI, which are based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) runs of the RCPs and the assessed uncertainties. Hence, the likelihood statements reflect different lines of evidence from both WGs. This WGI method was also applied for scenarios with intermediate concentration levels where no CMIP5 runs are available. The likelihood statements are indicative only *{WGIII 6.3}* and follow broadly the terms used by the WGI SPM for temperature projections: likely 66–100%, more likely than not >50–100%, about as likely as not 33–66%, and unlikely 0–33%. In addition the term more unlikely than likely 0–<50% is used.

[f] The CO_2-equivalent concentration (see Glossary) is calculated on the basis of the total forcing from a simple carbon cycle/climate model, MAGICC. The CO_2-equivalent concentration in 2011 is estimated to be 430 ppm (uncertainty range 340 to 520 ppm). This is based on the assessment of total anthropogenic radiative forcing for 2011 relative to 1750 in WGI, i.e., 2.3 W/m^2, uncertainty range 1.1 to 3.3 W/m^2.

[g] The vast majority of scenarios in this category overshoot the category boundary of 480 ppm CO_2-eq concentration.

[h] For scenarios in this category, no CMIP5 run or MAGICC realization stays below the respective temperature level. Still, an *unlikely* assignment is given to reflect uncertainties that may not be reflected by the current climate models.

[i] Scenarios in the 580 to 650 ppm CO_2-eq category include both overshoot scenarios and scenarios that do not exceed the concentration level at the high end of the category (e.g., RCP4.5). The latter type of scenarios, in general, have an assessed probability of *more unlikely than likely* to stay below the 2°C temperature level, while the former are mostly assessed to have an *unlikely* probability of staying below this level.

[j] In these scenarios, global CO_2-eq emissions in 2050 are between 70 to 95% below 2010 emissions, and they are between 110 to 120% below 2010 emissions in 2100.

different assumptions about the scale of bioenergy production, afforestation and reduced deforestation. Scenarios leading to concentrations of 500 ppm CO_2-eq by 2100 are characterized by a 25 to 55% reduction in GHG emissions by 2050, relative to 2010 levels. Scenarios that are *likely* to limit warming to 3°C relative to pre-industrial levels reduce emissions less rapidly than those limiting warming to 2°C. Only a limited number of studies provide scenarios that are *more likely than not* to limit warming to 1.5°C by 2100; these scenarios are characterized by concentrations below 430 ppm CO_2-eq by 2100 and 2050 emission reduction between 70 and 95% below 2010. For a comprehensive overview of the characteristics of emissions scenarios, their CO_2-equivalent concentrations and their likelihood to keep warming to below a range of temperature levels, see Table 3.1. *{WGIII SPM.4.1, TS.3.1, 6.3, 7.11}*

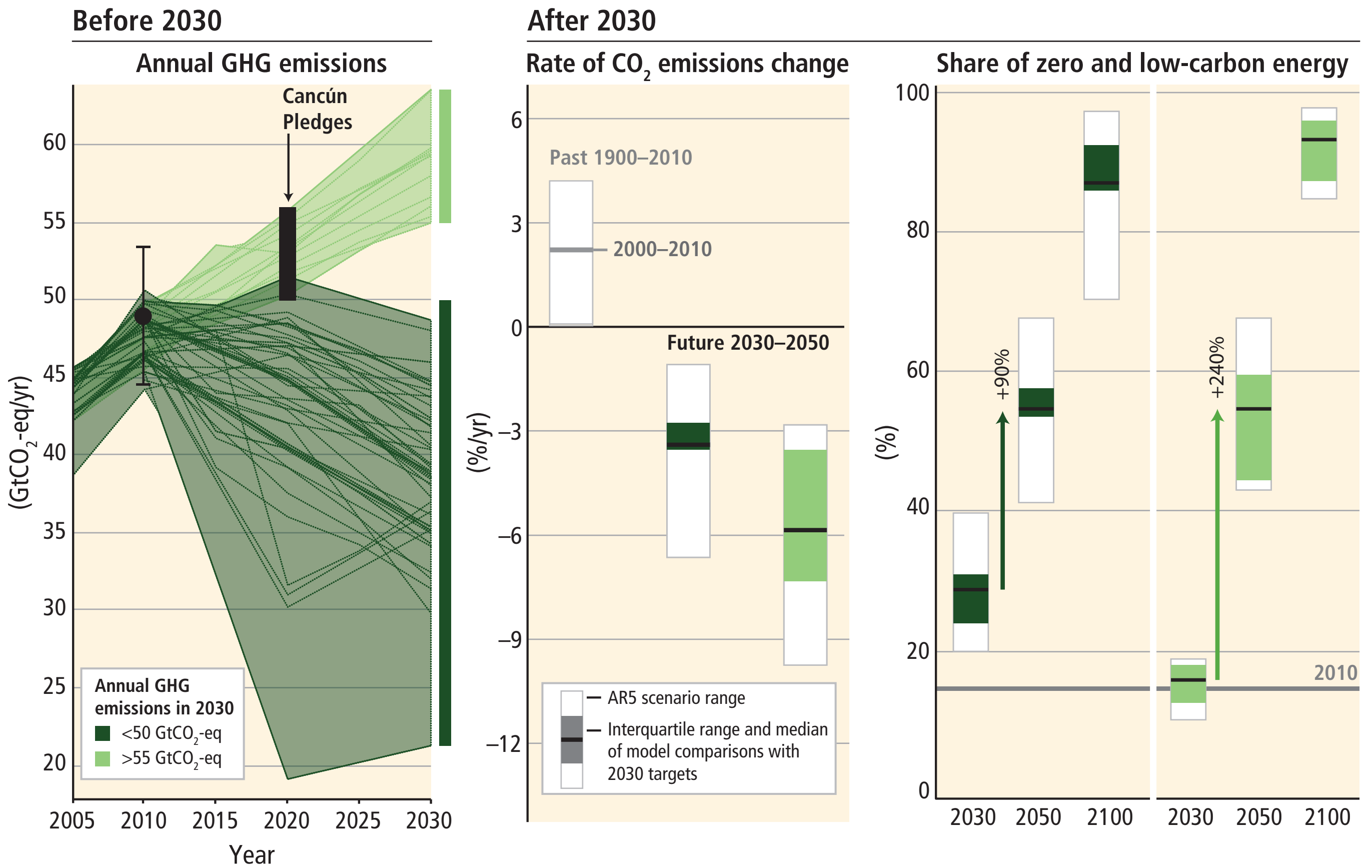

Figure 3.3 | The implications of different 2030 greenhouse gas (GHG) emissions levels for the rate of carbon dioxide (CO_2) emission reductions and low-carbon energy upscaling in mitigation scenarios that are at least *about as likely as not* to keep warming throughout the 21st century below 2°C relative to pre-industrial levels (2100 CO_2-eq concentrations 430 to 530 ppm). The scenarios are grouped according to different emissions levels by 2030 (coloured in different shades of green). The left panel shows the pathways of GHG emissions ($GtCO_2$-eq/yr) leading to these 2030 levels. Black dot with whiskers gives historic GHG emission levels and associated uncertainties in 2010 as reported in Figure 1.6. The black bar shows the estimated uncertainty range of GHG emissions implied by the Cancún Pledges. The middle panel denotes the average annual CO_2 emission reduction rates for the 2030–2050 period. It compares the median and interquartile range across scenarios from recent intermodel comparisons with explicit 2030 interim goals to the range of scenarios in the Scenario Database for WGIII AR5. Annual rates of historical emission changes (sustained over a period of 20 years) are shown as well. The arrows in the right panel show the magnitude of zero and low-carbon energy supply upscaling from between 2030 and 2050, subject to different 2030 GHG emission levels. Zero- and low-carbon energy supply includes renewable energy, nuclear energy and fossil energy with carbon dioxide capture and storage (CCS) or bioenergy with CCS (BECCS). Only scenarios that apply the full, unconstrained mitigation technology portfolio of the underlying models (default technology assumption) are shown. Scenarios with large net negative global emissions (>20 $GtCO_2$-eq/yr), scenarios with exogenous carbon price assumptions, and scenarios with 2010 emission levels that are significantly outside the historical range are excluded. *{WGIII Figure SPM.5, Figure 6.32, Figure 7.16, 13.13.1.3}*

Reducing emissions of non-CO_2 climate forcing agents can be an important element of mitigation strategies. Emissions of non-CO_2 gases (methane (CH_4), nitrous oxide (N_2O), and fluorinated gases) contributed about 27% to the total emissions of Kyoto gases in 2010. For most non-CO_2 gases, near-term, low-cost options are available to reduce their emissions. However, some sources of these non-CO_2 gases are difficult to mitigate, such as N_2O emissions from fertilizer use and CH_4 emissions from livestock. As a result, emissions of most non-CO_2 gases will not be reduced to zero, even under stringent mitigation scenarios (see Figure 4.1). The differences in radiative properties and lifetimes of CO_2 and non-CO_2 climate forcing agents have important implications for mitigation strategies (see also Box 3.2). *{WGIII 6.3.2}*

All current GHG emissions and other climate forcing agents affect the rate and magnitude of climate change over the next few decades. Reducing the emissions of certain short-lived climate forcing agents can reduce the rate of warming in the short term but will have only a limited effect on long-term warming, which is driven mainly by CO_2 emissions. There are large uncertainties related to the climate impacts of some of the short-lived climate forcing agents. Although the effects of CH_4 emissions are well understood, there are large uncertainties related to the effects of black carbon. Co-emitted components with cooling effects may further complicate and reduce the climate impacts of emission reductions. Reducing emissions of sulfur dioxide (SO_2) would cause warming. Near-term reductions in short-lived climate forcing agents can have a relatively fast impact on climate change and possible co-benefits for air pollution. *{WGI 8.2.3, 8.3.2, 8.3.4, 8.5.1, 8.7.2, FAQ 8.2, 12.5, WGIII 6.6.2.1}*

Delaying additional mitigation to 2030 will substantially increase the challenges associated with limiting warming over the 21st century to below 2°C relative to pre-industrial levels (*high confidence*). GHG emissions in 2030 lie between about 30 $GtCO_2$-eq/yr and 50 $GtCO_2$-eq/yr in cost-effective scenarios that are *likely* to *about as likely as not* to limit warming to less than 2°C this century relative to pre-industrial levels (2100 atmospheric concentration

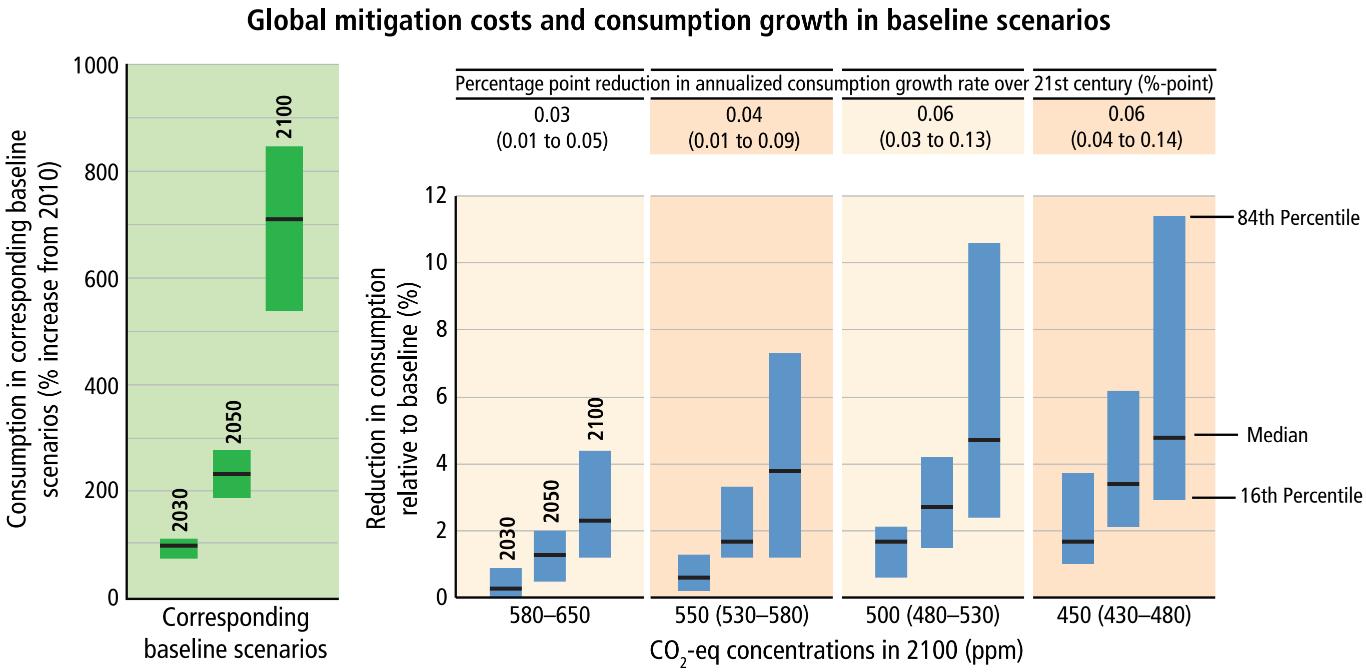

Figure 3.4 | Global mitigation costs in cost-effective scenarios at different atmospheric concentrations levels in 2100 (right panel) and growth in economic consumption in the corresponding baseline scenarios (those without additional mitigation) (left panel). The table at the top shows percentage points of annualized consumption growth reductions relative to consumption growth in the baseline of 1.6 to 3% per year (e.g., if the reduction is 0.06 percentage points per year due to mitigation, and baseline growth is 2.0% per year, then the growth rate with mitigation would be 1.94% per year). Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price, and they impose no additional limitations on technology relative to the models' default technology assumptions. Consumption losses are shown relative to a baseline development without climate policy. Cost estimates shown in this table do not consider the benefits of reduced climate change nor co-benefits and adverse side effects of mitigation. Estimates at the high end of these cost ranges are from models that are relatively inflexible to achieve the deep emissions reductions that would be required in the long run to meet these goals and/or include assumptions about market imperfections that would raise costs. *{WGIII Table SPM.2, Figure TS.12, 6.3.6, Figure 6.21}*

levels of about 450 ppm CO_2-eq to about 500 ppm CO_2-eq) (Figure 3.3, left panel). Scenarios with GHG emission levels of above 55 $GtCO_2$-eq/yr require substantially higher rates of emissions reductions between 2030 and 2050 (median estimate of 6%/yr as compared to 3%/yr in cost-effective scenarios; Figure 3.3, middle panel); much more rapid scale-up of zero and low-carbon energy over this period (more than a tripling compared to a doubling of the low-carbon energy share relative to 2010; Figure 3.3, right panel); a larger reliance on CDR technologies in the long term; and higher transitional and long-term economic impacts (Table 3.2). (3.5, 4.3) *{WGIII SPM.4.1, TS.3.1, 6.4, 7.11}*

Estimated global emission levels by 2020 based on the Cancún Pledges are not consistent with cost-effective long-term mitigation trajectories that are at least *about as likely as not* to limit warming to below 2°C relative to pre-industrial levels (2100 concentration levels of about 500 ppm CO_2-eq or below), but they do not preclude the option to meet this goal (*high confidence*). The Cancún Pledges are broadly consistent with cost-effective scenarios that are *likely* to limit temperature change to below 3°C relative to pre-industrial levels. *{WGIII SPM.4.1, 6.4, 13.13, Figure TS.11}*

Estimates of the aggregate economic costs of mitigation vary widely depending on methodologies and assumptions but increase with the stringency of mitigation (*high confidence*). Scenarios in which all countries of the world begin mitigation immediately, in which there is a single global carbon price, and in which all key technologies are available have been used as a cost-effective benchmark for estimating macroeconomic mitigation costs (Figure 3.4). Under these assumptions, mitigation scenarios that are *likely* to limit warming to below 2°C through the 21st century relative to pre-industrial levels entail losses in global consumption—not including benefits of reduced climate change (3.2) as well as co-benefits and adverse side effects of mitigation (3.5, 4.3)—of 1 to 4% (median: 1.7%) in 2030, 2 to 6% (median: 3.4%) in 2050, and 3% to 11% (median: 4.8%) in 2100, relative to consumption in baseline scenarios that grows anywhere from 300% to more than 900% over the century[41]. These numbers correspond to an annualized reduction of consumption growth by 0.04 to 0.14 (median: 0.06) percentage points over the century relative to annualized consumption growth in the baseline that is between 1.6% and 3% per year (Figure 3.4). In the absence or under limited availability of mitigation technologies (such as bioenergy, CCS, and their combination BECCS, nuclear, wind and solar), mitigation costs can increase substantially depending on the technology considered (Table 3.2). Delaying additional mitigation reduces near-term costs but increases mitigation costs in the medium- to long-term (Table 3.2). Many models could not limit *likely* warming to below 2°C over the 21st century relative to pre-industrial levels, if additional mitigation is considerably delayed, or if availability of key technologies, such as bioenergy, CCS and their combination (BECCS) are limited (*high confidence*) (Table 3.2). *{WGIII SPM.4.1, Table SPM.2, Table TS.2, TS.3.1, 6.3, 6.6}*

[41] Mitigation cost ranges cited here refer to the 16th to 84th percentile of the underlying sample (see Figure 3.4).

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Mitigation efforts and associated cost are expected to vary across countries. The distribution of costs can differ from the distribution of the actions themselves (*high confidence*). In globally cost-effective scenarios, the majority of mitigation efforts takes place in countries with the highest future GHG emissions in baseline scenarios. Some studies exploring particular effort-sharing frameworks, under the assumption of a global carbon market, have estimated substantial global financial flows associated with mitigation in scenarios that are *likely* to *more unlikely than likely* to limit warming during the 21st century to less than 2°C relative to pre-industrial levels. *{WGIII SPM.4.1, TS.3.1, Box 3.5, 4.6, 6.3.6, Table 6.4, Figure 6.9, Figure 6.27, Figure 6.28, Figure 6.29, 13.4.2.4}*

Table 3.2 | Increase in global mitigation costs due to either limited availability of specific technologies or delays in additional mitigation [a] relative to cost-effective scenarios [b]. The increase in costs is given for the median estimate and the 16th to 84th percentile range of the scenarios (in parentheses). The sample size of each scenario set is provided in the coloured symbols [c]. The colours of the symbols indicate the fraction of models from systematic model comparison exercises that could successfully reach the targeted concentration level. *{WGIII Table SPM.2, Table TS.2, Figure TS.13, Figure 6.24, Figure 6.25}*

	Mitigation cost increases in scenarios with limited availability of technologies [d] *[% increase in total discounted [e] mitigation costs (2015–2100) relative to default technology assumptions]*				**Mitigation cost increases due to delayed additional mitigation until 2030** *[% increase in mitigation costs relative to immediate mitigation]*	
2100 concentrations (ppm CO_2-eq)	no CCS	nuclear phase out	limited solar/wind	limited bioenergy	medium term costs (2030–2050)	long term costs (2050–2100)
450 (430 to 480)	138% (29 to 297%) 4	7% (4 to 18%) 8	6% (2 to 29%) 8	64% (44 to 78%) 8	44% (2 to 78%) 29	37% (16 to 82%) 29
500 (480 to 530)	not available (n.a.)	n.a.	n.a.	n.a.		
550 (530 to 580)	39% (18 to 78%) 11	13% (2 to 23%) 10	8% (5 to 15%) 10	18% (4 to 66%) 12	15% (3 to 32%)	16% (5 to 24%)
580 to 650	n.a.	n.a.	n.a.	n.a.		

Symbol legend—fraction of models successful in producing scenarios (numbers indicate the number of successful models)

- : all models successful
- : between 80 and 100% of models successful
- : between 50 and 80% of models successful
- : less than 50% of models successful

Notes:

[a] Delayed mitigation scenarios are associated with greenhouse gas emission of more than 55 $GtCO_2$-eq in 2030, and the increase in mitigation costs is measured relative to cost-effective mitigation scenarios for the same long-term concentration level.

[b] Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price, and impose no additional limitations on technology relative to the models' default technology assumptions.

[c] The range is determined by the central scenarios encompassing the 16th to 84th percentile range of the scenario set. Only scenarios with a time horizon until 2100 are included. Some models that are included in the cost ranges for concentration levels above 530 ppm CO_2-eq in 2100 could not produce associated scenarios for concentration levels below 530 ppm CO_2-eq in 2100 with assumptions about limited availability of technologies and/or delayed additional mitigation.

[d] No CCS: carbon dioxide capture and storage is not included in these scenarios. Nuclear phase out: no addition of nuclear power plants beyond those under construction, and operation of existing plants until the end of their lifetime. Limited Solar/Wind: a maximum of 20% global electricity generation from solar and wind power in any year of these scenarios. Limited Bioenergy: a maximum of 100 EJ/yr modern bioenergy supply globally (modern bioenergy used for heat, power, combinations and industry was around 18 EJ/yr in 2008). EJ = Exajoule = 10^{18} Joule.

[e] Percentage increase of net present value of consumption losses in percent of baseline consumption (for scenarios from general equilibrium models) and abatement costs in percent of baseline gross domestic product (GDP, for scenarios from partial equilibrium models) for the period 2015–2100, discounted at 5% per year.

Box 3.2 | Greenhouse Gas Metrics and Mitigation Pathways

This box focuses on emission-based metrics that are used for calculating CO_2-equivalent emissions for the formulation and evaluation of mitigation strategies. These emission metrics are distinct from the concentration-based metric used in SYR (CO_2-equivalent concentration). For an explanation of CO_2-equivalent emissions and CO_2-equivalent concentrations, see Glossary.

Emission metrics facilitate multi-component climate policies by allowing emissions of different greenhouse gases (GHGs) and other climate forcing agents to be expressed in a common unit (so-called 'CO_2-equivalent emissions'). The Global Warming Potential (GWP) was introduced in the IPCC First Assessment Report, where it was also used to illustrate the difficulties in comparing components with differing physical properties using a single metric. The 100-year GWP (GWP_{100}) was adopted by the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol and is now used widely as the default metric. It is only one of several possible emission metrics and time horizons. *{WGI 8.7, WGIII 3.9}*

The choice of emission metric and time horizon depends on type of application and policy context; hence, no single metric is optimal for all policy goals. All metrics have shortcomings, and choices contain value judgments, such as the climate effect considered and the weighting of effects over time (which explicitly or implicitly discounts impacts over time), the climate policy goal and the degree to which metrics incorporate economic or only physical considerations. There are significant uncertainties related to metrics, and the magnitudes of the uncertainties differ across metric type and time horizon. In general, the uncertainty increases for metrics along the cause–effect chain from emission to effects. *{WGI 8.7, WGIII 3.9}*

The weight assigned to non-CO_2 climate forcing agents relative to CO_2 depends strongly on the choice of metric and time horizon (*robust evidence, high agreement*). GWP compares components based on radiative forcing, integrated up to a chosen time horizon. Global Temperature change Potential (GTP; see Glossary) is based on the temperature response at a specific point in time with no weight on temperature response before or after the chosen point in time. Adoption of a fixed horizon of, for example, 20, 100 or 500 years for these metrics will inevitably put no weight on climate outcomes beyond the time horizon, which is significant for CO_2 as well as other long-lived gases. The choice of time horizon markedly affects the weighting especially of short-lived climate forcing agents, such as methane (CH_4) (see Box 3.2, Table 1; Box 3.2, Figure 1a). For some metrics (e.g., the dynamic GTP; see Glossary), the weighting changes over time as a chosen target year is approached. *{WGI 8.7, WGIII 3.9}*

Box 3.2, Table 1 | Examples of emission metric values from WGI [a].

		GWP		GTP	
	Lifetime (yr)	**Cumulative forcing over 20 years**	**Cumulative forcing over 100 years**	**Temperature change after 20 years**	**Temperature change after 100 years**
CO_2	[b]	1	1	1	1
CH_4	12.4	84	28	67	4
N_2O	121.0	264	265	277	234
CF_4	50,000.0	4880	6630	5270	8040
HFC-152a	1.5	506	138	174	19

Notes:

[a] Global Warming Potential (GWP) values have been updated in successive IPCC reports; the AR5 GWP_{100} values are different from those adopted for the Kyoto Protocol's First Commitment Period which are from the IPCC Second Assessment Report (SAR). Note that for consistency, equivalent CO_2 emissions given elsewhere in this Synthesis Report are also based on SAR, not AR5 values. For a comparison of emissions using SAR and AR5 GWP_{100} values for 2010 emissions, see Figure 1.6.

[b] No single lifetime can be given for CO_2. *{WGI Box 6.1, 6.1.1, 8.7}*

The choice of emission metric affects the timing and emphasis placed on abating short- and long-lived climate forcing agents. For most metrics, global cost differences are small under scenarios of global participation and cost-minimizing mitigation pathways, but implications for some individual countries and sectors could be more significant (*medium evidence, high agreement*). Different metrics and time horizons significantly affect the contributions from various sources/sectors and components, particularly short-lived climate forcing agents (Box 3.2, Figure 1b). A fixed time independent metric that gives less weight to short-lived agents such as CH_4 (e.g., using GTP_{100} instead of GWP_{100}) would require earlier and more stringent CO_2 abatement to achieve the same climate outcome for 2100. Using a time-dependent metric, such as a dynamic GTP, leads to less CH_4 mitigation

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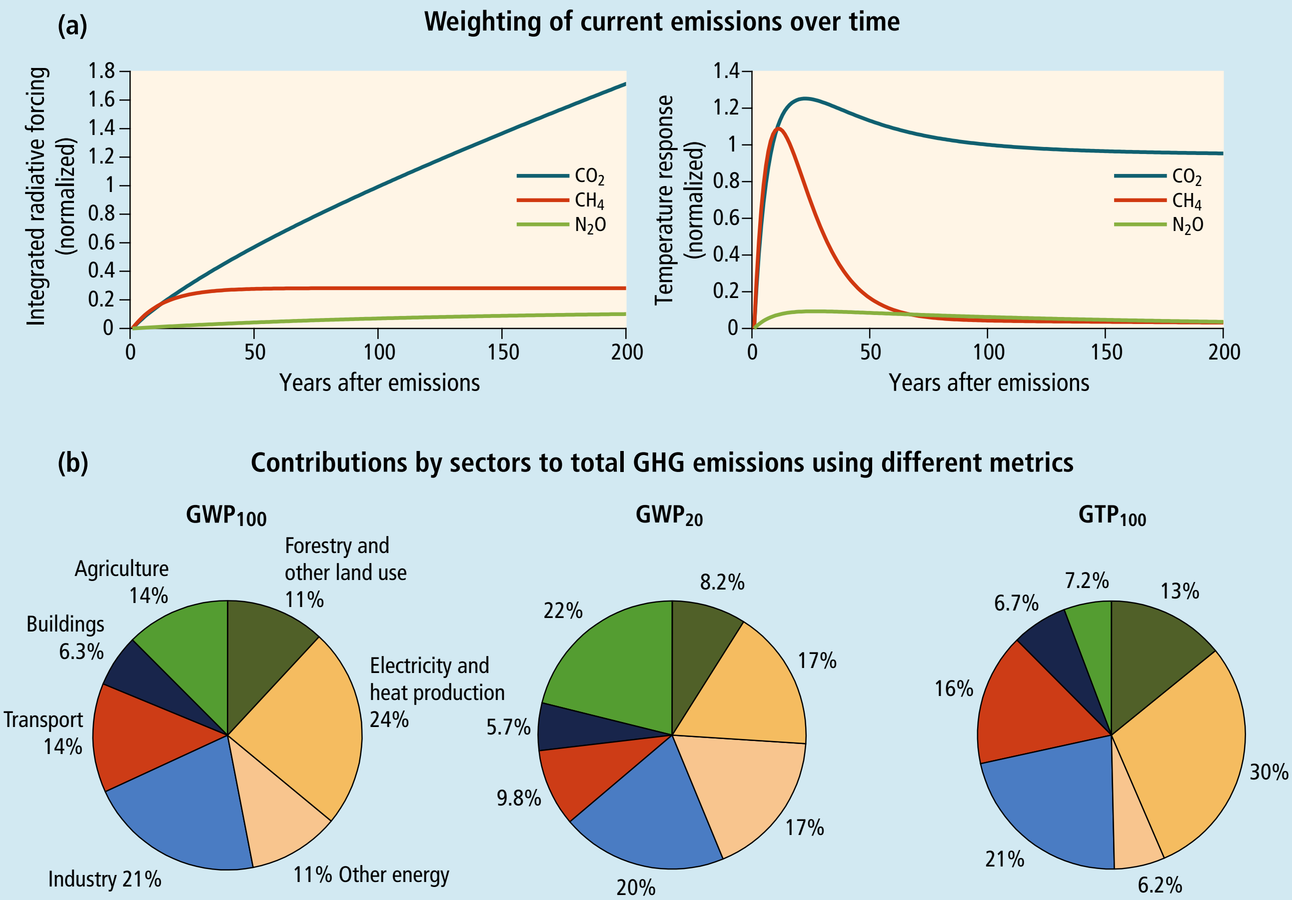
Box 3.2 (continued)

in the near term but to more in the long term as the target date is being approached. This implies that for some (short-lived) agents, the metric choice influences the choice of policies and the timing of mitigation (especially for sectors and countries with high non-CO_2 emission levels). *{WGI 8.7, WGIII 6.3}*



Box 3.2, Figure 1 | Implications of metric choices on the weighting of greenhouse gas (GHG) emissions and contributions by sectors for illustrative time horizons. Panel **(a)**: integrated radiative forcing (left panel) and warming resulting at a given future point in time (right panel) from global net emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the year 2010 (and no emissions thereafter), for time horizons of up to 200 years. Integrated radiative forcing is used in the calculation of Global Warming Potentials (GWP), while the warming at a future point in time is used in the calculation of Global Temperature change Potentials (GTP). Radiative forcing and warming were calculated based on global 2010 emission data from WGIII 5.2 and absolute GWPs and absolute GTPs from WGI 8.7, normalized to the integrated radiative forcing and warming, respectively, after 100 years, due to 2010 net CO_2 emissions. Panel **(b)**: Illustrative examples showing contributions from different sectors to total metric-weighted global GHG emissions in the year 2010, calculated using 100-year GWP (GWP_{100}, left), 20-year GWP (GWP_{20}, middle) or 100-year GTP (GTP_{100}, right) and the WGIII 2010 emissions database. *{WGIII 5.2}* Note that percentages differ slightly for the GWP_{100} case if values from the IPCC Second Assessment Report are used; see Topic 1, Figure 1.7. See WGIII for details of activities resulting in emissions in each sector.

Box 3.3 | Carbon Dioxide Removal and Solar Radiation Management Geoengineering Technologies—Possible Roles, Options, Risks and Status

Geoengineering refers to a broad set of methods and technologies operating on a large scale that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most methods seek to either reduce the amount of absorbed solar energy in the climate system (Solar Radiation Management, SRM) or increase the removal of carbon dioxide (CO_2) from the atmosphere by sinks to alter climate (Carbon Dioxide Removal, CDR, see Glossary). Limited evidence precludes a comprehensive assessment of feasibility, cost, side effects and environmental impacts of either CDR or SRM. *{WGI SPM E.8, 6.5, 7.7, WGII 6.4, Table 6-5, Box 20-4, WGIII TS.3.1.3, 6.9}*

CDR plays a major role in many mitigation scenarios. Bioenergy with carbon dioxide capture and storage (BECCS) and afforestation are the only CDR methods included in these scenarios. CDR technologies are particularly important in scenarios that temporarily overshoot atmospheric concentrations, but they are also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. Similar to mitigation, CDR would need to be deployed on a large scale and over a long time period to be able to significantly reduce CO_2 concentrations (see Section 3.1). *{WGII 6.4, WGIII SPM 4.1, TS.3.1.2, TS 3.1.3, 6.3, 6.9}*

Several CDR techniques could potentially reduce atmospheric greenhouse gas (GHG) levels. However, there are biogeochemical, technical and societal limitations that, to varying degrees, make it difficult to provide quantitative estimates of the potential for CDR. The emission mitigation from CDR is less than the removed CO_2, as some CO_2 is released from that previously stored in oceans and terrestrial carbon reservoirs. Sub-sea geologic storage has been implemented on a regional scale, with no evidence to date of ocean impact from leakage. The climatic and environmental side effects of CDR depend on technology and scale. Examples are associated with altered surface reflectance from afforestation and ocean de-oxygenation from ocean fertilization. Most terrestrial CDR techniques would involve competing demands for land and could involve local and regional risks, while maritime CDR techniques may involve significant risks for ocean ecosystems, so that their deployment could pose additional challenges for cooperation between countries. *{WGI 6.5, FAQ 7.3, WGII 6.4, Table 6.5, WGIII 6.9}*

SRM is untested, and is not included in any of the mitigation scenarios, but, if realisable, could to some degree offset global temperature rise and some of its effects. It could possibly provide rapid cooling in comparison to CO_2 mitigation. There is *medium confidence* that SRM through stratospheric aerosol injection is scalable to counter radiative forcing from a twofold increase in CO_2 concentrations and some of the climate responses associated with warming. Due to insufficient understanding there is no consensus on whether a similarly large negative counter radiative forcing could be achieved from cloud brightening. Land albedo change does not appear to be able to produce a large counter radiative forcing. Even if SRM could counter the global mean warming, differences in spatial patterns would remain. The scarcity of literature on other SRM techniques precludes their assessment. *{WGI 7.7, WGIII TS.3.1.3, 6.9}*

If it were deployed, SRM would entail numerous uncertainties, side effects, risks and shortcomings. Several lines of evidence indicate that SRM would itself produce a small but significant decrease in global precipitation (with larger differences on regional scales). Stratospheric aerosol SRM is *likely* to modestly increase ozone losses in the polar stratosphere. SRM would not prevent the CO_2 effects on ecosystems and ocean acidification that are unrelated to warming. There could also be other unanticipated consequences. For all future scenarios considered in AR5, SRM would need to increase commensurately, to counter the global mean warming, which would exacerbate side effects. Additionally, if SRM were increased to substantial levels and then terminated, there is *high confidence* that surface temperatures would rise very rapidly (within a decade or two). This would stress systems that are sensitive to the rate of warming. *{WGI 7.6–7.7, FAQ 7.3, WGII 19.5, WGIII 6.9}*

SRM technologies raise questions about costs, risks, governance and ethical implications of development and deployment. There are special challenges emerging for international institutions and mechanisms that could coordinate research and possibly restrain testing and deployment. Even if SRM would reduce human-made global temperature increase, it would imply spatial and temporal redistributions of risks. SRM thus introduces important questions of intragenerational and intergenerational justice. Research on SRM, as well as its eventual deployment, has been subject to ethical objections. In spite of the estimated low potential costs of some SRM deployment technologies, they will not necessarily pass a benefit–cost test that takes account of the range of risks and side effects. The governance implications of SRM are particularly challenging, especially as unilateral action might lead to significant effects and costs for others. *{WGIII TS.3.1.3, 1.4, 3.3, 6.9, 13.4}*

3.5 Interaction among mitigation, adaptation and sustainable development

Climate change is a threat to equitable and sustainable development. Adaptation, mitigation and sustainable development are closely related, with potential for synergies and trade-offs.

Climate change poses an increasing threat to equitable and sustainable development (*high confidence*). Some climate-related impacts on development are already being observed. Climate change is a threat multiplier. It exacerbates other threats to social and natural systems, placing additional burdens particularly on the poor and constraining possible development paths for all. Development along current global pathways can contribute to climate risk and vulnerability, further eroding the basis for sustainable development. *{WGII SPM B-2, 2.5, 10.9, 13.1–13.3, 20.1, 20.2, 20.6, WGIII SPM.2, 4.2}*

Aligning climate policy with sustainable development requires attention to both adaptation and mitigation (*high confidence*). Interaction among adaptation, mitigation and sustainable development occurs both within and across regions and scales, often in the context of multiple stressors. Some options for responding to climate change could impose risks of other environmental and social costs, have adverse distributional effects and draw resources away from other development priorities, including poverty eradication. *{WGII 2.5, 8.4, 9.3, 13.3–13.4, 20.2–20.4, 21.4, 25.9, 26.8, WGIII SPM.2, 4.8, 6.6}*

Both adaptation and mitigation can bring substantial co-benefits (*medium confidence*). Examples of actions with co-benefits include (i) improved air quality (see Figure 3.5); (ii) enhanced energy security, (iii) reduced energy and water consumption in urban areas through greening cities and recycling water; (iv) sustainable agriculture and forestry; and (v) protection of ecosystems for carbon storage and other ecosystem services. *{WGII SPM C-1, WGIII SPM.4.1}*

Strategies and actions can be pursued now that will move towards climate-resilient pathways for sustainable development, while at the same time helping to improve livelihoods, social and economic well-being and effective environmental management (*high confidence*). Prospects for climate-resilient pathways are related fundamentally to what the world accomplishes with climate change mitigation (*high confidence*). Since mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades. Delaying mitigation actions may reduce options for climate-resilient pathways in the future. *{WGII SPM C-2, 20.2, 20.6.2}*

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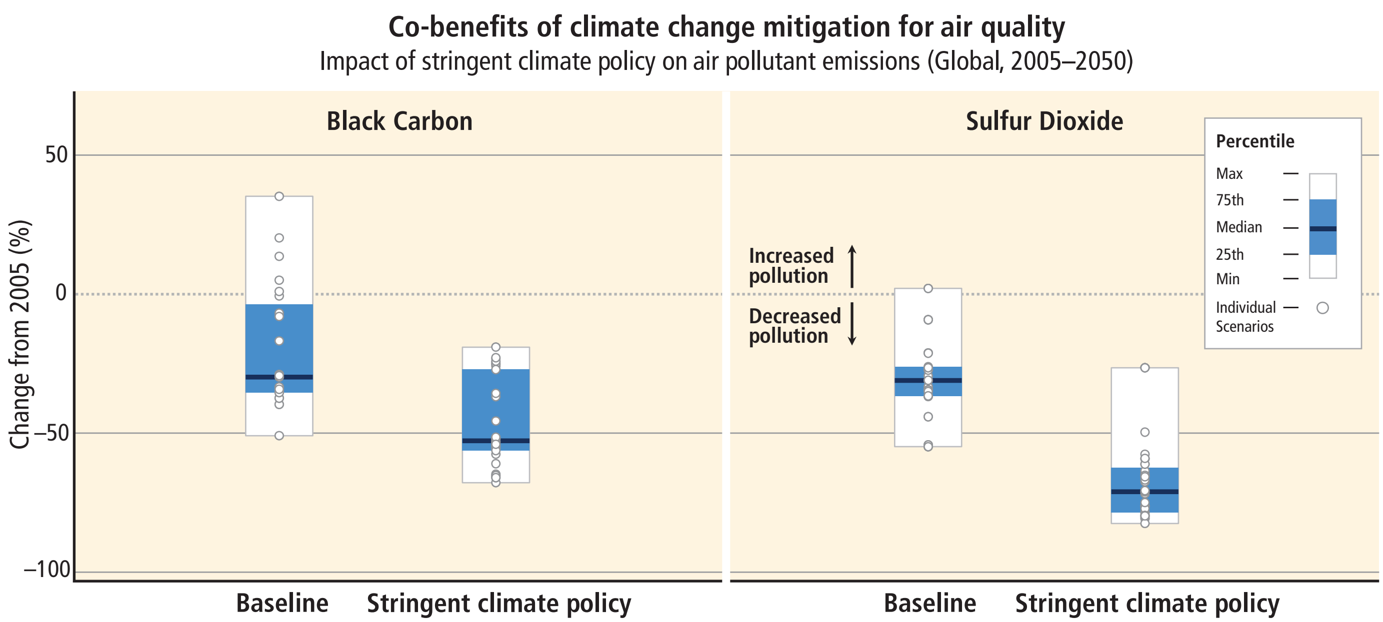

Figure 3.5 | Air pollutant emission levels of black carbon (BC) and sulfur dioxide (SO_2) by 2050, relative to 2005 (0 = 2005 levels). Baseline scenarios without additional efforts to reduce greenhouse gas (GHG) emissions beyond those in place today are compared to scenarios with stringent mitigation policies, which are consistent with reaching about 450 to about 500 (430 to 530) ppm CO_2-eq concentration levels by 2100. *{WGIII SPM.6, TS.14, Figure 6.33}*

Box 3.4 | Co-benefits and Adverse Side effects

A government policy or a measure intended to achieve one objective often affects other objectives, either positively or negatively. For example, mitigation policies can influence local air quality (see Figure 3.5). When the effects are positive they are called 'co-benefits', also referred to as 'ancillary benefits'. Negative effects are referred to as 'adverse side effects'. Some measures are labelled 'no or low regret' when their co-benefits are sufficient to justify their implementation, even in the absence of immediate direct benefits. Co-benefits and adverse side effects can be measured in monetary or non-monetary units. The effect of co-benefits and adverse side effects from climate policies on overall social welfare has not yet been quantitatively examined, with the exception of a few recent multi-objective studies. Many of these have not been well quantified, and effects can be case and site-specific as they will depend on local circumstances. *{WGII 11.9, 16.3.1, 17.2, 20.4.1, WGIII Box TS.11, 3.6, 5.7}*

Co-benefits of mitigation could affect achievement of other objectives, such as those related to energy security, air quality, efforts to address ecosystem impacts, income distribution, labour supply and employment and urban sprawl (see Table 4.2 and Table 4.5). In the absence of complementary policies, however, some mitigation measures may have adverse side effects (at least in the short term), for example on biodiversity, food security, energy access, economic growth and income distribution. The co-benefits of adaptation policies may include improved access to infrastructure and services, extended education and health systems, reduced disaster losses, better governance and others. *{WGII 4.4.4, 11.9, 15.2, 17.2, 20.3.3, 20.4.1, WGIII Box TS.11, 6.6}*

Comprehensive strategies in response to climate change that are consistent with sustainable development take into account the co-benefits, adverse side effects and risks that may arise from both adaptation and mitigation options. The assessment of overall social welfare impacts is complicated by this interaction between climate change response options and pre-existing non-climate policies. For example, in terms of air quality, the value of the extra tonne of sulfur dioxide (SO_2) reduction that occurs with climate change mitigation through reduced fossil fuel combustion depends greatly on the stringency of SO_2 control policies. If SO_2 policy is weak, the value of SO_2 reductions may be large, but if SO_2 policy is stringent, it may be near zero. Similarly, in terms of adaptation and disaster risk management, weak policies can lead to an adaptation deficit that increases human and economic losses from natural climate variability. 'Adaptation deficit' refers to the lack of capacity to manage adverse impacts of current climate variability. An existing adaptation deficit increases the benefits of adaptation policies that improve the management of climate variability and change. *{WGII 20.4.1, WGIII Box TS.11, 6.3}*

4 Adaptation and Mitigation

Topic 4: Adaptation and Mitigation

Many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself. Effective implementation depends on policies and cooperation at all scales and can be enhanced through integrated responses that link mitigation and adaptation with other societal objectives.

Topic 3 demonstrates the need and strategic considerations for both adaptation and global-scale mitigation to manage risks from climate change. Building on these insights, Topic 4 presents near-term response options that could help achieve such strategic goals. Near-term adaptation and mitigation actions will differ across sectors and regions, reflecting development status, response capacities and near- and long-term aspirations with regard to both climate and non-climate outcomes. Because adaptation and mitigation inevitably take place in the context of multiple objectives, particular attention is given to the ability to develop and implement integrated approaches that can build on co-benefits and manage trade-offs.

4.1 Common enabling factors and constraints for adaptation and mitigation responses

Adaptation and mitigation responses are underpinned by common enabling factors. These include effective institutions and governance, innovation and investments in environmentally sound technologies and infrastructure, sustainable livelihoods and behavioural and lifestyle choices.

Innovation and investments in environmentally sound infrastructure and technologies can reduce greenhouse gas (GHG) emissions and enhance resilience to climate change (*very high confidence*). Innovation and change can expand the availability and/or effectiveness of adaptation and mitigation options. For example, investments in low-carbon and carbon-neutral energy technologies can reduce the energy intensity of economic development, the carbon intensity of energy, GHG emissions, and the long-term costs of mitigation. Similarly, new technologies and infrastructure can increase the resilience of human systems while reducing adverse impacts on natural systems. Investments in technology and infrastructure rely on an enabling policy environment, access to finance and technology and broader economic development that builds capacity (Table 4.1, Section 4.4). *{WGII SPM C-2, Table SPM.1, Table TS.8, WGIII SPM.4.1, Table SPM.2, TS.3.1.1, TS 3.1.2, TS.3.2.1}*

Adaptation and mitigation are constrained by the inertia of global and regional trends in economic development, GHG emissions, resource consumption, infrastructure and settlement patterns, institutional behaviour and technology (*medium evidence, high agreement*). Such inertia may limit the capacity to reduce GHG emissions, remain below particular climate thresholds or avoid adverse impacts (Table 4.1). Some constraints may be overcome through new technologies, financial resources, increased institutional effectiveness and governance or changes in social and cultural attitudes and behaviours. *{WGII SPM C-1, WGIII SPM.3, SPM.4.2, Table SPM.2}*

Vulnerability to climate change, GHG emissions, and the capacity for adaptation and mitigation are strongly influenced by livelihoods, lifestyles, behaviour and culture (*medium evidence, medium agreement*) (Table 4.1). Shifts toward more energy-intensive lifestyles can contribute to higher energy and resource consumption, driving greater energy production and GHG emissions and increasing mitigation costs. In contrast, emissions can be substantially lowered through changes in consumption patterns (see 4.3 for details). The social acceptability and/or effectiveness of climate policies are influenced by the extent to which they incentivize or depend on regionally appropriate changes in lifestyles or behaviours. Similarly, livelihoods that depend on climate-sensitive sectors or resources may be particularly vulnerable to climate change and climate change policies. Economic development and urbanization of landscapes exposed to climate hazards may increase the exposure of human settlements and reduce the resilience of natural systems. *{WGII SPM A-2, SPM B-2, Table SPM.1, TS A-1, TS A-2, TS C-1, TS C-2, 16.3.2.7, WGIII SPM.4.2, TS.2.2, 4.2}*

For many regions and sectors, enhanced capacities to mitigate and adapt are part of the foundation essential for managing climate change risks (*high confidence*). Such capacities are place- and context-specific and therefore there is no single approach for reducing risk that is appropriate across all settings. For example, developing nations with low income levels have the lowest financial, technological and institutional capacities to pursue low-carbon, climate-resilient development pathways. Although developed nations generally have greater relative capacity to manage the risks of climate change, such capacity does not necessarily translate into the implementation of adaptation and mitigation options. *{WGII SPM B-1, SPM B-2, TS B-1, TS B-2, 16.3.1.1, 16.3.2, 16.5, WGIII SPM.5.1, TS.4.3, TS.4.5, 4.6}*

Improving institutions as well as enhancing coordination and cooperation in governance can help overcome regional constraints associated with mitigation, adaptation and disaster risk reduction (*very high confidence*). Despite the presence of a wide array of multilateral, national and sub-national institutions focused on adaptation and mitigation, global GHG emissions continue to increase and identified adaptation needs have not been adequately addressed. The implementation of effective adaptation and mitigation options may necessitate new institutions and institutional arrangements that span multiple scales (*medium confidence*) (Table 4.1). *{WGII SPM B-2, TS C-1, 16.3.2.4, 16.8, WGIII SPM.4.2.5, SPM.5.1, SPM.5.2, TS.1, TS.3.1.3, TS.4.1, TS.4.2, TS.4.4}*

Table 4.1 | Common factors that constrain the implementation of adaptation and mitigation options

Constraining Factor	Potential Implications for Adaptation	Potential Implications for Mitigation
Adverse externalities of population growth and urbanization	Increase exposure of human populations to climate variability and change as well as demands for, and pressures on, natural resources and ecosystem services *{WGII 16.3.2.3, Box 16-3}*	Drive economic growth, energy demand and energy consumption, resulting in increases in greenhouse gas emissions *{WGIII SPM.3}*
Deficits of knowledge, education and human capital	Reduce national, institutional and individual perceptions of the risks posed by climate change as well as the costs and benefits of different adaptation options *{WGII 16.3.2.1}*	Reduce national, institutional and individual risk perception, willingness to change behavioural patterns and practices and to adopt social and technological innovations to reduce emissions *{WGIII SPM.3, SPM.5.1, 2.4.1, 3.10.1.5, 4.3.5, 9.8, 11.8.1}*
Divergences in social and cultural attitudes, values and behaviours	Reduce societal consensus regarding climate risk and therefore demand for specific adaptation policies and measures *{WGII 16.3.2.7}*	Influence emission patterns, societal perceptions of the utility of mitigation policies and technologies, and willingness to pursue sustainable behaviours and technologies *{WGIII SPM.2, 2.4.5, 2.6.6.1, 3.7.2.2, 3.9.2, 4.3.4, 5.5.1}*
Challenges in governance and institutional arrangements	Reduce the ability to coordinate adaptation policies and measures and to deliver capacity to actors to plan and implement adaptation *{WGII 16.3.2.8}*	Undermine policies, incentives and cooperation regarding the development of mitigation policies and the implementation of efficient, carbon-neutral and renewable energy technologies *{WGIII SPM.3, SPM.5.2, 4.3.2, 6.4.3, 14.1.3.1, 14.3.2.2, 15.12.2, 16.5.3}*
Lack of access to national and international climate finance	Reduces the scale of investment in adaptation policies and measures and therefore their effectiveness *{WGII 16.3.2.5}*	Reduces the capacity of developed and, particularly, developing nations to pursue policies and technologies that reduce emissions. *{WGIII TS.4.3, 12.6.2, 16.2.2.2}*
Inadequate technology	Reduces the range of available adaptation options as well as their effectiveness in reducing or avoiding risk from increasing rates or magnitudes of climate change *{WGII 16.3.2.1}*	Slows the rate at which society can reduce the carbon intensity of energy services and transition toward low-carbon and carbon-neutral technologies *{WGIII TS.3.1.3, 4.3.6, 6.3.2.2, 11.8.4}*
Insufficient quality and/or quantity of natural resources	Reduce the coping range of actors, vulnerability to non-climatic factors and potential competition for resources that enhances vulnerability *{WGII 16.3.2.3}*	Reduce the long-term sustainability of different energy technologies *{WGIII 4.3.7, 4.4.1, 11.8.3}*
Adaptation and development deficits	Increase vulnerability to current climate variability as well as future climate change *{WGII TS A-1, Table TS 5, 16.3.2.4}*	Reduce mitigative capacity and undermine international cooperative efforts on climate owing to a contentious legacy of cooperation on development *{WGIII 4.3.1, 4.6.1}*
Inequality	Places the impacts of climate change and the burden of adaptation disproportionately on the most vulnerable and/or transfers them to future generations *{WGII TS B-2, Box TS 4, Box 13-1, 16.7}*	Constrains the ability for developing nations with low income levels, or different communities or sectors within nations, to contribute to greenhouse gas mitigation *{WGIII 4.6.2.1}*

4.2 Response options for adaptation

Adaptation options exist in all sectors, but their context for implementation and potential to reduce climate-related risks differs across sectors and regions. Some adaptation responses involve significant co-benefits, synergies and trade-offs. Increasing climate change will increase challenges for many adaptation options.

People, governments and the private sector are starting to adapt to a changing climate. Since the IPCC Fourth Assessment Report (AR4), understanding of response options has increased, with improved knowledge of their benefits, costs and links to sustainable development. Adaptation can take a variety of approaches depending on its context in vulnerability reduction, disaster risk management or proactive adaptation planning. These include (see Table 4.2 for examples and details):

- Social, ecological asset and infrastructure development
- Technological process optimization
- Integrated natural resources management
- Institutional, educational and behavioural change or reinforcement
- Financial services, including risk transfer
- Information systems to support early warning and proactive planning

There is increasing recognition of the value of social (including local and indigenous), institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Effective strategies and actions consider the potential for co-benefits and opportunities within wider strategic goals and development plans. *{WGII SPM A-2, SPM C-1, TS A-2, 6.4, 8.3, 9.4, 15.3}*

Opportunities to enable adaptation planning and implementation exist in all sectors and regions, with diverse potential and approaches depending on context. The need for adaptation along with associated challenges is expected to increase with climate change (*very high confidence*). Examples of key adaptation approaches for particular sectors, including constraints and limits, are summarized below. *{WGII SPM B, SPM C, 16.4, 16.6, 17.2, 19.6, 19.7, Table 16.3}*

Table 4.2 | Approaches for managing the risks of climate change through adaptation. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Examples are presented in no specific order and can be relevant to more than one category. *{WGII Table SPM.1}*

Overlapping Approaches	Category	Examples	WGII References
Vulnerability & Exposure Reduction through development, planning & practices including many low-regrets measures	Human development	Improved access to education, nutrition, health facilities, energy, safe housing & settlement structures, & social support structures; Reduced gender inequality & marginalization in other forms.	8.3, 9.3, 13.1-3, 14.2-3, 22.4
	Poverty alleviation	Improved access to & control of local resources; Land tenure; Disaster risk reduction; Social safety nets & social protection; Insurance schemes.	8.3-4, 9.3, 13.1-3
	Livelihood security	Income, asset & livelihood diversification; Improved infrastructure; Access to technology & decision-making fora; Increased decision-making power; Changed cropping, livestock & aquaculture practices; Reliance on social networks.	7.5, 9.4, 13.1-3, 22.3-4, 23.4, 26.5, 27.3, 29.6, Table SM24-7
	Disaster risk management	Early warning systems; Hazard & vulnerability mapping; Diversifying water resources; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements.	8.2-4, 11.7, 14.3, 15.4, 22.4, 24.4, 26.6, 28.4, Box 25-1, Table 3-3
Adaptation including incremental & transformational adjustments	Ecosystem management	Maintaining wetlands & urban green spaces; Coastal afforestation; Watershed & reservoir management; Reduction of other stressors on ecosystems & of habitat fragmentation; Maintenance of genetic diversity; Manipulation of disturbance regimes; Community-based natural resource management.	4.3-4, 8.3, 22.4, Table 3-3, Boxes 4-3, 8-2, 15-1, 25-8, 25-9 & CC-EA
	Spatial or land-use planning	Provisioning of adequate housing, infrastructure & services; Managing development in flood prone & other high risk areas; Urban planning & upgrading programs; Land zoning laws; Easements; Protected areas.	4.4, 8.1-4, 22.4, 23.7-8, 27.3, Box 25-8
	Structural/physical	***Engineered & built-environment options***: Sea walls & coastal protection structures; Flood levees; Water storage; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements; Floating houses; Power plant & electricity grid adjustments.	3.5-6, 5.5, 8.2-3, 10.2, 11.7, 23.3, 24.4, 25.7, 26.3, 26.8, Boxes 15-1, 25-1, 25-2 & 25-8
		Technological options: New crop & animal varieties; Indigenous, traditional & local knowledge, technologies & methods; Efficient irrigation; Water-saving technologies; Desalinisation; Conservation agriculture; Food storage & preservation facilities; Hazard & vulnerability mapping & monitoring; Early warning systems; Building insulation; Mechanical & passive cooling; Technology development, transfer & diffusion.	7.5, 8.3, 9.4, 10.3, 15.4, 22.4, 24.4, 26.3, 26.5, 27.3, 28.2, 28.4, 29.6-7, Boxes 20-5 & 25-2, Tables 3-3 & 15-1
		Ecosystem-based options: Ecological restoration; Soil conservation; Afforestation & reforestation; Mangrove conservation & replanting; Green infrastructure (e.g., shade trees, green roofs); Controlling overfishing; Fisheries co-management; Assisted species migration & dispersal; Ecological corridors; Seed banks, gene banks & other *ex situ* conservation; Community-based natural resource management.	4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 15.4, 22.4, 23.6-7, 24.4, 25.6, 27.3, 28.2, 29.7, 30.6, Boxes 15-1, 22-2, 25-9, 26-2 & CC-EA
		Services: Social safety nets & social protection; Food banks & distribution of food surplus; Municipal services including water & sanitation; Vaccination programs; Essential public health services; Enhanced emergency medical services.	3.5-6, 8.3, 9.3, 11.7, 11.9, 22.4, 29.6, Box 13-2
	Institutional	***Economic options***: Financial incentives; Insurance; Catastrophe bonds; Payments for ecosystem services; Pricing water to encourage universal provision and careful use; Microfinance; Disaster contingency funds; Cash transfers; Public-private partnerships.	8.3-4, 9.4, 10.7, 11.7, 13.3, 15.4, 17.5, 22.4, 26.7, 27.6, 29.6, Box 25-7
		Laws & regulations: Land zoning laws; Building standards & practices; Easements; Water regulations & agreements; Laws to support disaster risk reduction; Laws to encourage insurance purchasing; Defined property rights & land tenure security; Protected areas; Fishing quotas; Patent pools & technology transfer.	4.4, 8.3, 9.3, 10.5, 10.7, 15.2, 15.4, 17.5, 22.4, 23.4, 23.7, 24.4, 25.4, 26.3, 27.3, 30.6, Table 25-2, Box CC-CR
		National & government policies & programs: National & regional adaptation plans including mainstreaming; Sub-national & local adaptation plans; Economic diversification; Urban upgrading programs; Municipal water management programs; Disaster planning & preparedness; Integrated water resource management; Integrated coastal zone management; Ecosystem-based management; Community-based adaptation.	2.4, 3.6, 4.4, 5.5, 6.4, 7.5, 8.3, 11.7, 15.2-5, 22.4, 23.7, 25.4, 25.8, 26.8-9, 27.3-4, 29.6, Boxes 25-1, 25-2 & 25-9, Tables 9-2 & 17-1
	Social	***Educational options***: Awareness raising & integrating into education; Gender equity in education; Extension services; Sharing indigenous, traditional & local knowledge; Participatory action research & social learning; Knowledge-sharing & learning platforms.	8.3-4, 9.4, 11.7, 12.3, 15.2-4, 22.4, 25.4, 28.4, 29.6, Tables 15-1 & 25-2
		Informational options: Hazard & vulnerability mapping; Early warning & response systems; Systematic monitoring & remote sensing; Climate services; Use of indigenous climate observations; Participatory scenario development; Integrated assessments.	2.4, 5.5, 8.3-4, 9.4, 11.7, 15.2-4, 22.4, 23.5, 24.4, 25.8, 26.6, 26.8, 27.3, 28.2, 28.5, 30.6, Table 25-2, Box 26-3
		Behavioural options: Household preparation & evacuation planning; Migration; Soil & water conservation; Storm drain clearance; Livelihood diversification; Changed cropping, livestock & aquaculture practices; Reliance on social networks.	5.5, 7.5, 9.4, 12.4, 22.3-4, 23.4, 23.7, 25.7, 26.5, 27.3, 29.6, Table SM24-7, Box 25-5
Transformation	Spheres of change	***Practical***: Social & technical innovations, behavioural shifts, or institutional & managerial changes that produce substantial shifts in outcomes.	8.3, 17.3, 20.5, Box 25-5
		Political: Political, social, cultural & ecological decisions & actions consistent with reducing vulnerability & risk & supporting adaptation, mitigation & sustainable development.	14.2-3, 20.5, 25.4, 30.7, Table 14-1
		Personal: Individual & collective assumptions, beliefs, values & worldviews influencing climate-change responses.	14.2-3, 20.5, 25.4, Table 14-1

Freshwater resources

Adaptive water management techniques, including scenario planning, learning-based approaches and flexible and low-regret solutions, can help adjust to uncertain hydrological changes due to climate change and their impacts (*limited evidence, high agreement*). Strategies include adopting integrated water management, augmenting supply, reducing the mismatch between water supply and demand, reducing non-climate stressors, strengthening institutional capacities and adopting more water-efficient technologies and water-saving strategies. *{WGII SPM B-2, Assessment Box SPM.2 Table 1, SPM B-3, 3.6, 22.3–22.4, 23.4, 23.7, 24.4, 27.2–27.3, Box 25-2}*

Terrestrial and freshwater ecosystems

Management actions can reduce but not eliminate risks of impacts to terrestrial and freshwater ecosystems due to climate change (*high confidence*). Actions include maintenance of genetic diversity, assisted species migration and dispersal, manipulation of disturbance regimes (e.g., fires, floods) and reduction of other stressors. Management options that reduce non-climatic stressors, such as habitat modification, overexploitation, pollution and invasive species, increase the inherent capacity of ecosystems and their species to adapt to a changing climate. Other options include improving early warning systems and associated response systems. Enhanced connectivity of vulnerable ecosystems may also assist autonomous adaptation. Translocation of species is controversial and is expected to become less feasible where whole ecosystems are at risk. *{WGII SPM B-2, SPM B-3, Figure SPM.5, Table TS.8, 4.4, 25.6, 26.4, Box CC-RF}*

Coastal systems and low-lying areas

Increasingly, coastal adaptation options include those based on integrated coastal zone management, local community participation, ecosystems-based approaches and disaster risk reduction, mainstreamed into relevant strategies and management plans (*high confidence*). The analysis and implementation of coastal adaptation has progressed more significantly in developed countries than in developing countries (*high confidence*). The relative costs of coastal adaptation are expected to vary strongly among and within regions and countries. *{WGII SPM B-2, SPM B-3, 5.5, 8.3, 22.3, 24.4, 26.8, Box 25-1}*

Marine systems and oceans

Marine forecasting and early warning systems as well as reducing non-climatic stressors have the potential to reduce risks for some fisheries and aquaculture industries, but options for unique ecosystems such as coral reefs are limited (*high confidence*). Fisheries and some aquaculture industries with high-technology and/or large investments have high capacities for adaptation due to greater development of environmental monitoring, modelling and resource assessments. Adaptation options include large-scale translocation of industrial fishing activities and flexible management that can react to variability and change. For smaller-scale fisheries and nations with limited adaptive capacities, building social resilience, alternative livelihoods and occupational flexibility are important strategies. Adaptation options for coral reef systems are generally limited to reducing other stressors, mainly by enhancing water quality and limiting pressures from tourism and fishing, but their efficacy will be severely reduced as thermal stress and ocean acidification increase. *{WGII SPM B-2, SPM Assessment Box SPM.2 Table 1, TS B-2, 5.5, 6.4, 7.5, 25.6.2, 29.4, 30.6-7, Box CC-MB, Box CC-CR}*

Food production system/Rural areas

Adaptation options for agriculture include technological responses, enhancing smallholder access to credit and other critical production resources, strengthening institutions at local to regional levels and improving market access through trade reform (*medium confidence*). Responses to decreased food production and quality include: developing new crop varieties adapted to changes in CO_2, temperature, and drought; enhancing the capacity for climate risk management; and offsetting economic impacts of land use change. Improving financial support and investing in the production of small-scale farms can also provide benefits. Expanding agricultural markets and improving the predictability and reliability of the world trading system could result in reduced market volatility and help manage food supply shortages caused by climate change. *{WGII SPM B-2, SPM B-3, 7.5, 9.3, 22.4, 22.6, 25.9, 27.3}*

Urban areas/Key economic sectors and services

Urban adaptation benefits from effective multi-level governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector and appropriate financing and institutional development (*medium confidence*). Enhancing the capacity of low-income groups and vulnerable communities and their partnerships with local governments can also be an effective urban climate adaptation strategy. Examples of adaptation mechanisms include large-scale public-private risk reduction initiatives and economic diversification and government insurance for the non-diversifiable portion of risk. In some locations, especially at the upper end of projected climate changes, responses could also require transformational changes such as managed retreat. *{WGII SPM B-2, 8.3–8.4, 24.4, 24.5, 26.8, Box 25-9}*

Human health, security and livelihoods

Adaptation options that focus on strengthening existing delivery systems and institutions, as well as insurance and social protection strategies, can improve health, security and livelihoods in the near term (*high confidence*). The most effective vulnerability reduction measures for health in the near term are programmes that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response and alleviate poverty (*very high confidence*). Options to address heat related mortality include health warning systems linked to response strategies, urban planning and improvements to the built environment to reduce heat stress. Robust institutions can manage many transboundary impacts of climate change to reduce risk of conflicts over shared natural resources. Insurance programmes, social protection measures and disaster risk management may enhance long-term livelihood resilience among the poor and marginalized people, if policies address multi-dimensional poverty. *{WGII SPM B-2, SPM B-3, 8.2, 10.8, 11.7–11.8, 12.5–12.6, 22.3, 23.9, 25.8, 26.6, Box CC-HS}*

Table 4.3 | Examples of potential trade-offs associated with an illustrative set of adaptation options that could be implemented by actors to achieve specific management objectives. *{WGII Table 16-2}*

Sector	Actor's adaptation objective	Adaptation option	Real or perceived trade-off
Agriculture	Enhance drought and pest resistance; enhance yields	Biotechnology and genetically modified crops	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments
	Provide financial safety net for farmers to ensure continuation of farming enterprises	Subsidized drought assistance; crop insurance	Creates moral hazard and distributional inequalities if not appropriately administered
	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased use of chemical fertilizer and pesticides	Increased discharge of nutrients and chemical pollution to the environment; adverse impacts of pesticide use on non-target species; increased emissions of greenhouse gases; increased human exposure to pollutants
Biodiversity	Enhance capacity for natural adaptation and migration to changing climatic conditions	Migration corridors; expansion of conservation areas	Unknown efficacy; concerns over property rights regarding land acquisition; governance challenges
	Enhance regulatory protections for species potentially at risk due to climate and non-climatic changes	Protection of critical habitat for vulnerable species	Addresses secondary rather than primary pressures on species; concerns over property rights; regulatory barriers to regional economic development
	Facilitate conservation of valued species by shifting populations to alternative areas as the climate changes	Assisted migration	Difficult to predict ultimate success of assisted migration; possible adverse impacts on indigenous flora and fauna from introduction of species into new ecological regions
Coasts	Provide near-term protection to financial assets from inundation and/or erosion	Sea walls	High direct and opportunity costs; equity concerns; ecological impacts to coastal wetlands
	Allow natural coastal and ecological processes to proceed; reduce long-term risk to property and assets	Managed retreat	Undermines private property rights; significant governance challenges associated with implementation
	Preserve public health and safety; minimize property damage and risk of stranded assets	Migration out of low-lying areas	Loss of sense of place and cultural identity; erosion of kinship and familial ties; impacts to receiving communities
Water resources management	Increase water resource reliability and drought resilience	Desalination	Ecological risk of saline discharge; high energy demand and associated carbon emissions; creates disincentives for conservation
	Maximize efficiency of water management and use; increase flexibility	Water trading	Undermines public good/social aspects of water
	Enhance efficiency of available water resources	Water recycling/reuse	Perceived risk to public health and safety

Significant co-benefits, synergies and trade-offs exist between adaptation and mitigation and among different adaptation responses; interactions occur both within and across regions and sectors (*very high confidence*). For example, investments in crop varieties adapted to climate change can increase the capacity to cope with drought, and public health measures to address vector-borne diseases can enhance the capacity of health systems to address other challenges. Similarly, locating infrastructure away from low-lying coastal areas helps settlements and ecosystems adapt to sea level rise while also protecting against tsunamis. However, some adaptation options may have adverse side effects that imply real or perceived trade-offs with other adaptation objectives (see Table 4.3 for examples), mitigation objectives or broader development goals. For example, while protection of ecosystems can assist adaptation to climate change and enhance carbon storage, increased use of air conditioning to maintain thermal comfort in buildings or the use of desalination to enhance water resource security can increase energy demand, and therefore, GHG emissions. *{WGII SPM B-2, SPM C-1, 5.4.2, 16.3.2.9, 17.2.3.1, Table 16-2}*

4.3 Response options for mitigation

Mitigation options are available in every major sector. Mitigation can be more cost-effective if using an integrated approach that combines measures to reduce energy use and the greenhouse gas intensity of end-use sectors, decarbonize energy supply, reduce net emissions and enhance carbon sinks in land-based sectors.

A broad range of sectoral mitigation options is available that can reduce GHG emission intensity, improve energy intensity through enhancements of technology, behaviour, production and resource efficiency and enable structural changes or changes in activity. In addition, direct options in agriculture, forestry and other land use (AFOLU) involve reducing CO_2 emissions by reducing deforestation, forest degradation and forest fires; storing carbon in terrestrial systems (for example, through afforestation); and providing bioenergy feedstocks. Options to reduce non-CO_2 emissions exist across all sectors but most notably in agriculture, energy supply and

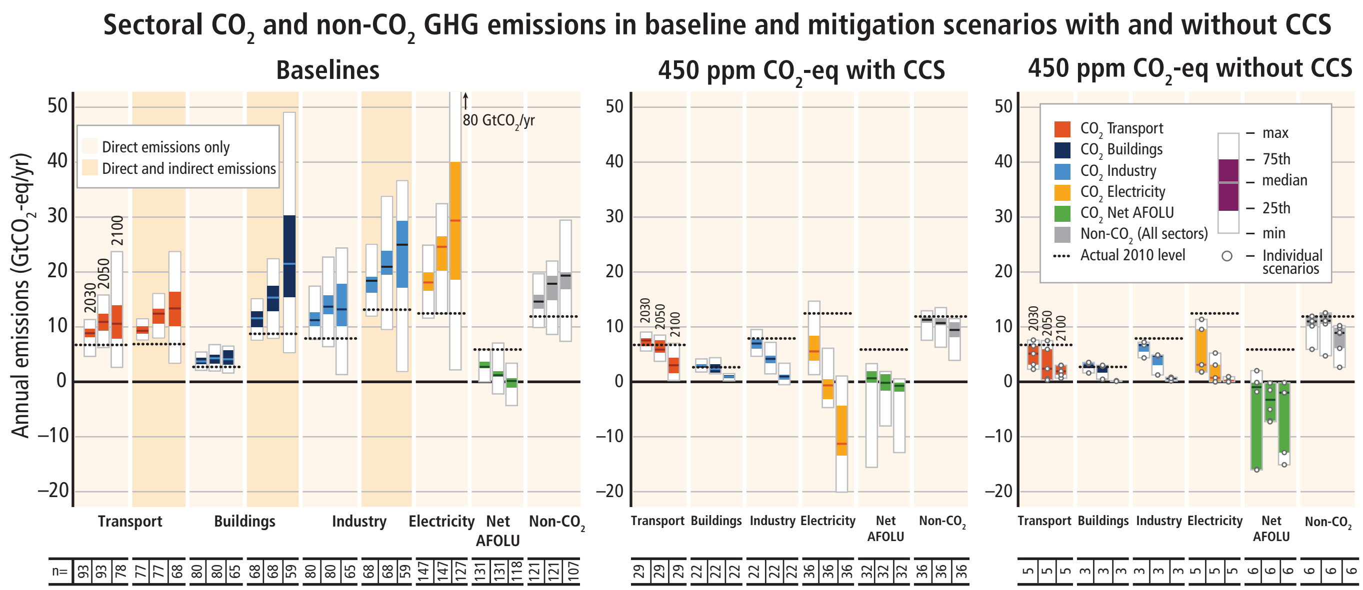

Figure 4.1 | Carbon dioxide (CO_2) emissions by sector and total non-CO_2 greenhouse gas (GHG) emissions (Kyoto gases) across sectors in baseline (left panel) and mitigation scenarios that reach about 450 (430 to 480) ppm CO_2-eq (*likely* to limit warming to 2°C above pre-industrial levels) with carbon dioxide capture and storage (CCS, middle panel) and without CCS (right panel). Light yellow background denotes direct CO_2 and non-CO_2 GHG emissions for both the baseline and mitigation scenarios. In addition, for the baseline scenarios, the sum of direct and indirect emissions from the energy end-use sectors (transport, buildings and industry) is also shown (dark yellow background). Mitigation scenarios show direct emissions only. However, mitigation in the end-use sectors leads also to indirect emissions reductions in the upstream energy supply sector. Direct emissions of the end-use sectors thus do not include the emission reduction potential at the supply-side due to, for example, reduced electricity demand. Note that for calculating the indirect emissions only electricity emissions are allocated from energy supply to end-use sectors. The numbers at the bottom of the graphs refer to the number of scenarios included in the range, which differs across sectors and time due to different sectoral resolution and time horizon of models. Note that many models cannot reach concentrations of about 450 ppm CO_2-eq by 2100 in the absence of CCS, resulting in a low number of scenarios for the right panel. Negative emissions in the electricity sector are due to the application of bioenergy with carbon dioxide capture and storage (BECCS). 'Net' agriculture, forestry and other land use (AFOLU) emissions consider afforestation, reforestation as well as deforestation activities. *{WGIII Figure SPM.7, Figure TS.15}*

industry. An overview of sectoral mitigation options and potentials is provided in Table 4.4. *{WGIII TS 3.2.1}*

Well-designed systemic and cross-sectoral mitigation strategies are more cost-effective in cutting emissions than a focus on individual technologies and sectors with efforts in one sector affecting the need for mitigation in others (*medium confidence*). In baseline scenarios without new mitigation policies, GHG emissions are projected to grow in all sectors, except for net CO_2 emissions in the AFOLU sector (Figure 4.1, left panel). Mitigation scenarios reaching around 450 ppm CO_2-eq[42] concentration by 2100[43] (*likely* to limit warming to 2°C above pre-industrial levels) show large-scale global changes in the energy supply sector (Figure 4.1, middle and right panel). While rapid decarbonization of energy supply generally entails more flexibility for end-use and AFOLU sectors, stronger demand reductions lessen the mitigation challenge for the supply side of the energy system (Figures 4.1 and 4.2). There are thus strong interdependencies across sectors and the resulting distribution of the mitigation effort is strongly influenced by the availability and performance of future technologies, particularly BECCS and large scale afforestation (Figure 4.1, middle and right panel). The next two decades present a window of opportunity for mitigation in urban areas, as a large portion of the world's urban areas will be developed during this period. *{WGIII SPM.4.2, TS.3.2}*

Decarbonizing (i.e., reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies in achieving low stabilization levels (of about 450 to about 500 ppm CO_2-eq, at least *about as likely as not* to limit warming to 2°C above pre-industrial levels) (*medium evidence, high agreement*). In most integrated modelling scenarios, decarbonization happens more rapidly in electricity generation than in the industry, buildings and transport sectors. In scenarios reaching 450 ppm CO_2-eq concentrations by 2100, global CO_2 emissions from the energy supply sector are projected to decline over the next decade and are characterized by reductions of 90% or more below 2010 levels between 2040 and 2070. *{WGIII SPM.4.2, 6.8, 7.11}*

Efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development, are a key mitigation strategy in scenarios reaching atmospheric CO_2-eq concentrations of about 450 to about 500 ppm by 2100 (*robust evidence, high agreement*). Near-term reductions in energy demand are an important

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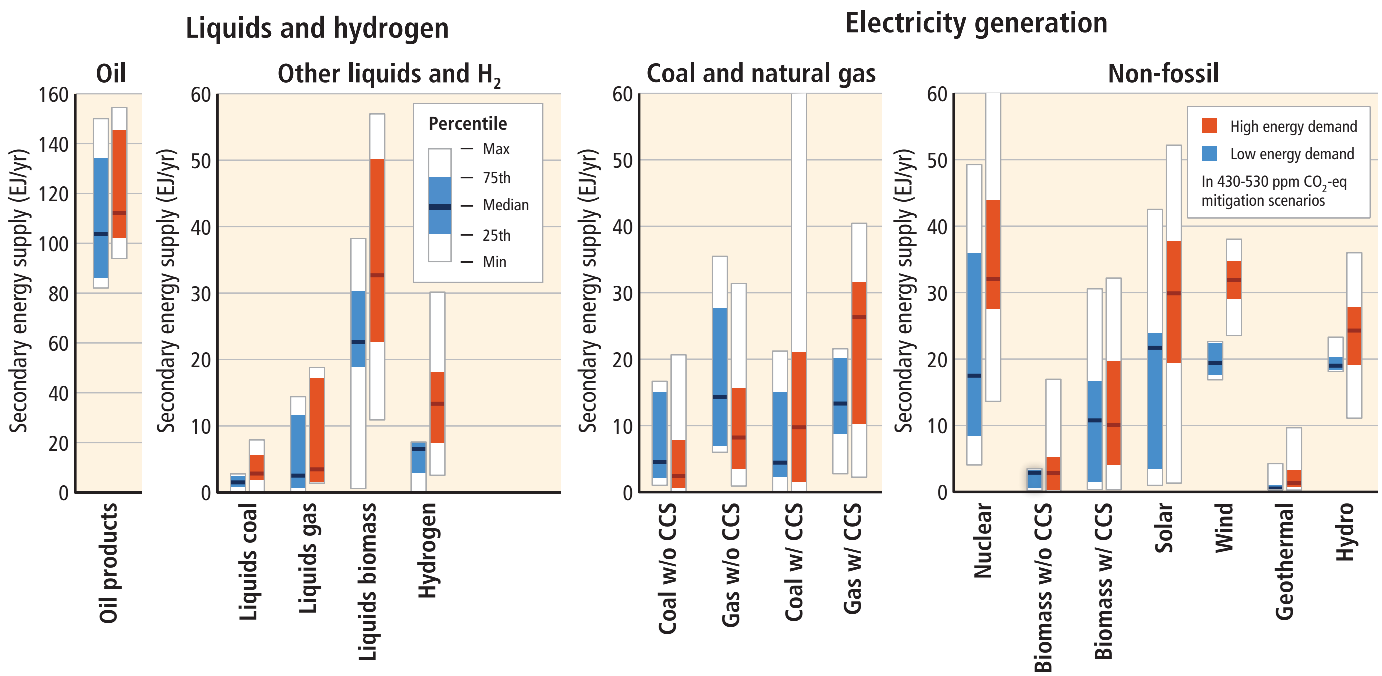
[42] See Glossary for definition of CO_2-eq concentrations and emissions; also Box 3.2 for metrics to calculate the CO_2-equivalence of non-CO_2 emissions and their influence on sectoral abatement strategies.

[43] For comparison, the CO_2-eq concentration in 2011 is estimated to be 430 [340 to 520] ppm.



1	2	3	4
High energy demand scenarios show higher levels of oil supply.	In high energy demand scenarios, alternative liquid and hydrogen technologies are scaled up more rapidly.	High energy demand scenarios show a more rapid up-scaling of CCS technologies but a more rapid phase-out of unabated fossil fuel conversion technologies.	In high energy demand scenarios non-fossil electricity generation technologies are scaled up more rapidly.

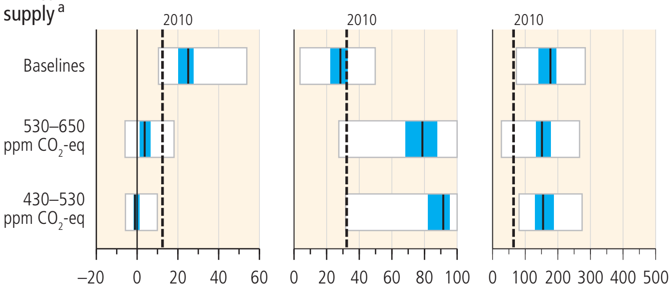
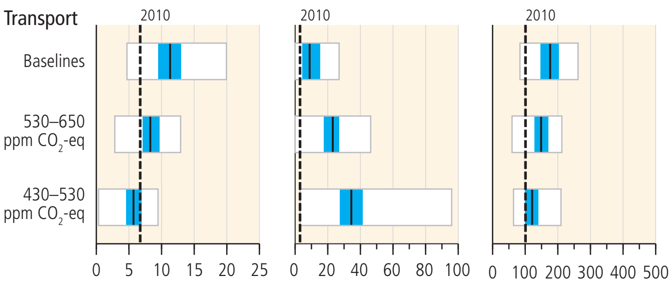
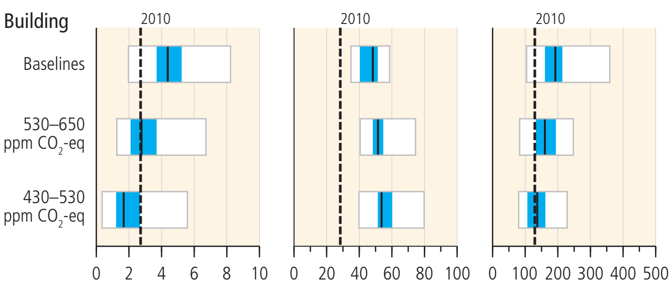
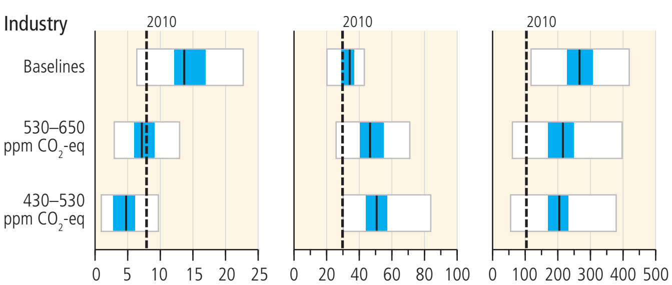
Figure 4.2 | Influence of energy demand on the deployment of energy supply technologies in 2050 in mitigation scenarios reaching about 450 to about 500 ppm CO_2-eq concentrations by 2100 (at least *about as likely as not* to limit warming to 2°C above pre-industrial levels). Blue bars for 'low energy demand' show the deployment range of scenarios with limited growth in final energy demand of <20% in 2050 compared to 2010. Red bars show the deployment range of technologies in a case of 'high energy demand' (>20% growth in 2050 compared to 2010). For each technology, the median, interquartile and full deployment range is displayed. Notes: Scenarios assuming technology restrictions are excluded. Ranges include results from many different integrated models. Multiple scenario results from the same model were averaged to avoid sampling biases. *{WGIII Figure TS.16}*

element of cost-effective mitigation strategies, provide more flexibility for reducing carbon intensity in the energy supply sector, hedge against related supply-side risks, avoid lock-in to carbon-intensive infrastructures and are associated with important co-benefits (Figure 4.2, Table 4.4). Emissions can be substantially lowered through changes in consumption patterns (e.g., mobility demand and mode, energy use in households, choice of longer-lasting products) and dietary change and reduction in food wastes. A number of options including monetary and non-monetary incentives as well as information measures may facilitate behavioural changes. *{WGIII SPM.4.2}*

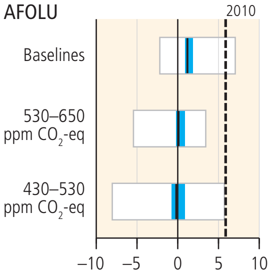
Decarbonization of the energy supply sector (i.e., reducing the carbon intensity) requires upscaling of low- and zero-carbon electricity generation technologies (*high confidence*). In the majority of low-concentration stabilization scenarios (about 450 to about 500 ppm CO_2-eq , at least *about as likely as not* to limit warming to 2°C above pre-industrial levels), the share of low-carbon electricity supply (comprising renewable energy (RE), nuclear and CCS, including BECCS) increases from the current share of approximately 30% to more than 80% by 2050 and 90% by 2100, and fossil fuel power generation without CCS is phased out almost entirely by 2100. Among these low-carbon technologies, a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale since AR4 (*robust evidence, high agreement*) and nuclear energy is a mature low-GHG emission source of baseload power, but its share of global electricity generation has been declining (since 1993). GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined-cycle power plants or combined heat and power plants, provided that natural gas is available and the fugitive emissions associated with extraction and supply are low or mitigated. *{WGIII SPM.4.2}*

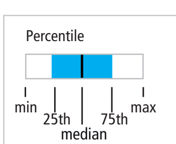
Behaviour, lifestyle and culture have a considerable influence on energy use and associated emissions, with high mitigation potential in some sectors, in particular when complementing technological and structural change (*medium evidence, medium agreement*). In the transport sector, technical and behavioural mitigation measures for all modes, plus new infrastructure and urban redevelopment investments, could reduce final energy demand significantly below baseline levels (*robust evidence, medium agreement*) (Table 4.4). While opportunities for switching to low-carbon fuels exist, the rate of decarbonization in the transport sector might be constrained by challenges associated with energy storage and the relatively low

Table 4.4 | Sectoral carbon dioxide (CO_2) emissions, associated energy system changes and examples of mitigation measures (including for non-CO_2 gases; see Box 3.2 for metrics regarding the weighting and abatement of non-CO_2 emissions). *{WGIII SPM.7, Figure SPM.8, Table TS.2, 7.11.3, 7.13, 7.14}*

Sectoral CO_2 emissions and related energy system changes	Examples for sectoral mitigation measures		
Sector / CO_2 emission ($GtCO_2$, 2050) / Low-carbon fuel share (%, 2050) / Final energy demand (EJ, 2050)	Key low-carbon energy options	Key energy saving options	Other options
Energy supply[a] 	Renewables (wind, solar bioenergy, geothermal, hydro, etc.), nuclear, CCS, BECCS, fossil fuel switching	Energy efficiency improvements of energy supply technologies, improved transmission and distribution, CHP and cogeneration	Fugitive CH_4 emissions control
Transport 	Fuel switching to low-carbon fuels (e.g., hydrogen/electricity from low-carbon sources), biofuels	Efficiency improvements (engines, vehicle design, appliances, lighter materials), modal shift (e.g., from LDVs to public transport or from aviation to HDVs to rail), eco-driving, improved freight logistics, journey avoidance, higher occupancy rates	Transport (infrastructure) planning, urban planning
Building 	Building integrated RES, fuel switching to low-carbon fuels (e.g., electricity from low-carbon sources, biofuels)	Device efficiency (heating/cooling systems, water heating, cooking, lighting, appliances), systemic efficiency (integrated design, low/zero energy buildings, district heating/cooling, CHP, smart meters/grids), behavioural and lifestyle changes (e.g., appliance use, thermostat setting, dwelling size)	Urban planning, building lifetime, durability of building components and appliances, low energy/GHG intensive construction and materials
Industry 	Process emissions reductions, use of waste and CCS in industry, fuel switching among fossil fuels and switch to low-carbon energy (e.g., electricity) or biomass	Energy efficiency and BAT (e.g., furnace/boilers, steam systems, electric motors and control systems, (waste) heat exchanges, recycling), reduction of demand for goods, more intensive use of goods (e.g., improve durability or car sharing)	HFC replacement and leak repair, material efficiency (e.g., process innovation, re-using old materials, product design, etc.)

AFOLU





Emissions reduction measures:	Sequestration options:	Substitution options:	Demand-side measures:
Methane (e.g., livestock management), nitrous oxide (e.g., fertilizer use), conservation of existing carbon pools (sustainable forest management, reduced deforestation and forest degradation, fire prevention, agroforestry), reduction in emissions intensity	Increasing existing carbon pools (e.g., afforestation, reforestation, integrated systems, carbon sequestration in soils)	Use of biological products instead of fossil/GHG intensive products (e.g., bioenergy, insulation products)	Reduction of loss and waste of food, changes in human diets, use of long-lived wood products

[a] CO_2 emissions, low carbon fuel shares, and final energy demand are shown for electricity generation only

energy density of low-carbon transport fuels (*medium confidence*). In the building sector, recent advances in technologies, know-how and policies provide opportunities to stabilize or reduce global energy use to about current levels by mid-century. In addition, recent improvements in performance and costs make very low energy construction and retrofits of buildings economically attractive, sometimes even at net negative costs (*robust evidence, high agreement*). In the industry sector, improvements in GHG emission efficiency and in the efficiency of material use, recycling and reuse of materials and products, and overall reductions in product demand (e.g., through a more intensive use of products) and service demand could, in addition to energy efficiency, help reduce GHG emissions below the baseline level. Prevalent approaches for promoting energy efficiency in industry include information programmes followed by economic instruments, regulatory approaches and voluntary actions. Important options for mitigation in waste management are waste reduction, followed by re-use, recycling and energy recovery (*robust evidence, high agreement*). *{WGIII SPM.4.2, Box TS.12, TS.3.2}*

The most cost-effective mitigation options in forestry are afforestation, sustainable forest management and reducing deforestation, with large differences in their relative importance across regions. In agriculture, the most cost-effective mitigation options are cropland management, grazing land management and restoration of organic soils (*medium evidence, high agreement*). About a third of mitigation potential in forestry can be achieved at a cost <20 USD/tCO_2-eq emission. Demand-side measures, such as changes in diet and reductions of losses in the food supply chain, have a significant, but uncertain, potential to reduce GHG emissions from food production (*medium evidence, medium agreement*). *{WGIII SPM 4.2.4}*

Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems (*robust evidence, medium agreement*). Evidence suggests that bioenergy options with low lifecycle emissions, some already available, can reduce GHG emissions; outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems', and sustainable land use management and governance. Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. *{WGIII SPM.4.2}*

Mitigation measures intersect with other societal goals, creating the possibility of co-benefits or adverse side-effects. These intersections, if well-managed, can strengthen the basis for undertaking climate mitigation actions (*robust evidence, medium agreement*). Mitigation can positively or negatively influence the achievement of other societal goals, such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods and equitable sustainable development (see also Section 4.5). On the other hand, policies towards other societal goals can influence the achievement of mitigation and adaptation objectives. These influences can be substantial, although sometimes difficult to quantify, especially in welfare terms. This multi-objective perspective is important in part because it helps to identify areas where support for policies that advance multiple goals will be robust. Potential co-benefits and adverse side effects of the main sectoral mitigation measures are summarized in Table 4.5. Overall, the potential for co-benefits for energy end-use measures outweigh the potential for adverse side effects, whereas the evidence suggests this may not be the case for all energy supply and AFOLU measures. *{WGIII SPM.2}*

4.4 Policy approaches for adaptation and mitigation, technology and finance

Effective adaptation and mitigation responses will depend on policies and measures across multiple scales: international, regional, national and sub-national. Policies across all scales supporting technology development, diffusion and transfer, as well as finance for responses to climate change, can complement and enhance the effectiveness of policies that directly promote adaptation and mitigation.

4.4.1 International and regional cooperation on adaptation and mitigation

Because climate change has the characteristics of a collective action problem at the global scale (see 3.1), effective mitigation will not be achieved if individual agents advance their own interests independently, even though mitigation can also have local co-benefits. Cooperative responses, including international cooperation, are therefore required to effectively mitigate GHG emissions and address other climate change issues. While adaptation focuses primarily on local to national scale outcomes, its effectiveness can be enhanced through coordination across governance scales, including international cooperation. In fact, international cooperation has helped to facilitate the creation of adaptation strategies, plans, and actions at national, sub-national, and local levels. A variety of climate policy instruments have been employed, and even more could be employed, at international and regional levels to address mitigation and to support and promote adaptation at national and sub-national scales. Evidence suggests that outcomes seen as equitable can lead to more effective cooperation. *{WGII SPM C-1, 2.2, 15.2, WGIII 13.ES, 14.3, 15.8, SREX SPM, 7.ES}*

The United Nations Framework Convention on Climate Change (UNFCCC) is the main multilateral forum focused on addressing climate change, with nearly universal participation. UNFCCC activities since 2007, which include the 2010 Cancún Agreements and the 2011 Durban Platform for Enhanced Action, have sought to enhance actions under the Convention, and have led to an increasing number of institutions and other arrangements for international climate change cooperation. Other institutions organized at different levels of governance have resulted in diversifying international climate change cooperation. *{WGIII SPM.5.2, 13.5}*

Existing and proposed international climate change cooperation arrangements vary in their focus and degree of centralization and coordination. They span: multilateral agreements, harmonized national policies and decentralized but coordinated national policies, as well as regional and regionally-coordinated policies (see Figure 4.3). *{WGIII SPM.5.2}*

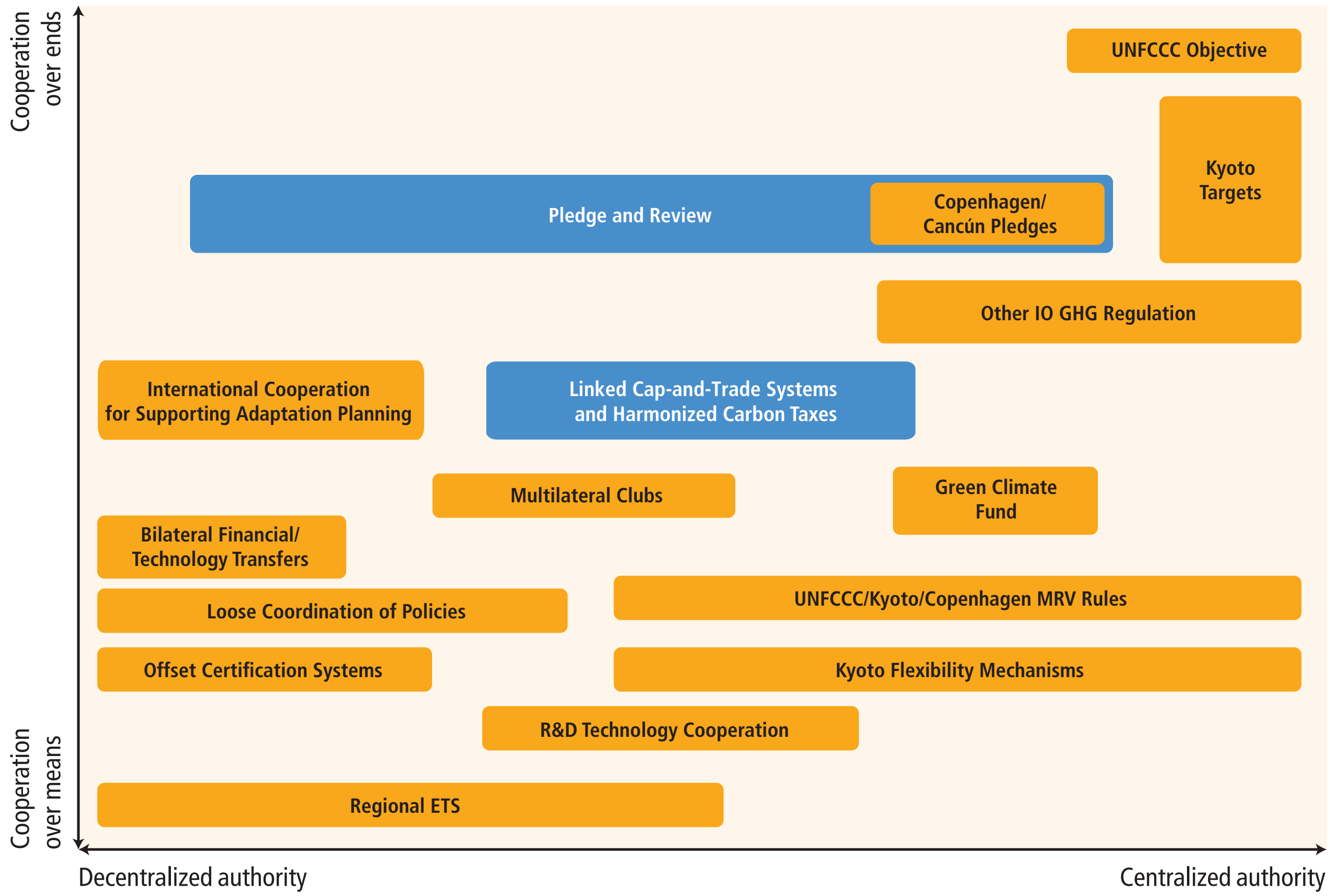
Table 4.5 | Potential co-benefits (blue text) and adverse side effects (red text) of the main sectoral mitigation measures. Co-benefits and adverse side effects, and their overall positive or negative effect, all depend on local circumstances as well as on the implementation practice, pace and scale. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies, see Section 3.4. The uncertainty qualifiers between brackets denote the level of evidence and agreement on the respective effect. Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. *{WGIII Table TS.3, Table TS.4, Table TS.5, Table TS.6, Table TS.7, Table 6.7}*

Sectoral mitigation measures	**Effect on additional objectives/concerns**		
	Economic	**Social**	**Environmental**
Energy Supply	*For possible upstream effects of biomass supply for bioenergy, see AFOLU.*		
Nuclear replacing coal power	Energy security (reduced exposure to fuel price volatility) (***m/m***); local employment impact (but uncertain net effect) (***l/m***); legacy/cost of waste and abandoned reactors (***m/h***)	Mixed health impact via reduced air pollution and coal mining accidents (***m/h***), nuclear accidents and waste treatment, uranium mining and milling (***m/l***); safety and waste concerns (***r/h***); proliferation risk (***m/m***)	Mixed ecosystem impact via reduced air pollution (***m/h***) and coal mining (***l/h***), nuclear accidents (***m/m***)
Renewable energy (wind, PV, CSP, hydro, geothermal, bioenergy) replacing coal	Energy security (***r/m***); local employment (but uncertain net effect) (***m/m***); water management (for some hydro energy) (***m/h***); extra measures to match demand (for PV, wind, some CSP) (***r/h***); higher use of critical metals for PV and direct drive wind turbines (***r/m***)	Reduced health impact via reduced air pollution (except bioenergy) (***r/h***) and coal mining accidents (***m/h***); contribution to (off-grid) energy access (***m/l***); threat of displacement (for large hydro installations) (***m/h***)	Mixed ecosystem impact via reduced air pollution (except bioenergy) (***m/h***) and coal mining (***l/h***), habitat impact (for some hydro energy) (***m/m***), landscape and wildlife impact (***m/m***); lower/higher water use (for wind, PV (***m/m***); bioenergy, CSP, geothermal and reservoir hydro (***m/h***))
Fossil energy with CCS replacing coal	Preservation vs. lock-in of human and physical capital in the fossil industry (***m/m***); long-term monitoring of CO_2 storage (***m/h***)	Health impact via risk of CO_2 leakage (***m/m***) and additional upstream supply-chain activities (***m/h***); safety concerns (CO_2 storage and transport) (***m/h***)	Ecosystem impact via additional upstream supply-chain activities (***m/m***) and higher water use (***m/h***)
CH_4 leakage prevention, capture or treatment	Energy security (potential to use gas in some cases) (***l/h***)	Reduced health impact via reduced air pollution (***m/m***); occupational safety at coal mines (***m/m***)	Reduced ecosystem impact via reduced air pollution (***l/m***)
Transport	*For possible upstream effects of low-carbon electricity, see Energy Supply. For biomass supply, see AFOLU.*		
Reduction of carbon intensity of fuel	Energy security (diversification, reduced oil dependence and exposure to oil price volatility) (***m/m***); technological spillovers (***l/l***)	Mixed health impact via increased/reduced urban air pollution by electricity and hydrogen (***r/h***), diesel (***l/m***); road safety concerns (***l/l***) but reduced health impact via reduced noise (***l/m***) of electric LDVs	Mixed ecosystem impact of electricity and hydrogen via reduced urban air pollution (***m/m***) and material use (unsustainable mining) (***l/l***)
Reduction of energy intensity	Energy security (reduced oil dependence and exposure to oil price volatility) (***m/m***)	Reduced health impact via reduced urban air pollution (***r/h***); road safety (crash-worthiness depending on the design of the standards) (***m/m***)	Reduced ecosystem and biodiversity impact via reduced urban air pollution (***m/h***)
Compact urban form and improved transport infrastructure Modal shift	Energy security (reduced oil dependence and exposure to oil price volatility) (***m/m***); productivity (reduced urban congestion and travel times, affordable and accessible transport) (***m/h***)	Mixed health impact for non-motorized modes via increased physical activity (***r/h***), potentially higher exposure to air pollution (***r/h***), reduced noise (via modal shift and travel reduction) (***r/h***); equitable mobility access to employment opportunities (***r/h***); road safety (via modal shift) (***r/h***)	Reduced ecosystem impact via reduced urban air pollution (***r/h***) and land use competition (***m/m***)
Journey distance reduction and avoidance	Energy security (reduced oil dependence and exposure to oil price volatility) (***r/h***); productivity (reduced urban congestion/travel times, walking) (***r/h***)	Reduced health impact (for non-motorized transport modes) (***r/h***)	Mixed ecosystem impact via reduced urban air pollution (***r/h***), new/shorter shipping routes (***r/h***); reduced land use competition from transport infrastructure (***r/h***)
Buildings	*For possible upstream effects of fuel switching and RES, see Energy Supply.*		
Reduction of GHG emissions intensity (e.g., fuel switching, RES incorporation, green roofs)	Energy security (***m/h***); employment impact (***m/m***); lower need for energy subsidies (***l/l***); asset values of buildings (***l/m***)	Fuel poverty alleviation via reduced energy demand (***m/h***); energy access (for higher energy cost) (***l/m***); productive time for women/children (for replaced traditional cookstoves) (***m/h***)	Reduced health impact in residential buildings and ecosystem impact (via reduced fuel poverty (***r/h***), indoor/outdoor air pollution (***r/h***) and UHI effect) (***l/m***); urban biodiversity (for green roofs) (***m/m***)
Retrofits of existing buildings Exemplary new buildings Efficient equipment	Energy security (***m/h***); employment impact (***m/m***); productivity (for commercial buildings) (***m/h***); less need for energy subsidies (***l/l***); asset value of buildings (***l/m***); disaster resilience (***l/m***)	Fuel poverty alleviation via reduced energy demand (for retrofits and efficient equipment) (***m/h***); energy access (higher housing cost) (***l/m***); thermal comfort (***m/h***); productive time for women and children (for replaced traditional cookstoves) (***m/h***)	Reduced health and ecosystem impact (e.g., via reduced fuel poverty (***r/h***), indoor/outdoor air pollution (***r/h***), UHI effect (***l/m***), improved indoor environmental conditions (***m/h***)); health risk via insufficient ventilation (***m/m***); reduced water consumption and sewage production (***l/l***)

continue on next page

Table 4.5 (continued)

Sectoral mitigation measures	Effect on additional objectives/concerns		
	Economic	Social	Environmental
Behavioural changes reducing energy demand	Energy security (*m/h*); less need for energy subsidies (*l/l*)		Reduced health and ecosystem impact (e.g., via improved indoor environmental conditions (*m/h*) and less outdoor air pollution (*r/h*))
Industry	*For possible upstream effects of low-carbon energy supply (incl. CCS), see Energy Supply and of biomass supply, see AFOLU.*		
Reduction of CO_2/non-CO_2 GHG emission intensity	Competitiveness and productivity (*m/h*)	Reduced health impact via reduced local air pollution and better working conditions (PFC from aluminium) (*m/m*)	Reduced ecosystem impact (via reduced local air and water pollution) (*m/m*); water conservation (*l/m*)
Technical energy efficiency improvements via new processes/technologies	Energy security (via lower energy intensity) (*m/m*); employment impact (*l/l*); competitiveness and productivity (*m/h*); technological spillovers in DCs (*l/l*)	Reduced health impact via reduced local pollution (*l/m*); new business opportunities (*m/m*); increased water availability and quality (*l/l*); improved safety, working conditions and job satisfaction (*m/m*)	Reduced ecosystem impact via reduced fossil fuel extraction (*l/l*) and reduced local pollution and waste (*m/m*)
Material efficiency of goods, recycling	Decreased national sales tax revenue in the medium term (*l/l*); employment impact (waste recycling) (*l/l*); competitiveness in manufacturing (*l/l*); new infrastructure for industrial clusters (*l/l*)	Reduced health impacts and safety concerns (*l/m*); new business opportunities (*m/m*) and reduced local conflicts (reduced resource extraction) (*l/m*)	Reduced ecosystem impact via reduced local air and water pollution and waste material disposal (*m/m*); reduced use of raw/virgin materials and natural resources implying reduced unsustainable resource mining (*l/l*)
Product demand reductions	Decreased national sales tax revenue in the medium term (*l/l*)	Increased wellbeing via diverse lifestyle choices (*l/l*)	Reduced post-consumption waste (*l/l*)
AFOLU	*Note: co-benefits and adverse side effects depend on the development context and the scale of the intervention (size).*		
Supply side: forestry, land-based agriculture, livestock, integrated systems and bioenergy Demand side: reduced losses in the food supply chain, changes in human diets and in demand for wood and forestry products	Mixed employment impact via entrepreneurship development (*m/h*), use of less labour-intensive technologies in agriculture (*m/m*); diversification of income sources and access to markets (*r/h*); additional income to sustainable landscape management (*m/h*); income concentration (*m/m*); energy security (resource sufficiency) (*m/h*); Innovative financing mechanisms for sustainable resource management (*m/h*); technology innovation and transfer (*m/m*)	Increased food-crops production through integrated systems and sustainable agriculture intensification (*r/m*); decreased food production (locally) due to large-scale monocultures of non-food crops (*r/l*); increased cultural habitats and recreational areas via (sustainable) forest management and conservation (*m/m*); improved human health and animal welfare (e.g., through less use of pesticides, reduced burning practices and agroforestry and silvo-pastoral systems) (*m/h*); human health impact related to burning practices (in agriculture or bioenergy) (*m/m*); mixed impacts on gender, intra- and inter-generational equity via participation and fair benefit sharing (*r/h*) and higher concentration of benefits (*m/m*)	Mixed impact on ecosystem services via large-scale monocultures (*r/h*), ecosystem conservation, sustainable management as well as sustainable agriculture (*r/h*); increased land use competition (*r/m*); increased soil quality (*r/h*); decreased erosion (*r/h*); increased ecosystem resilience (*m/h*); albedo and evaporation (*r/h*) Institutional aspects: mixed impact on tenure and use rights at the local level (for indigenous people and local communities) (*r/h*) and on access to participative mechanisms for land management decisions (*r/h*); enforcement of existing policies for sustainable resource management (*r/h*)
Human Settlements and Infrastructure	*For compact urban form and improved transport infrastructure, see also Transport.*		
Compact development and infrastructure	Increased innovation and efficient resource use (*r/h*); higher rents and property values (*m/m*)	Improved health from increased physical activity: *see Transport*	Preservation of open space (*m/m*)
Increased accessibility	Commute savings (*r/h*)	Improved health from increased physical activity: *see Transport*; increased social interaction and mental health (*m/m*)	Improved air quality and reduced ecosystem and health impacts (*m/h*)
Mixed land use	Commute savings (*r/h*); higher rents and property values (*m/m*)	Improved health from increased physical activity (*r/h*); social interaction and mental health (*l/m*)	Improved air quality and reduced ecosystem and health impacts (*m/h*)



Loose coordination of policies: examples include transnational city networks and Nationally Appropriate Mitigation Actions (NAMAs); R&D technology cooperation: examples include the Major Economies Forum on Energy and Climate (MEF), Global Methane Initiative (GMI), or Renewable Energy and Energy Efficiency Partnership (REEEP); Other international organization (IO) GHG regulation: examples include the Montreal Protocol, International Civil Aviation Organization (ICAO), International Maritime Organization (IMO); See WGIII Figure 13.1 for the details of these examples.

Figure 4.3 | Alternative forms of international cooperation. The figure represents a compilation of existing and possible forms of international cooperation, based upon a survey of published research, but is not intended to be exhaustive of existing or potential policy architectures, nor is it intended to be prescriptive. Examples in orange are existing agreements. Examples in blue are structures for agreements proposed in the literature. The width of individual boxes indicates the range of possible degrees of centralization for a particular agreement. The degree of centralization indicates the authority an agreement confers on an international institution, not the process of negotiating the agreement. *{WGIII Figure 13.2}*

While a number of new institutions are focused on adaptation funding and coordination, adaptation has historically received less attention than mitigation in international climate policy (*robust evidence, medium agreement*). Inclusion of adaptation is increasingly important to reduce the risk from climate change impacts and may engage a greater number of countries. *{WGIII 13.2, 13.3.3, 13.5.1.1, 13.14}*

The Kyoto Protocol offers lessons towards achieving the ultimate objective of the UNFCCC, particularly with respect to participation, implementation, flexibility mechanisms, and environmental effectiveness (*medium evidence, low agreement*). The Protocol was the first binding step toward implementing the principles and goals provided by the UNFCCC. According to national GHG inventories through 2012 submitted to the UNFCCC by October 2013, Annex B Parties with quantified emission limitations (and reduction obligations) in aggregate may have bettered their collective emission reduction target in the first commitment period,[44] but some emissions reductions that would have occurred even in its absence were also counted. The Protocol's Clean Development Mechanism (CDM) created a market for emissions offsets from developing countries, the purpose being two-fold: to help Annex I countries fulfill their commitments and to assist non-Annex I countries achieve sustainable development. The CDM generated Certified Emission Reductions (offsets) equivalent to emissions of over 1.4 $GtCO_2$-eq[42] by October 2013, led to significant project investments, and generated investment flows for a variety of functions, including the UNFCCC Adaptation Fund. However, its environmental effectiveness has been questioned by some, particularly

[44] The final conclusion regarding compliance of Annex B Parties remains subject to the review process under the Kyoto Protocol as of October 2014.

in regard to its early years, due to concerns about the additionality of projects (that is, whether projects bring about emissions that are different from business as usual (BAU) circumstances), the validity of baselines, and the possibility of emissions leakage (*medium evidence, medium agreement*). Such concerns about additionality are common to any emission-reduction-credit (offset) program, and are not specific to the CDM. Due to market forces, the majority of single CDM projects have been concentrated in a limited number of countries, while Programmes of Activities, though less frequent, have been more evenly distributed. In addition, the Kyoto Protocol created two other 'flexibility mechanisms': Joint Implementation and International Emissions Trading. *{WGIII SPM.5.2, Table TS.9, 13.7, 13.13.1.1, 14.3}*

Several conceptual models for effort-sharing have been identified in research. However, realized distributional impacts from actual international cooperative agreements depend not only on the approach taken but also on criteria applied to operationalize equity and the manner in which developing countries' emissions reduction plans are financed. *{WGIII 4.6, 13.4}*

Policy linkages among regional, national and sub-national climate policies offer potential climate change mitigation benefits (*medium evidence, medium agreement*). Linkages have been established between carbon markets and in principle could also be established between and among a heterogeneous set of policy instruments including non-market-based policies, such as performance standards. Potential advantages include lower mitigation costs, decreased emission leakage and increased market liquidity. *{WGIII SPM.5.2, 13.3, 13.5, 13.6, 13.7, 14.5}*

Regional initiatives between national and global scales are being developed and implemented, but their impact on global mitigation has been limited to date (*medium confidence*). Some climate policies could be more environmentally and economically effective if implemented across broad regions, such as by embodying mitigation objectives in trade agreements or jointly constructing infrastructures that facilitate reduction in carbon emissions. *{WGIII Table TS.9, 13.13, 14.4, 14.5}*

International cooperation for supporting adaptation planning and implementation has assisted in the creation of adaptation strategies, plans and actions at national, sub-national and local levels (*high confidence*). For example, a range of multilateral and regionally targeted funding mechanisms have been established for adaptation; UN agencies, international development organizations and non-governmental organisations (NGOs) have provided information, methodologies and guidelines; and global and regional initiatives supported and promoted the creation of national adaptation strategies in both developing and developed countries. Closer integration of disaster risk reduction and climate change adaptation at the international level, and the mainstreaming of both into international development assistance, may foster greater efficiency in the use of resources and capacity. However, stronger efforts at the international level do not necessarily lead to substantive and rapid results at the local level. *{WGII 15.2, 15.3, SREX SPM, 7.4, 8.2, 8.5}*

4.4.2 National and sub-national policies

4.4.2.1 Adaptation

Adaptation experience is accumulating across regions in the public and private sector and within communities (*high confidence*). Adaptation options adopted to date (see Table 4.6) emphasize incremental adjustments and co-benefits and are starting to emphasize flexibility and learning (*medium evidence, medium agreement*). Most assessments of adaptation have been restricted to impacts, vulnerability and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions (*medium evidence, high agreement*). *{WGII SPM A-2, TS A-2}*

Table 4.6 | Recent adaptation actions in the public and private sector across regions. *{WGII SPM A-2}*

Region	Example of actions
Africa	Most national governments are initiating governance systems for adaptation. Disaster risk management, adjustments in technologies and infrastructure, ecosystem-based approaches, basic public health measures and livelihood diversification are reducing vulnerability, although efforts to date tend to be isolated.
Europe	Adaptation policy has been developed across all levels of government, with some adaptation planning integrated into coastal and water management, into environmental protection and land planning and into disaster risk management.
Asia	Adaptation is being facilitated in some areas through mainstreaming climate adaptation action into sub-national development planning, early warning systems, integrated water resources management, agroforestry and coastal reforestation of mangroves.
Australasia	Planning for sea level rise, and in southern Australia for reduced water availability, is becoming adopted widely. Planning for sea level rise has evolved considerably over the past two decades and shows a diversity of approaches, although its implementation remains piecemeal.
North America	Governments are engaging in incremental adaptation assessment and planning, particularly at the municipal level. Some proactive adaptation is occurring to protect longer-term investments in energy and public infrastructure.
Central and South America	Ecosystem-based adaptation including protected areas, conservation agreements and community management of natural areas is occurring. Resilient crop varieties, climate forecasts and integrated water resources management are being adopted within the agricultural sector in some areas.
The Arctic	Some communities have begun to deploy adaptive co-management strategies and communications infrastructure, combining traditional and scientific knowledge.
Small Islands	Small islands have diverse physical and human attributes; community-based adaptation has been shown to generate larger benefits when delivered in conjunction with other development activities.
The Ocean	International cooperation and marine spatial planning are starting to facilitate adaptation to climate change, with constraints from challenges of spatial scale and governance issues.

National governments play key roles in adaptation planning and implementation (*robust evidence, high agreement*). There has been substantial progress since the AR4 in the development of national adaptation strategies and plans. This includes National Adaptation Programmes of Action (NAPAs) by least developed countries, the National Adaptation Plan (NAP) process, and strategic frameworks for national adaptation in Organisation for Economic Co-operation and Development (OECD) countries. National governments can coordinate adaptation efforts of local and sub-national governments, for example by protecting vulnerable groups, by supporting economic diversification, and by providing information, policy and legal frameworks and financial support. *{WGII SPM C-1, 15.2}*

While local government and the private sector have different functions, which vary regionally, they are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households and civil society and in managing risk information and financing (*medium evidence*, *high agreement*). There is a significant increase in the number of planned adaptation responses at the local level in rural and urban communities of developed and developing countries since the AR4. However, local councils and planners are often confronted by the complexity of adaptation without adequate access to guiding information or data on local vulnerabilities and potential impacts. Steps for mainstreaming adaptation into local decision-making have been identified but challenges remain in their implementation. Hence, scholars stress the important role of linkages with national and sub-national levels of government as well as partnerships among public, civic and private sectors in implementing local adaptation responses. *{WGII SPM A-2, SPM C-1, 14.2, 15.2}*

Institutional dimensions of adaptation governance, including the integration of adaptation into planning and decision-making, play a key role in promoting the transition from planning to implementation of adaptation (*robust evidence, high agreement*). The most commonly emphasized institutional barriers or enablers for adaptation planning and implementation are: 1) multilevel institutional co-ordination between different political and administrative levels in society; 2) key actors, advocates and champions initiating, mainstreaming and sustaining momentum for climate adaptation; 3) horizontal interplay between sectors, actors and policies operating at similar administrative levels; 4) political dimensions in planning and implementation; and 5) coordination between formal governmental, administrative agencies and private sectors and stakeholders to increase efficiency, representation and support for climate adaptation measures. *{WGII 15.2, 15.5, 16.3, Box 15-1}*

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*medium confidence*). Instruments include public-private finance partnerships, loans, payments for environmental services, improved resource pricing, charges and subsidies, norms and regulations and risk sharing and transfer mechanisms. Risk financing mechanisms in the public and private sector, such as insurance and risk pools, can contribute to increasing resilience, but without attention to major design challenges, they can also provide disincentives, cause market failure and decrease equity. Governments often play key roles as regulators, providers or insurers of last resort. *{WGII SPM C-1}*

4.4.2.2 Mitigation

There has been a considerable increase in national and sub-national mitigation plans and strategies since AR4. In 2012, 67% of global GHG emissions[42] were subject to national legislation or strategies versus 45% in 2007. However, there has not yet been a substantial deviation in global emissions from the past trend. These plans and strategies are in their early stages of development and implementation in many countries, making it difficult to assess their aggregate impact on future global emissions (*medium evidence, high agreement*). *{WGIII SPM.5.1}*

Since AR4, there has been an increased focus on policies designed to integrate multiple objectives, increase co-benefits and reduce adverse side effects (*high confidence*). Governments often explicitly reference co-benefits in climate and sectoral plans and strategies. *{WGIII SPM.5.1}*

Sector-specific policies have been more widely used than economy-wide policies (Table 4.7) (*medium evidence, high agreement*). Although most economic theory suggests that economy-wide policies for mitigation would be more cost-effective than sector-specific policies, administrative and political barriers may make economy-wide policies harder to design and implement than sector-specific policies. The latter may be better suited to address barriers or market failures specific to certain sectors and may be bundled in packages of complementary policies *{WGIII SPM.5.1}*

In principle, mechanisms that set a carbon price, including cap and trade systems and carbon taxes, can achieve mitigation in a cost-effective way, but have been implemented with diverse effects due in part to national circumstances as well as policy design. The short-run environmental effects of cap and trade systems have been limited as a result of loose caps or caps that have not proved to be constraining (*limited evidence, medium agreement*). In some countries, tax-based policies specifically aimed at reducing GHG emissions—alongside technology and other policies—have helped to weaken the link between GHG emissions and gross domestic product (GDP) (*high confidence*). In addition, in a large group of countries, fuel taxes (although not necessarily designed for the purpose of mitigation) have had effects that are akin to sectoral carbon taxes (*robust evidence, medium agreement*). Revenues from carbon taxes or auctioned emission allowances are used in some countries to reduce other taxes and/or to provide transfers to low-income groups. This illustrates the general principle that mitigation policies that raise government revenue generally have lower social costs than approaches which do not. *{WGIII SPM.5.1}*

Economic instruments in the form of subsidies may be applied across sectors, and include a variety of policy designs, such as tax rebates or exemptions, grants, loans and credit lines. An increasing number and variety of RE policies including subsidies—motivated by many factors—have driven escalated growth of RE technologies in recent years. Government policies play a crucial role in accelerating the deployment of RE technologies. Energy access and social and economic development have been the primary drivers in most developing countries whereas secure energy supply and environmental concerns have been most important in developed countries. The focus of policies is

Table 4.7 | Sectoral Policy Instruments. *{WGIII Table 15.2}*

Policy Instruments	Energy	Transport	Buildings	Industry	AFOLU	Human Settlements and Infrastructure
Economic Instruments – Taxes (carbon taxes may be economy-wide)	- Carbon tax (e.g., applied to electricity or fuels)	- Fuel taxes - Congestion charges, vehicle registration fees, road tolls - Vehicle taxes	- Carbon and/or energy taxes (either sectoral or economy-wide)	- Carbon tax or energy tax - Waste disposal taxes or charges	- Fertilizer or nitrogen taxes to reduce nitrous oxide (N_2O)	- Sprawl taxes, Impact fees, exactions, split-rate property taxes, tax increment finance, betterment taxes, congestion charges
Economic Instruments – Tradable Allowances (may be economy-wide)	- Emission trading - Emission credits under the Clean Development Mechanism (CDM) - Tradable Green Certificates	- Fuel and vehicle standards	- Tradable certificates for energy efficiency improvements (white certificates)	- Emission trading - Emission credits under CDM - Tradable Green Certificates	- Emission credits under CDM - Compliance schemes outside Kyoto protocol (national schemes) - Voluntary carbon markets	- Urban-scale cap and trade
Economic Instruments – Subsidies	- Fossil fuel subsidy removal - Feed in tariffs (FITs) for renewable energy	- Biofuel subsidies - Vehicle purchase subsidies - Feebates	- Subsidies or tax exemptions for investment in efficient buildings, retrofits and products - Subsidized loans	- Subsidies (e.g., for energy audits) - Fiscal incentives (e.g., for fuel switching)	- Credit lines for low-carbon agriculture, sustainable forestry	- Special Improvement or Redevelopment Districts
Regulatory Approaches	- Efficiency or environmental performance standards - Renewable Portfolio Standards (RPS) for renewable energy (RE) - Equitable access to electricity grid - Legal status of long-term CO_2 storage	- Fuel economy performance standards - Fuel quality standards - Greenhouse gas (GHG) emission performance standards - Regulatory restrictions to encourage modal shifts (road to rail) - Restriction on use of vehicles in certain areas - Environmental capacity constraints on airports - Urban planning and zoning restrictions	- Building codes and standards - Equipment and appliance standards - Mandates for energy retailers to assist customers invest in energy efficiency	- Energy efficiency standards for equipment - Energy management systems (also voluntary) - Voluntary agreements (where bound by regulation) - Labelling and public procurement regulations	- National policies to support REDD+ including monitoring, reporting and verification - Forest laws to reduce deforestation - Air and water pollution control GHG precursors - Land use planning and governance	- Mixed use zoning - Development restrictions - Affordable housing mandates - Site access controls - Transfer development rights - Design codes - Building codes - Street codes - Design standards
Information Programmes		- Fuel labelling - Vehicle efficiency labelling	- Energy audits - Labelling programmes - Energy advice programmes	- Energy audits - Benchmarking - Brokerage for industrial cooperation	- Certification schemes for sustainable forest practices - Information policies to support REDD+ including monitoring, reporting and verification	
Government Provision of Public Goods or Services	- Research and development - Infrastructure expansion (district heating/cooling or common carrier)	- Investment in transit and human powered transport - Investment in alternative fuel infrastructure - Low-emission vehicle procurement	- Public procurement of efficient buildings and appliances	- Training and education - Brokerage for industrial cooperation	- Protection of national, state, and local forests. - Investment in improvement and diffusion of innovative technologies in agriculture and forestry	- Provision of utility infrastructure, such as electricity distribution, district heating/cooling and wastewater connections, etc. - Park improvements - Trail improvements - Urban rail
Voluntary Actions			- Labelling programmes for efficient buildings - Product eco-labelling	- Voluntary agreements on energy targets, adoption of energy management systems, or resource efficiency	- Promotion of sustainability by developing standards and educational campaigns	

broadening from a concentration primarily on RE electricity to include RE heating and cooling and transportation. *{SRREN SPM.7}*

The reduction of subsidies for GHG-related activities in various sectors can achieve emission reductions, depending on the social and economic context (*high confidence*). While subsidies can affect emissions in many sectors, most of the recent literature has focused on subsidies for fossil fuels. Since AR4 a small but growing literature based on economy-wide models has projected that complete removal of subsidies to fossil fuels in all countries could result in reductions in global aggregate emissions by mid-century (*medium evidence, medium agreement*). Studies vary in methodology, the type and definition of subsidies and the time frame for phase out considered. In particular, the studies assess the impacts of complete removal of all fossil fuel subsides without seeking to assess which subsidies are wasteful and inefficient, keeping in mind national circumstances. *{WGIII SPM.5.1}*

Regulatory approaches and information measures are widely used and are often environmentally effective (*medium evidence, medium agreement*). Examples of regulatory approaches include energy efficiency standards; examples of information programmes include labelling programmes that can help consumers make better-informed decisions. *{WGIII SPM.5.1}*

Mitigation policy could devalue fossil fuel assets and reduce revenues for fossil fuel exporters, but differences between regions and fuels exist (*high confidence*). Most mitigation scenarios are associated with reduced revenues from coal and oil trade for major exporters. The effect on natural gas export revenues is more uncertain. The availability of CCS would reduce the adverse effect of mitigation on the value of fossil fuel assets (*medium confidence*). *{WGIII SPM.5.1}*

Interactions between or among mitigation policies may be synergistic or may have no additive effect on reducing emissions (*medium evidence, high agreement*). For instance, a carbon tax can have an additive environmental effect to policies such as subsidies for the supply of RE. By contrast, if a cap and trade system has a sufficiently stringent cap to affect emission-related decisions, then other policies have no further impact on reducing emissions (although they may affect costs and possibly the viability of more stringent future targets) (*medium evidence, high agreement*). In either case, additional policies may be needed to address market failures relating to innovation and technology diffusion. *{WGIII SPM.5.1}*

Sub-national climate policies are increasingly prevalent, both in countries with national policies and in those without. These policies include state and provincial climate plans combining market, regulatory and information instruments, and sub-national cap-and-trade systems. In addition, transnational cooperation has arisen among sub-national actors, notably among institutional investors, NGOs seeking to govern carbon offset markets, and networks of cities seeking to collaborate in generating low-carbon urban development. *{WGIII 13.5.2, 15.2.4, 15.8}*

Co-benefits and adverse side effects of mitigation could affect achievement of other objectives such as those related to human health, food security, biodiversity, local environmental quality, energy access, livelihoods and equitable sustainable development: *{WGIII SPM.2}*

- Mitigation scenarios reaching about 450 or 500 ppm CO_2-equivalent by 2100 show reduced costs for achieving air quality and energy security objectives, with significant co-benefits for human health, ecosystem impacts and sufficiency of resources and resilience of the energy system. *{WGIII SPM.4.1}*

- Some mitigation policies raise the prices for some energy services and could hamper the ability of societies to expand access to modern energy services to underserved populations (*low confidence*). These potential adverse side effects can be avoided with the adoption of complementary policies such as income tax rebates or other benefit transfer mechanisms (*medium confidence*). The costs of achieving nearly universal access to electricity and clean fuels for cooking and heating are projected to be between USD 72 to 95 billion per year until 2030 with minimal effects on GHG emissions (*limited evidence, medium agreement*) and multiple benefits in health and air pollutant reduction (*high confidence*). *{WGIII SPM.5.1}*

Whether or not side effects materialize, and to what extent side effects materialize, will be case- and site-specific, and depend on local circumstances and the scale, scope and pace of implementation. Many co-benefits and adverse side effects have not been well-quantified. *{WGIII SPM.4.1}*

4.4.3 Technology development and transfer

Technology policy (development, diffusion and transfer) complements other mitigation policies across all scales from international to sub-national, but worldwide investment in research in support of GHG mitigation is small relative to overall public research spending (*high confidence*). Technology policy includes technology-push (e.g., publicly-funded R&D) and demand-pull (e.g., governmental procurement programmes). Such policies address a pervasive market failure because, in the absence of government policy such as patent protection, the invention of new technologies and practices from R&D efforts has aspects of a public good and thus tends to be under-provided by market forces alone. Technology support policies have promoted substantial innovation and diffusion of new technologies, but the cost-effectiveness of such policies is often difficult to assess. Technology policy can increase incentives for participation and compliance with international cooperative efforts, particularly in the long run. *{WGIII SPM.5.1, 2.6.5, 3.11, 13.9, 13.12, 15.6.5}*

Many adaptation efforts also critically rely on diffusion and transfer of technologies and management practices, but their effective use depends on a suitable institutional, regulatory, social and cultural context (*high confidence*). Adaptation technologies are often familiar and already applied elsewhere. However, the success of technology transfer may involve not only the provision of finance and information, but also strengthening of policy and regulatory environments and capacities to absorb, employ and improve technologies appropriate to local circumstances. *{WGII 15.4}*

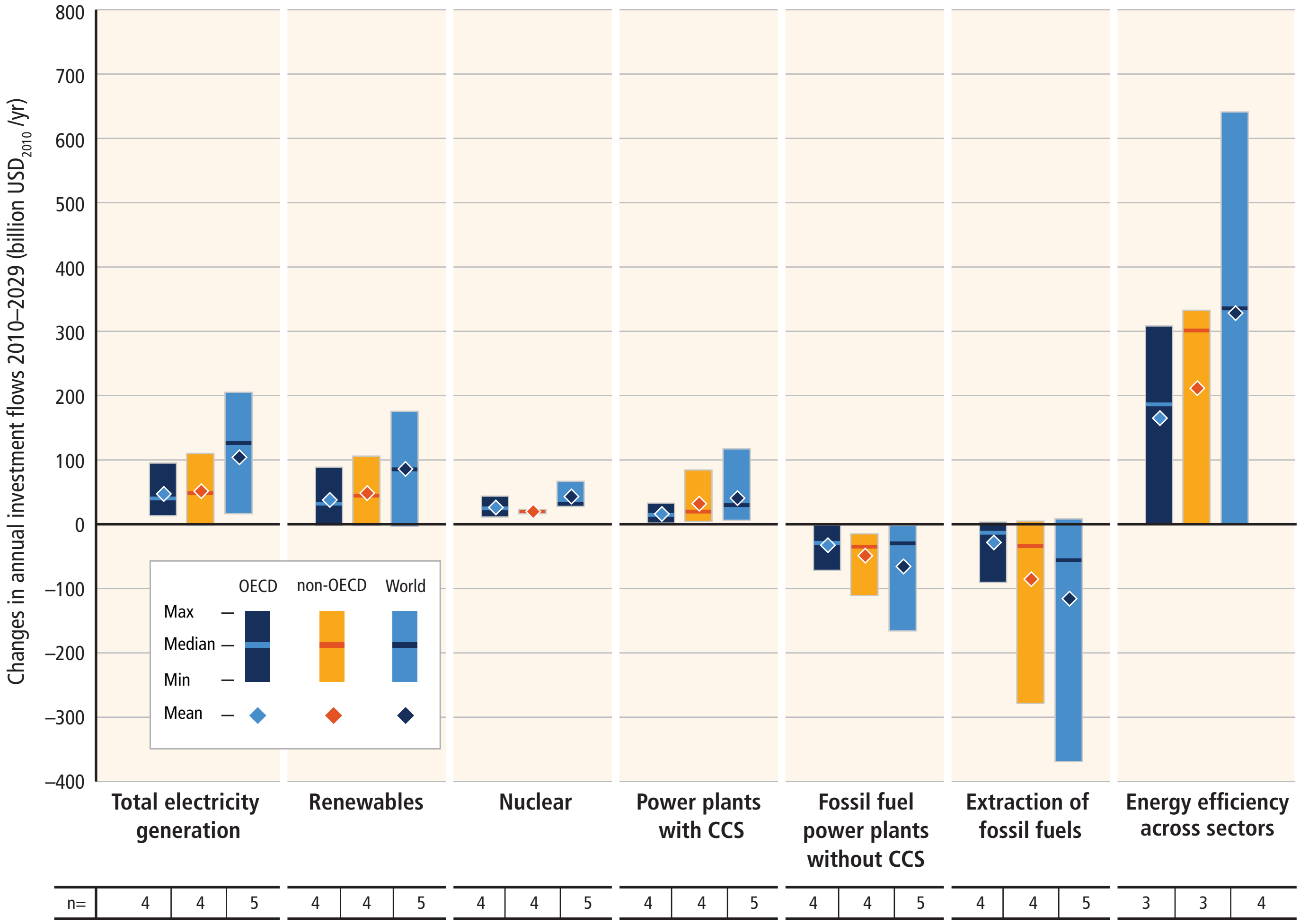


Figure 4.4 | Change in annual investment flows from the average baseline level over the next two decades (2010 to 2029) for mitigation scenarios that stabilize concentrations (without overshoot) within the range of approximately 430 to 530 ppm CO_2-eq by 2100. Total electricity generation (leftmost column) is the sum of renewable and nuclear energy, power plants with CCS, and fossil-fuel power plants without CCS. The vertical bars indicate the range between the minimum and maximum estimate; the horizontal bar indicates the median. The numbers in the bottom row show the total number of studies in the literature used in the assessment. Individual technologies shown are found to be used in different model scenarios in either a complementary or a synergistic way, depending largely on technology-specific assumptions and the timing and ambition level of the phase-in of global climate policies. *{WGIII Figure SPM.9}*

4.4.4 Investment and finance

Substantial reductions in emissions would require large changes in investment patterns (*high confidence*). Mitigation scenarios in which policies stabilize atmospheric concentrations (without overshoot) in the range from 430 to 530 ppm CO_2-eq by 2100[45] lead to substantial shifts in annual investment flows during the period 2010–2029 compared to baseline scenarios. Over the next two decades (2010–2029), annual investments in conventional fossil fuel technologies associated with the electricity supply sector are projected to decline in the scenarios by about USD 30 (2 to 166) billion (median: –20% compared to 2010) while annual investment in low carbon electricity supply (i.e., renewables, nuclear and electricity with CCS) is projected to rise in the scenarios by about USD 147 (31 to 360) billion (median: +100% compared to 2010) (*limited evidence, medium agreement*). In addition, annual incremental energy efficiency investments in transport, industry and buildings is projected to rise in the scenarios by about USD 336 (1 to 641) billion. Global total annual investment in the energy system is presently about USD 1,200 billion. This number includes only energy supply of electricity and heat and respective upstream and downstream activities. Energy efficiency investment or underlying sector investment is not included (Figure 4.4). *{WGIII SPM.5.1, 16.2}*

There is no widely agreed definition of what constitutes climate finance, but estimates of the financial flows associated with climate change mitigation and adaptation are available. See Figure 4.5 for an overview of climate finance flows. Published assessments of all current annual financial flows whose expected effect is to reduce net GHG emissions and/or to enhance resilience to climate change and climate variability show USD 343 to 385 billion per year

[45] This range comprises scenarios that reach 430 to 480 ppm CO_2-eq by 2100 (*likely* to limit warming to 2°C above pre-industrial levels) and scenarios that reach 480 to 530 ppm CO_2-eq by 2100 (without overshoot: *more likely than not* to limit warming to 2°C above pre-industrial levels).

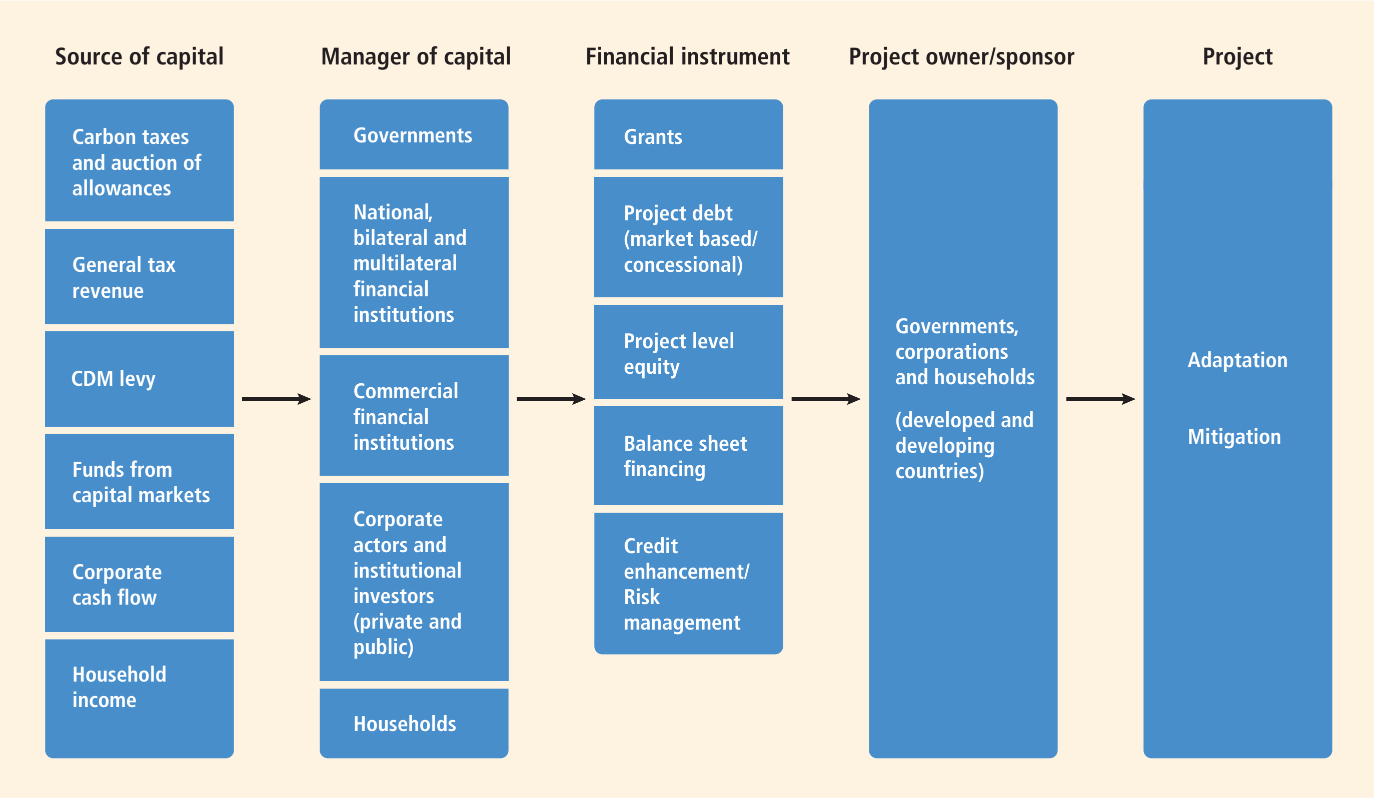


Figure 4.5 | Overview of climate finance flows. Note: Capital should be understood to include all relevant financial flows. The size of the boxes is not related to the magnitude of the financial flow. *{WGIII Figure TS.40}*

globally (*medium confidence*). Out of this, total public climate finance that flowed to developing countries is estimated to be between USD 35 and 49 billion per year in 2011 and 2012 (*medium confidence*). Estimates of international private climate finance flowing to developing countries range from USD 10 to 72 billion per year including foreign direct investment as equity and loans in the range of USD 10 to 37 billion per year over the period of 2008–2011 (*medium confidence*). *{WGIII SPM.5.1}*

In many countries, the private sector plays central roles in the processes that lead to emissions as well as to mitigation and adaptation. Within appropriate enabling environments, the private sector, along with the public sector, can play an important role in financing mitigation and adaptation (*medium evidence, high agreement*). The share of total mitigation finance from the private sector, acknowledging data limitations, is estimated to be on average between two-thirds and three-fourths on the global level (2010–2012) (*limited evidence, medium agreement*). In many countries, public finance interventions by governments and international development banks encourage climate investments by the private sector and provide finance where private sector investment is limited. The quality of a country's enabling environment includes the effectiveness of its institutions, regulations and guidelines regarding the private sector, security of property rights, credibility of policies and other factors that have a substantial impact on whether private firms invest in new technologies and infrastructures. Dedicated policy instruments and financial arrangements, for example, credit insurance, feed-in tariffs, concessional finance or rebates provide an incentive for mitigation investment by improving the return adjusted for the risk for private actors. Public-private risk reduction initiatives (such as in the context of insurance systems) and economic diversification are examples of adaptation action enabling and relying on private sector participation. *{WGII SPM B-2, SPM C-1, WGIII SPM.5.1}*

Financial resources for adaptation have become available more slowly than for mitigation in both developed and developing countries. Limited evidence indicates that there is a gap between global adaptation needs and the funds available for adaptation (*medium confidence*). Potential synergies between international finance for disaster risk management and adaptation to climate change have not yet been fully realized (*high confidence*). There is a need for better assessment of global adaptation costs, funding and investment. Studies estimating the global cost of adaptation are characterized by shortcomings in data, methods and coverage (*high confidence*). *{WGII SPM C-1, 14.2, SREX SPM}*

4.5 Trade-offs, synergies and integrated responses

There are many opportunities to link mitigation, adaptation and the pursuit of other societal objectives through integrated responses (*high confidence*). Successful implementation relies on relevant tools, suitable governance structures and enhanced capacity to respond (*medium confidence*).

A growing evidence base indicates close links between adaptation and mitigation, their co-benefits and adverse side effects, and recognizes sustainable development as the overarching context for climate policy (see Sections 3.5, 4.1, 4.2 and 4.3). Developing tools to address these linkages is critical to the success of climate policy in the context of sustainable development (see also Sections 4.4 and 3.5). This section presents examples of integrated responses in specific policy arenas, as well as some of the factors that promote or impede policies aimed at multiple objectives.

Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, encompassing connections among human health, water, energy, land use and biodiversity (*very high confidence*). Mitigation can support the achievement of other societal goals, such as those related to human health, food security, environmental quality, energy access, livelihoods and sustainable development, although there can also be negative effects. Adaptation measures also have the potential to deliver mitigation co-benefits, and vice versa, and support other societal goals, though trade-offs can also arise. *{WGII SPM C-1, SPM C-2, 8.4, 9.3–9.4, 11.9, Box CC-WE, WGIII Table TS.3, Table TS.4, Table TS.5, Table TS.6, Table TS.7}*

Integration of adaptation and mitigation into planning and decision-making can create synergies with sustainable development (*high confidence*). Synergies and trade-offs among mitigation and adaptation policies and policies advancing other societal goals can be substantial, although sometimes difficult to quantify especially in welfare terms (see also Section 3.5). A multi-objective approach to policy-making can help manage these synergies and trade-offs. Policies advancing multiple goals may also attract greater support. *{WGII SPM C-1, SPM C-2, 20.3, WGIII 1.2.1, 3.6.3, 4.3, 4.6, 4.8, 6.6.1}*

Effective integrated responses depend on suitable tools and governance structures, as well as adequate capacity (*medium confidence*). Managing trade-offs and synergies is challenging and requires tools to help understand interactions and support decision-making at local and regional scales. Integrated responses also depend on governance that enables coordination across scales and sectors, supported by appropriate institutions. Developing and implementing suitable tools and governance structures often requires upgrading the human and institutional capacity to design and deploy integrated responses. *{WGII SPM C-1, SPM C-2, 2.2, 2.4, 15.4, 15.5, 16.3, Table 14-1, Table 16-1, WGIII TS.1, TS.3, 15.2}*

An integrated approach to energy planning and implementation that explicitly assesses the potential for co-benefits and the presence of adverse side effects can capture complementarities across multiple climate, social and environmental objectives (*medium confidence*). There are strong interactive effects across various energy policy objectives, such as energy security, air quality, health and energy access (see Figure 3.5) and between a range of social and environmental objectives and climate mitigation objectives (see Table 4.5). An integrated approach can be assisted by tools such as cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis and expected utility theory. It also requires appropriate coordinating institutions. *{WGIII Figure SPM.6, TS.1, TS.3}*

Explicit consideration of interactions among water, food, energy and biological carbon sequestration plays an important role in supporting effective decisions for climate resilient pathways (*medium evidence, high agreement*). Both biofuel-based power generation and large-scale afforestation designed to mitigate climate change can reduce catchment run-off, which may conflict with alternative water uses for food production, human consumption or the maintenance of ecosystem function and services (see also Box 3.4). Conversely, irrigation can increase the climate resilience of food and fibre production but reduces water availability for other uses. *{WGII Box CC-WE, Box TS.9}*

An integrated response to urbanization provides substantial opportunities for enhanced resilience, reduced emissions and more sustainable development (*medium confidence*). Urban areas account for more than half of global primary energy use and energy-related CO_2 emissions (*medium evidence, high agreement*) and contain a high proportion of the population and economic activities at risk from climate change. In rapidly growing and urbanizing regions, mitigation strategies based on spatial planning and efficient infrastructure supply can avoid the lock-in of high emission patterns. Mixed-use zoning, transport-oriented development, increased density and co-located jobs and homes can reduce direct and indirect energy use across sectors. Compact development of urban spaces and intelligent densification can preserve land carbon stocks and land for agriculture and bioenergy. Reduced energy and water consumption in urban areas through greening cities and recycling water are examples of mitigation actions with adaptation benefits. Building resilient infrastructure systems can reduce vulnerability of urban settlements and cities to coastal flooding, sea level rise and other climate-induced stresses. *{WGII SPM B-2, SPM C-1, TS B-2, TS C-1, TS C-2, WGIII SPM.4.2.5, TS.3}*

Annexes

ANNEX I

User Guide

I

User Guide

As defined in the IPCC Procedures, the Synthesis Report (SYR) synthesises and integrates material contained within IPCC Assessment Reports and Special Reports. The scope of the SYR of the Fifth Assessment Report (AR5) includes material contained in the three Working Group contributions to the AR5, and it draws on information contained in other IPCC Reports as required. The SYR is based exclusively on assessments by the IPCC Working Groups; it does not refer to or assess the primary scientific literature itself.

The SYR is a self-contained, condensed summary of the much richer information contained in the underlying Working Group Reports. Users may wish to access relevant material at the required level of detail in the following manner: the report contains a Summary for Policymakers (SPM) that provides the most condensed summary of the current understanding of scientific, technical and socio-economic aspects of climate change. All references in curly brackets in this SPM refer to sections in the longer report. The longer report consists of an Introduction and four Topics. The numbers of the SPM sections largely correspond with the section numbers of the Topics. At the end of each paragraph, references are provided in italics between curly brackets. These refer to the Summaries for Policymakers (SPMs), Technical Summaries (TSs), Executive Summaries of chapters (ESs) and chapters (with chapter and section numbers) of the underlying Working Group contributions to the AR5 and Special Reports of the AR5. References to the IPCC Fourth Assessment Report (AR4) in 2007 are identified by adding "AR4" to the reference.

Users who wish to gain a better understanding of scientific details or access the primary scientific literature on which the SYR is based should refer to chapter sections of the underlying Working Group reports that are cited in the longer report of the SYR. The individual chapters of the Working Group reports provide references to the primary scientific literature on which IPCC assessments are based, and also offer the most detailed region- and sector-specific information.

A glossary, a list of acronyms, lists of authors and reviewers, a list of IPCC publications (annexes) and an index are provided to further facilitate the use of this report.

ANNEX II

Glossary

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This annex should be cited as:

IPCC, 2014: Annex II: Glossary [Mach, K.J., S. Planton and C. von Stechow (eds.)]. In: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, pp. 117-130.

This glossary defines some specific terms as the Core Writing Team of the Synthesis Report intends them to be interpreted in the context of this report. Red, italicized words indicate that the term is defined in the glossary. The references to Working Groups (WG) I, II and III in italics at the end of each term in this glossary refer to the AR5 WG glossaries and should be read as: WGI (IPCC, 2013a), WGII (IPCC, 2014a), and WGIII (IPCC, 2014b).

Abrupt change/abrupt climate change
Abrupt change refers to a change that is substantially faster than the rate of change in the recent history of the affected components of a system. Abrupt *climate change* refers to a large-scale change in the *climate system* that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades and causes substantial disruptions in human and natural systems. *{WGI, II, III}*

Adaptation
The process of adjustment to actual or expected *climate* and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected *climate* and its effects[1]. *{WGII, III}*

Adaptation deficit
The gap between the current state of a system and a state that minimizes adverse *impacts* from existing *climate* conditions and variability. *{WGII}*

Adaptation limit
The point at which an actor's objectives (or system needs) cannot be secured from intolerable *risks* through adaptive actions. *{WGII}*

Hard adaptation limit
No adaptive actions are possible to avoid intolerable *risks*.

Soft adaptation limit
Options are currently not available to avoid intolerable *risks* through adaptive action.

Adaptive capacity
The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences[2]. *{WGII, III}*

Adverse side effects
The negative effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Adverse side effects are often subject to *uncertainty* and depend on local circumstances and implementation practices, among other factors. See also *Co-benefits* and *Risk*. *{WGIII}*

Afforestation
Planting of new *forests* on lands that historically have not contained *forests*. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation* and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000b). See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). *{WGI, III}*

Agriculture, Forestry and Other Land Use (AFOLU and FOLU/LULUCF)
AFOLU plays a central role for *food security* and *sustainable development*. The main *mitigation* options within AFOLU involve one or more of three strategies: prevention of emissions to the atmosphere by conserving existing carbon pools in soils or vegetation or by reducing emissions of methane and nitrous oxide; *sequestration*—increasing the size of existing carbon pools and thereby extracting carbon dioxide (CO_2) from the atmosphere; and substitution—substituting biological products for fossil fuels or energy-intensive products, thereby reducing CO_2 emissions. Demand-side measures (e.g., reducing losses and wastes of food, changes in human diet, or changes in wood consumption) may also play a role.

FOLU (Forestry and Other Land Use)—also referred to as LULUCF (Land Use, Land-Use Change, and Forestry)—is the subset of AFOLU emissions and removals of greenhouse gases (GHGs) resulting from direct human-induced *land use, land-use change,* and forestry activities excluding agricultural emissions. *{WGIII}*

Albedo
The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the albedo of soils ranges from high to low and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes. *{WGI, III}*

Altimetry
A technique for measuring the height of the Earth's surface with respect to the geocentre of the Earth within a defined terrestrial reference frame (geocentric sea level). *{WGI}*

Ancillary benefits
See *Co-benefits*. *{WGII, III}*

Attribution
See *Detection and attribution*. *{WGI, II}.*

Baseline/reference
The baseline (or reference) is the state against which change is measured. A baseline period is the period relative to which anomalies are computed. In the context of *transformation pathways*, the term *baseline*

[1] Reflecting progress in science, this glossary entry differs in breadth and focus from the entry used in the Fourth Assessment Report and other IPCC reports.

[2] This glossary entry builds from definitions used in previous IPCC reports and the Millennium Ecosystem Assessment (MEA, 2005).

scenarios refers to scenarios that are based on the assumption that no *mitigation* policies or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Baseline scenarios are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight the level of emissions that would occur without further policy effort. Typically, baseline scenarios are then compared to *mitigation scenarios* that are constructed to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations or temperature change. The term *baseline scenario* is used interchangeably with *reference scenario* and *no policy scenario*. In much of the literature the term is also synonymous with the term *business-as-usual (BAU) scenario*, although the term *BAU* has fallen out of favour because the idea of *business as usual* in century-long socio-economic *projections* is hard to fathom. See also *Emission scenario*, *Representative Concentration Pathways (RCPs)* and *SRES scenarios*. *{WGI, II, III}*

Biodiversity
The variability among living organisms from terrestrial, marine and other *ecosystems*. Biodiversity includes variability at the genetic, species and *ecosystem* levels[3]. *{WGII, III}*

Bioenergy and Carbon Dioxide Capture and Storage (BECCS)
The application of *Carbon Dioxide Capture and Storage (CCS)* technology to bioenergy conversion processes. Depending on the total life-cycle emissions, including total marginal consequential effects (from *indirect land-use change (iLUC)* and other processes), BECCS has the potential for net carbon dioxide (CO_2) removal from the atmosphere. See also *Sequestration*. *{WGIII}*

Burden sharing/effort sharing
In the context of *mitigation*, burden sharing refers to sharing the effort of reducing the sources or enhancing the *sinks* of greenhouse gases (GHGs) from historical or projected levels, usually allocated by some criteria, as well as sharing the cost burden across countries. *{WGIII}*

Cancún Agreements
A set of decisions adopted at the 16th Session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), including the following, among others: the newly established Green Climate Fund (GCF), a newly established technology mechanism, a process for advancing discussions on *adaptation*, a formal process for reporting *mitigation* commitments, a goal of limiting global mean surface temperature increase to 2°C and an agreement on MRV—Measurement, Reporting and Verification for those countries that receive international support for their *mitigation* efforts. *{WGIII}*

Cancún Pledges
During 2010, many countries submitted their existing plans for controlling greenhouse gas (GHG) emissions to the Climate Change Secretariat and these proposals have now been formally acknowledged under the United Nations Framework Convention on Climate Change (UNFCCC). Developed countries presented their plans in the shape of economy-wide targets to reduce emissions, mainly up to 2020, while developing countries proposed ways to limit their growth of emissions in the shape of plans of action. *{WGIII}*

Carbon cycle
The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide (CO_2)) through the atmosphere, ocean, terrestrial and marine biosphere and lithosphere. In this report, the reference unit for the global carbon cycle is $GtCO_2$ or GtC (Gigatonne of carbon = 1 GtC = 10^{15} grams of carbon. This corresponds to 3.667 $GtCO_2$). *{WGI, II, III}*

Carbon Dioxide Capture and Storage (CCS)
A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. See also *Bioenergy and Carbon Dioxide Capture and Storage (BECCS)* and *Sequestration*. *{WGIII}*

II

Carbon Dioxide Removal (CDR)
Carbon Dioxide Removal methods refer to a set of techniques that aim to remove CO_2 directly from the atmosphere by either (1) increasing natural *sinks* for carbon or (2) using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration. CDR methods involve the ocean, land and technical systems, including such methods as iron fertilization, large-scale *afforestation* and direct capture of CO_2 from the atmosphere using engineered chemical means. Some CDR methods fall under the category of *geoengineering*, though this may not be the case for others, with the distinction being based on the magnitude, scale and impact of the particular CDR activities. The boundary between CDR and *mitigation* is not clear and there could be some overlap between the two given current definitions (IPCC, 2012b, p. 2). See also *Solar Radiation Management (SRM)*. *{WGI, III}*

Carbon intensity
The amount of emissions of carbon dioxide (CO_2) released per unit of another variable such as Gross Domestic Product (GDP), output energy use or transport. *{WGIII}*

Carbon price
The price for avoided or released carbon dioxide (CO_2) or *CO_2-equivalent emissions*. This may refer to the rate of a *carbon tax*, or the price of emission permits. In many models that are used to assess the economic costs of *mitigation*, carbon prices are used as a proxy to represent the level of effort in mitigation policies. *{WGIII}*

Carbon tax
A levy on the carbon content of fossil fuels. Because virtually all of the carbon in fossil fuels is ultimately emitted as carbon dioxide (CO_2), a carbon tax is equivalent to an emission tax on CO_2 emissions. *{WGIII}*

Climate
Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these

[3] This glossary entry builds from definitions used in the Global Biodiversity Assessment (Heywood, 1995) and the Millennium Ecosystem Assessment (MEA, 2005).

variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the *climate system*. *{WGI, II, III}*

Climate change
Climate change refers to a change in the state of the *climate* that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or *external forcings* such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in *land use*. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of *climate* which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural *climate variability* observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and *climate variability* attributable to natural causes. See also *Detection and Attribution*. *{WGI, II, III}*

Climate extreme (extreme weather or climate event)
See *Extreme weather event*. *{WGI, II}*

Climate feedback
An interaction in which a perturbation in one *climate* quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first. A negative *feedback* is one in which the initial perturbation is weakened by the changes it causes; a positive *feedback* is one in which the initial perturbation is enhanced. In the Fifth Assessment Report, a somewhat narrower definition is often used in which the climate quantity that is perturbed is the global mean surface temperature, which in turn causes changes in the global radiation budget. In either case, the initial perturbation can either be externally forced or arise as part of *internal variability*. *{WGI, II, III}*

Climate finance
There is no agreed definition of climate finance. The term *climate finance* is applied both to the financial resources devoted to addressing *climate change* globally and to financial flows to developing countries to assist them in addressing *climate change*. The literature includes several concepts in these categories, among which the most commonly used include: *{WGIII}*

Incremental costs
The cost of capital of the *incremental investment* and the change of operating and maintenance costs for a *mitigation* or *adaptation* project in comparison to a reference project. It can be calculated as the difference of the net present values of the two projects.

Incremental investment
The extra capital required for the initial investment for a *mitigation* or *adaptation* project in comparison to a reference project.

Total climate finance
All financial flows whose expected effect is to reduce net greenhouse gas (GHG) emissions and/or to enhance *resilience* to the *impacts* of *climate variability* and the projected *climate change*. This covers private and public funds, domestic and international flows and expenditures for *mitigation* and *adaptation* to current *climate variability* as well as future *climate change*.

Total climate finance flowing to developing countries
The amount of the *total climate finance* invested in developing countries that comes from developed countries. This covers private and public funds.

Private climate finance flowing to developing countries
Finance and investment by private actors in/from developed countries for *mitigation* and *adaptation* activities in developing countries.

Public climate finance flowing to developing countries
Finance provided by developed countries' governments and bilateral institutions as well as by multilateral institutions for *mitigation* and *adaptation* activities in developing countries. Most of the funds provided are concessional loans and grants.

Climate model (spectrum or hierarchy)
A numerical representation of the *climate system* based on the physical, chemical and biological properties of its components, their interactions and *feedback* processes and accounting for some of its known properties. The *climate system* can be represented by models of varying complexity; that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved. Coupled Atmosphere–Ocean *General Circulation Model*s (AOGCMs) provide a representation of the *climate system* that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the *climate* and for operational purposes, including monthly, seasonal and interannual climate predictions. *{WGI, II, III}*

Climate projection
A climate projection is the simulated response of the *climate system* to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using *climate models*. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized. *{WGI, II, III}*

Climate-resilient pathways
Iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with *climate change*. *{WGII}*

Climate response
See *Climate sensitivity*. *{WGI}*

Climate sensitivity
In IPCC reports, *equilibrium climate sensitivity* (units: °C) refers to the equilibrium (steady state) change in the annual global mean surface

temperature following a doubling of the atmospheric *equivalent carbon dioxide (CO_2) concentration*. Owing to computational constraints, the *equilibrium climate sensitivity* in a *climate model* is sometimes estimated by running an atmospheric *general circulation model* coupled to a mixed-layer ocean model, because *equilibrium climate sensitivity* is largely determined by atmospheric processes. Efficient models can be run to equilibrium with a dynamic ocean. The climate sensitivity parameter (units: °C (W $m^{-2})^{-1}$) refers to the equilibrium change in the annual global mean surface temperature following a unit change in *radiative forcing*.

The *effective climate sensitivity* (units: °C) is an estimate of the global mean surface temperature response to doubled CO_2 concentration that is evaluated from model output or observations for evolving non-equilibrium conditions. It is a measure of the strengths of the *climate feedbacks* at a particular time and may vary with forcing history and *climate* state and therefore may differ from *equilibrium climate sensitivity*.

The *transient climate response* (units: °C) is the change in the global mean surface temperature, averaged over a 20-year period, centered at the time of atmospheric CO_2 doubling, in a *climate model* simulation in which CO_2 increases at 1%/yr. It is a measure of the strength and rapidity of the surface temperature response to greenhouse gas (GHG) forcing. *{WGI, II, III}*

Climate system
The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of *external forcings* such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and *land-use change*. *{WGI, II, III}*

Climate variability
Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the *climate* on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the *climate system* (*internal variability*), or to variations in natural or anthropogenic *external forcing* (external variability). See also *Climate change*. *{WGI, II, III}*

CO_2-equivalent (CO_2-eq) concentration
The concentration of carbon dioxide (CO_2) that would cause the same *radiative forcing* as a given mixture of CO_2 and other forcing components. Those values may consider only greenhouse gases (GHGs), or a combination of GHGs, aerosols and surface *albedo* change. CO_2-equivalent concentration is a metric for comparing *radiative forcing* of a mix of different forcing components at a particular time but does not imply equivalence of the corresponding climate change responses nor future forcing. There is generally no connection between *CO_2-equivalent emissions* and resulting CO_2-equivalent concentrations. *{WGI, III}*

CO_2-equivalent (CO_2-eq) emission
The amount of carbon dioxide (CO_2) emission that would cause the same integrated *radiative forcing*, over a given time horizon, as an emitted amount of a greenhouse gas (GHG) or a mixture of GHGs. The CO_2-equivalent emission is obtained by multiplying the emission of a GHG by its *Global Warming Potential (GWP)* for the given time horizon (see WGI Chapter 8, Table 8.A.1 and WGIII Annex II.9.1 for *GWP* values of the different GHGs used here). For a mix of GHGs it is obtained by summing the CO_2-equivalent emissions of each gas. CO_2-equivalent emission is a common scale for comparing emissions of different GHGs but does not imply equivalence of the corresponding climate change responses. There is generally no connection between CO_2-equivalent emissions and resulting *CO_2-equivalent concentrations*. *{WGI, III}*

Co-benefits
The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to *uncertainty* and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as *ancillary benefits*. *{WGII, III}*

Confidence
The validity of a finding based on the type, amount, quality and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. In this report, confidence is expressed qualitatively (Mastrandrea et al., 2010). See WGI AR5 Figure 1.11 for the levels of confidence; see WGI AR5 Table 1.2 for the list of *likelihood* qualifiers; see WGII AR5 Box 1-1. See also *Uncertainty*. *{WGI, II, III}*

Cost-effectiveness
A policy is more cost-effective if it achieves a given policy goal at lower cost. *Integrated models* approximate cost-effective solutions, unless they are specifically constrained to behave otherwise. Cost-effective *mitigation scenarios* are those based on a stylized implementation approach in which a single price on carbon dioxide (CO_2) and other greenhouse gases (GHGs) is applied across the globe in every sector of every country and that rises over time in a way that achieves lowest global discounted costs. *{WGIII}*

Decarbonization
The process by which countries or other entities aim to achieve a low-carbon economy, or by which individuals aim to reduce their consumption of carbon. *{WGII, III}*

Deforestation
Conversion of *forest* to non-*forest*. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation* and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000b). See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). *{WGI, II}*

Detection and attribution
Detection of change is defined as the process of demonstrating that *climate* or a system affected by *climate* has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its *likelihood* of occurrence by chance due to *internal variability* alone is determined to be small,

for example, <10%. *Attribution* is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence (Hegerl et al., 2010). *{WGI, II}*

Detection of impacts of climate change
For a natural, human or managed system, identification of a change from a specified *baseline*. The *baseline* characterizes behavior in the absence of *climate change* and may be stationary or non-stationary (e.g., due to *land-use change*). *{WGII}*

Disaster
Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery. *{WGII}*

Discounting
A mathematical operation making monetary (or other) amounts received or expended at different times (years) comparable across time. The discounter uses a fixed or possibly time-varying discount rate (>0) from year to year that makes future value worth less today. *{WGII, III}*

Drought
A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. For example, shortage of precipitation during the growing season impinges on crop production or *ecosystem* function in general (due to soil moisture drought, also termed agricultural drought) and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in precipitation. A period with an abnormal precipitation deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more. For the corresponding indices, see WGI AR5 Box 2.4. *{WGI, II}*

Early warning system
The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a *hazard* to prepare to act promptly and appropriately to reduce the possibility of harm or loss[4]. *{WGII}*

Earth System Model (ESM)
A coupled atmosphere–ocean *general circulation model* in which a representation of the *carbon cycle* is included, allowing for interactive calculation of atmospheric CO_2 or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included. See also *Climate model*. *{WGI, II}*

Ecosystem
An ecosystem is a functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment. *{WGI, II, III}*

Ecosystem services
Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or *biodiversity* maintenance, (2) provisioning services such as food, fiber or fish, (3) regulating services such as *climate* regulation or carbon *sequestration* and (4) cultural services such as tourism or spiritual and aesthetic appreciation. *{WGII, III}*

El Niño-Southern Oscillation (ENSO)
The term *El Niño* was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the *Southern Oscillation*. This coupled atmosphere–ocean phenomenon, with preferred time scales of two to about seven years, is known as the *El Niño-Southern Oscillation (ENSO).* It is often measured by the surface pressure anomaly difference between Tahiti and Darwin or the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called *La Niña*. For the corresponding indices, see WGI AR5 Box 2.5. *{WGI, II}*

Emission scenario
A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases (GHGs), aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and *land use*) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a *climate model* to compute *climate projections*. In IPCC (1992) a set of emission scenarios was presented which were used as a basis for the *climate projections* in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emissions Scenarios (IPCC, 2000a) emission scenarios, the so-called *SRES scenarios*, were published, some of

[4] This glossary entry builds from the definitions used in UNISDR (2009) and IPCC (2012a).

which were used, among others, as a basis for the *climate projections* presented in Chapters 9 to 11 of IPCC WGI TAR (IPCC, 2001a) and Chapters 10 and 11 of IPCC WGI AR4 (IPCC, 2007) as well as in the IPCC WGI AR5 (IPCC, 2013b). New emission scenarios for *climate change*, the four *Representative Concentration Pathways*, were developed for, but independently of, the present IPCC assessment. See also *Baseline/reference*, *Mitigation scenario* and *Transformation pathway*. *{WGI, II, III}*

Energy access
Access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses (AGECC, 2010). *{WGIII}*

Energy intensity
The ratio of energy use to economic or physical output. *{WGIII}*

Energy security
The goal of a given country, or the global community as a whole, to maintain an adequate, stable and predictable energy supply. Measures encompass safeguarding the sufficiency of energy resources to meet national energy demand at competitive and stable prices and the *resilience* of the energy supply; enabling development and deployment of technologies; building sufficient infrastructure to generate, store and transmit energy supplies and ensuring enforceable contracts of delivery. *{WGIII}*

Ensemble
A collection of model simulations characterizing a *climate* prediction or *projection*. Differences in initial conditions and model formulation result in different evolutions of the modeled system and may give information on uncertainty associated with model error and error in initial conditions in the case of *climate* forecasts and on *uncertainty* associated with model error and with internally generated *climate variability* in the case of *climate projections*. *{WGI, II}*

Equilibrium climate sensitivity
See *Climate sensitivity*. *{WGI}*

Eutrophication
Over-enrichment of water by nutrients such as nitrogen and phosphorus. It is one of the leading causes of water quality impairment. The two most acute symptoms of eutrophication are hypoxia (or oxygen depletion) and harmful algal blooms. *{WGII}*

Exposure
The presence of people, livelihoods, species or *ecosystems*, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. *{WGII}*

External forcing
External forcing refers to a forcing agent outside the *climate system* causing a change in the *climate system*. Volcanic eruptions, solar variations and anthropogenic changes in the composition of the atmosphere and *land-use change* are external forcings. Orbital forcing is also an external forcing as the insolation changes with orbital parameters eccentricity, tilt and precession of the equinox. *{WGI, II}*

Extreme weather event
An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an *extreme climate event*, especially if it yields an average or total that is itself extreme (e.g., *drought* or heavy rainfall over a season). *{WGI, II}*

Feedback
See *Climate feedback*. *{WGI, II}*

Flood
The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods and glacial lake outburst floods. *{WGII}*

Food security
A state that prevails when people have secure access to sufficient amounts of safe and nutritious food for normal growth, development and an active and healthy life. *{WGII, III}*

Forest
A vegetation type dominated by trees. Many definitions of the term *forest* are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure and economics. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation* and *deforestation,* see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000b). See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). *{WGI, III}*

Fuel poverty
A condition in which a household is unable to guarantee a certain level of consumption of domestic energy services (especially heating) or suffers disproportionate expenditure burdens to meet these needs. *{WGIII}*

Geoengineering
Geoengineering refers to a broad set of methods and technologies that aim to deliberately alter the *climate system* in order to alleviate the *impacts* of *climate change*. Most, but not all, methods seek to either (1) reduce the amount of absorbed solar energy in the *climate system* (*Solar Radiation Management*) or (2) increase net carbon *sinks* from the atmosphere at a scale sufficiently large to alter *climate* (*Carbon Dioxide Removal*). Scale and intent are of central importance. Two key characteristics of geoengineering methods of particular concern are that they use or affect the *climate system* (e.g., atmosphere, land or ocean) globally or regionally and/or could have substantive unintended effects that cross national boundaries. Geoengineering is different from weather modification and ecological engineering, but the boundary can be fuzzy (IPCC, 2012b, p. 2). *{WGI, II, III}*

II

Global climate model (also referred to as general circulation model, both abbreviated as GCM)
See *Climate model*. *{WGI, II}*

Global Temperature change Potential (GTP)
An index measuring the change in global mean surface temperature at a chosen point in time following an emission of a unit mass of a given substance, relative to that of the reference substance, carbon dioxide (CO_2). The Global Temperature change Potential (GTP) thus represents the combined effect of the differing times these substances remain in the atmosphere, their effectiveness in causing *radiative forcing* and the response of the *climate system*. The GTP has been defined in two different ways:

- Fixed GTP: based on a fixed time horizon in the future (such as GTP_{100} for a time horizon of 100 years)
- Dynamic GTP: based on a target year (such as the year when global mean temperature is expected to reach a target level). In the dynamic GTP, the time horizon reduces over time as the target year is approached and hence the GTP value changes for emissions occurring further in the future. *{WGI Chapter 8}*

Global warming
Global warming refers to the gradual increase, observed or projected, in global surface temperature, as one of the consequences of *radiative forcing* caused by anthropogenic emissions. *{WGIII}*

Global Warming Potential (GWP)
An index measuring the *radiative forcing* following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide (CO_2). The GWP thus represents the combined effect of the differing times these substances remain in the atmosphere and their effectiveness in causing *radiative forcing*. *(WGI, III}*

Hazard
The potential occurrence of a natural or human-induced physical event or trend or physical *impact* that may cause loss of life, injury, or other health *impacts*, as well as damage and loss to property, infrastructure, livelihoods, service provision, *ecosystems* and environmental resources. In this report, the term *hazard* usually refers to *climate*-related physical events or trends or their physical *impacts*. *{WGII}*

Heat wave
A period of abnormally and uncomfortably hot weather. *{WGI, II}*

Hydrological cycle
The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condenses to form clouds, precipitates over ocean and land as rain or snow, which on land can be intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams and ultimately flows out into the oceans, from which it will eventually evaporate again. The various systems involved in the hydrological cycle are usually referred to as hydrological systems. *{WGI, II}*

Impacts (consequences, outcomes)
Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of *extreme weather and climate events* and of *climate change*. Impacts generally refer to effects on lives, livelihoods, health, *ecosystems*, economies, societies, cultures, services and infrastructure due to the interaction of *climate changes* or hazardous climate events occurring within a specific time period and the *vulnerability* of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of *climate change* on geophysical systems, including *floods*, *droughts* and sea level rise, are a subset of impacts called physical impacts. *{WGII}*

Indirect emissions
Emissions that are a consequence of the activities within well-defined boundaries of, for instance, a region, an economic sector, a company or process, but which occur outside the specified boundaries. For example, emissions are described as indirect if they relate to the use of heat but physically arise outside the boundaries of the heat user, or to electricity production but physically arise outside of the boundaries of the power supply sector. *{WGIII}*

Industrial Revolution
A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil carbon dioxide (CO_2). In this report the terms *pre-industrial* and *industrial* refer, somewhat arbitrarily, to the periods before and after 1750, respectively. *{WGI, II, III}*

Integrated assessment
A method of analysis that combines results and models from the physical, biological, economic and social sciences and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it. See also *Integrated models*. *{WGII, III}*

Integrated Coastal Zone Management (ICZM)
An integrated approach for sustainably managing coastal areas, taking into account all coastal habitats and uses. *{WGII}*

Integrated models
Integrated models explore the interactions between multiple sectors of the economy or components of particular systems, such as the energy system. In the context of *transformation pathways*, they refer to models that, at a minimum, include full and disaggregated representations of the energy system and its linkage to the overall economy that will allow for consideration of interactions among different elements of that system. Integrated models may also include representations of the full economy, *land use and land-use change (LUC)* and the *climate system*. See also *Integrated assessment*. *{WGIII}*

Internal variability
See *Climate variability*. *{WGI}*

Irreversibility
A perturbed state of a dynamical system is defined as irreversible on a given timescale, if the recovery timescale from this state due to natural processes is substantially longer than the time it takes for the system to reach this perturbed state. In the context of this report, the time scale of interest is centennial to millennial. See also *Tipping point*. *{WGI}*

Land use and land-use change
Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term *land use* is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction and conservation). In urban settlements it is related to land uses within cities and their hinterlands. Urban land use has implications on city management, structure and form and thus on energy demand, greenhouse gas (GHG) emissions and mobility, among other aspects. *{WGI, II, III}*

Land-use change (LUC)
Land-use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land-use change may have an impact on the surface *albedo*, evapotranspiration, sources and *sinks* of greenhouse gases (GHGs), or other properties of the *climate system* and may thus give rise to *radiative forcing* and/or other *impacts* on *climate*, locally or globally. See also the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000b).

Indirect land-use change (iLUC)
Indirect land-use change refers to shifts in land use induced by a change in the production level of an agricultural product elsewhere, often mediated by markets or driven by policies. For example, if agricultural land is diverted to fuel production, *forest* clearance may occur elsewhere to replace the former agricultural production. See also *Agriculture, Forestry and Other Land Use (AFOLU)*, *Afforestation*, *Deforestation* and *Reforestation*.

Leakage
Phenomena whereby the reduction in emissions (relative to a *baseline*) in a jurisdiction/sector associated with the implementation of *mitigation* policy is offset to some degree by an increase outside the jurisdiction/sector through induced changes in consumption, production, prices, *land use* and/or trade across the jurisdictions/sectors. Leakage can occur at a number of levels, be it a project, state, province, nation or world region.

In the context of *Carbon Dioxide Capture and Storage (CCS)*, *CO_2 leakage* refers to the escape of injected carbon dioxide (CO_2) from the storage location and eventual release to the atmosphere. In the context of other substances, the term is used more generically, such as for *methane (CH_4) leakag*e (e.g., from fossil fuel extraction activities) and *hydrofluorocarbon (HFC) leakage* (e.g., from refrigeration and air-conditioning systems). *{WGIII}*

Likelihood
The chance of a specific outcome occurring, where this might be estimated probabilistically. Likelihood is expressed in this report using a standard terminology (Mastrandrea et al., 2010), defined in WGI AR5 Table 1.2 and WGII AR5 Box 1-1. See also *Confidence* and *Uncertainty*. *{WGI, II, III}*

Lock-in
Lock-in occurs when a market is stuck with a standard even though participants would be better off with an alternative. In this report, lock-in is used more broadly as path dependence, which is the generic situation where decisions, events or outcomes at one point in time constrain *adaptation*, *mitigation* or other actions or options at a later point in time. *{WGII, III}*

Low regrets policy
A policy that would generate net social and/or economic benefits under current *climate* and a range of future *climate change* scenarios. *{WGII}*

Marine-based ice sheet
An ice sheet containing a substantial region that rests on a bed lying below sea level and whose perimeter is in contact with the ocean. The best known example is the West Antarctic ice sheet. *{WGI}*

Meridional Overturning Circulation (MOC)
Meridional (north–south) overturning circulation in the ocean quantified by zonal (east–west) sums of mass transports in depth or density layers. In the North Atlantic, away from the subpolar regions, the MOC (which is in principle an observable quantity) is often identified with the thermohaline circulation (THC), which is a conceptual and incomplete interpretation. It must be borne in mind that the MOC is also driven by wind and can also include shallower overturning cells such as occur in the upper ocean in the tropics and subtropics, in which warm (light) waters moving poleward are transformed to slightly denser waters and subducted equatorward at deeper levels. *{WGI, II}*

Mitigation (of climate change)
A human intervention to reduce the sources or enhance the *sinks* of greenhouse gases (GHGs). This report also assesses human interventions to reduce the sources of other substances which may contribute directly or indirectly to limiting *climate change*, including, for example, the reduction of particulate matter emissions that can directly alter the radiation balance (e.g., black carbon) or measures that control emissions of carbon monoxide, nitrogen oxides, Volatile Organic Compounds and other pollutants that can alter the concentration of tropospheric ozone which has an indirect effect on the *climate*. *{WGI, II, III}*

Mitigation scenario
A plausible description of the future that describes how the (studied) system responds to the implementation of *mitigation* policies and measures. See also *Baseline/reference*, *Emission scenario*, *Representative Concentration Pathways (RCPs)*, *SRES scenarios* and *Transformation pathway*. *{WGIII}*

Net negative emissions
A situation of net negative emissions is achieved when, as result of human activities, more greenhouse gases (GHGs) are sequestered or stored than are released into the atmosphere. *{SYR Box 2.2, footnote 29}*

Ocean acidification
Ocean acidification refers to a reduction in the *pH* of the ocean over an extended period, typically decades or longer, which is caused primarily

by uptake of carbon dioxide (CO_2) from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. *Anthropogenic ocean acidification* refers to the component of *pH* reduction that is caused by human activity (IPCC, 2011, p. 37). *{WGI, II}*

Overshoot pathways
Emissions, concentration or temperature pathways in which the metric of interest temporarily exceeds, or *overshoots* the long-term goal. *{WGIII}*

Oxygen Minimum Zone (OMZ)
The midwater layer (200–1000 m) in the open ocean in which oxygen saturation is the lowest in the ocean. The degree of oxygen depletion depends on the largely bacterial consumption of organic matter and the distribution of the OMZs is influenced by large-scale ocean circulation. In coastal oceans, OMZs extend to the shelves and may also affect benthic *ecosystems*. *{WGII}*

Permafrost
Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years. *{WGI, II}*

pH
pH is a dimensionless measure of the acidity of water (or any solution) given by its concentration of hydrogen ions (H^+). pH is measured on a logarithmic scale where $pH = -\log_{10}(H^+)$. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H^+, or acidity. *{WGI}*

Poverty
Poverty is a complex concept with several definitions stemming from different schools of thought. It can refer to material circumstances (such as need, pattern of deprivation or limited resources), economic conditions (such as standard of living, inequality or economic position) and/or social relationships (such as social class, dependency, exclusion, lack of basic security or lack of entitlement). *{WGII}*

Pre-industrial
See *Industrial Revolution*. *{WGI, II, III}*

Private costs
Private costs are carried by individuals, companies or other private entities that undertake an action, whereas *social costs* include additionally the external costs on the environment and on society as a whole. Quantitative estimates of both private and social costs may be incomplete, because of difficulties in measuring all relevant effects. *{WGIII}*

Projection
A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized. See also *Climate projection*. *{WGI, II}*

Radiative forcing
The strength of drivers is quantified as Radiative Forcing (RF) in units watts per square meter (W/m^2) as in previous IPCC assessments. RF is the change in energy flux caused by a driver and is calculated at the tropopause or at the top of the atmosphere. *{WGI}*

Reasons For Concern (RFCs)
Elements of a classification framework, first developed in the IPCC Third Assessment Report (IPCC, 2001b), which aims to facilitate judgments about what level of *climate change* may be *dangerous* (in the language of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC)) by aggregating *impacts*, *risks* and *vulnerabilities*. *{WGII}*

Reducing Emissions from Deforestation and Forest Degradation (REDD)
An effort to create financial value for the carbon stored in *forests*, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to *sustainable development* (SD). It is therefore a mechanism for *mitigation* that results from avoiding *deforestation*. REDD+ goes beyond *reforestation* and *forest* degradation and includes the role of conservation, sustainable management of *forests* and enhancement of *forest* carbon stocks. The concept was first introduced in 2005 in the 11th Session of the Conference of the Parties (COP) in Montreal and later given greater recognition in the 13th Session of the COP in 2007 at Bali and inclusion in the Bali Action Plan which called for 'policy approaches and positive incentives on issues relating to reducing emissions from *deforestation* and *forest* degradation in developing countries (REDD) and the role of conservation, sustainable management of *forests* and enhancement of *forest* carbon stock in developing countries'. Since then, support for REDD has increased and has slowly become a framework for action supported by a number of countries. *{WGIII}*

Reforestation
Planting of *forests* on lands that have previously contained *forests* but that have been converted to some other use. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation* and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000b). See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013). See also the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). *{WGI, II, III}*

Representative Concentration Pathways (RCPs)
Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as *land use*/land cover (Moss et al., 2008). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific *radiative forcing* characteristics. The term *pathway* emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss et al., 2010).

RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models produced corresponding *emission scenarios*. Extended Concentration Pathways (ECPs) describe extensions of the RCPs from 2100 to 2500 that were calculated using simple rules generated by stakeholder consultations and do not represent fully consistent scenarios.

Four RCPs produced from *Integrated Assessment Models* were selected from the published literature and are used in the present IPCC Assessment as a basis for the *climate* predictions and *projections* presented in WGI AR5 Chapters 11 to 14 (IPCC, 2013b):

RCP2.6
One pathway where *radiative forcing* peaks at approximately 3 W/m^2 before 2100 and then declines (the corresponding ECP assuming constant emissions after 2100).

RCP4.5 and RCP6.0
Two intermediate stabilization pathways in which *radiative forcing* is stabilized at approximately 4.5 W/m^2 and 6.0 W/m^2 after 2100 (the corresponding ECPs assuming constant concentrations after 2150).

RCP8.5
One high pathway for which *radiative forcing* reaches >8.5 W/m^2 by 2100 and continues to rise for some amount of time (the corresponding ECP assuming constant emissions after 2100 and constant concentrations after 2250).

For further description of future scenarios, see WGI AR5 Box 1.1. See also van Vuuren et al., 2011. *{WGI, II, III}*

Resilience
The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for *adaptation*, learning and *transformation*[5]. *{WGII, III}*

Risk
The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or *likelihood* of occurrence of hazardous events or trends multiplied by the *impacts* if these events or trends occur. In this report, the term *risk* is often used to refer to the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, *ecosystems* and species, economic, social and cultural assets, services (including environmental services) and infrastructure. *{WGII, III}*

Risk management
The plans, actions or policies to reduce the *likelihood* and/or consequences of *risks* or to respond to consequences. *{WGII}*

Sequestration
The uptake (i.e., the addition of a substance of concern to a reservoir) of carbon containing substances, in particular carbon dioxide (CO_2), in terrestrial or marine reservoirs. Biological sequestration includes direct removal of CO_2 from the atmosphere through *land-use change (LUC)*, *afforestation*, *reforestation*, revegetation, carbon storage in landfills and practices that enhance soil carbon in agriculture (cropland management, grazing land management). In parts of the literature, but not in this report, (carbon) sequestration is used to refer to *Carbon Dioxide Capture and Storage (CCS)*. *{WGIII}*

Sink
Any process, activity or mechanism that removes a greenhouse gas (GHG), an aerosol or a precursor of a GHG or aerosol from the atmosphere. *{WGI, II, III}*

Social cost of carbon
The net present value of climate damages (with harmful damages expressed as a positive number) from one more tonne of carbon in the form of carbon dioxide (CO_2), conditional on a global emissions trajectory over time. *{WGII, III}*

Social costs
See *Private costs*. *{WGIII}*

Solar Radiation Management (SRM)
Solar Radiation Management refers to the intentional modification of the Earth's shortwave radiative budget with the aim to reduce *climate change* according to a given metric (e.g., surface temperature, precipitation, regional *impacts*, etc.). Artificial injection of stratospheric aerosols and cloud brightening are two examples of SRM techniques. Methods to modify some fast-responding elements of the long wave radiative budget (such as cirrus clouds), although not strictly speaking SRM, can be related to SRM. SRM techniques do not fall within the usual definitions of *mitigation* and *adaptation* (IPCC, 2012b, p. 2). See also *Carbon Dioxide Removal (CDR)* and *Geoengineering*. *{WGI, III}*

SRES scenarios
SRES scenarios are *emission scenarios* developed by IPCC (2000a) and used, among others, as a basis for some of the *climate projections* shown in Chapters 9 to 11 of IPCC WGI TAR (IPCC, 2001a), Chapters 10 and 11 of IPCC WGI AR4 (IPCC, 2007), as well as in the IPCC WGI AR5 (IPCC, 2013b). *{WGI, II, III}*

Storm surge
The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place. *{WGI, II}*

Structural change
Changes, for example, in the relative share of gross domestic product (GDP) produced by the industrial, agricultural, or services sectors of an economy, or more generally, systems *transformations* whereby some components are either replaced or potentially substituted by other components. *{WGIII}*

Sustainability
A dynamic process that guarantees the persistence of natural and human systems in an equitable manner. *{WGII, III}*

II

[5] This definition builds from the definition used in Arctic Council (2013).

Sustainable development
Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). *{WGII, III}*

Thermal expansion
In connection with sea level, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level. *{WGI, II}*

Tipping point
A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the *climate system*, it refers to a critical threshold when global or regional *climate changes* from one stable state to another stable state. The tipping point event may be irreversible. See also *Irreversibility*. *{WGI, II, III}*

Transformation
A change in the fundamental attributes of natural and human systems. *{WGII}*

Transformation pathway
The trajectory taken over time to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperature change that implies a set of economic, technological and behavioural changes. This can encompass changes in the way energy and infrastructure are used and produced, natural resources are managed and institutions are set up and in the pace and direction of technological change (TC). See also *Baseline/reference*, *Emission scenario*, *Mitigation scenario, Representative Concentration Pathways (RCPs)* and *SRES scenarios*. *{WGIII}*

Transient Climate Response to Cumulative CO_2 Emissions (TCRE)
The transient global average surface temperature change per unit cumulated CO_2 emissions, usually 1000 PgC. TCRE combines both information on the airborne fraction of cumulated CO_2 emissions (the fraction of the total CO_2 emitted that remains in the atmosphere) and on the transient climate response (TCR). *{WGI}*

Uncertainty
A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts) (see Moss and Schneider, 2000; Manning et al., 2004; Mastrandrea et al., 2010). See also *Confidence* and *Likelihood*. *{WGI, II, III}*

Vulnerability
The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. *{WGII}*

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ANNEX III

Acronyms, Chemical Symbols and Scientific Units

µatm	Microatmosphere
AFOLU	Agriculture, Forestry and Other Land Use
AMOC	Atlantic Meridional Overturning Circulation
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
BAT	Best Available Technique
BAU	Business As Usual
BECCS	Bioenergy with Carbon Dioxide Capture and Storage
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CDR	Carbon Dioxide Removal
CF_4	Perfluoromethane
CH_4	Methane
CHP	Combined Heat and Power
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
CSP	Concentrating Solar Power
DC	Developing Country
ECS	Equilibrium Climate Sensitivity
EDGAR	Emission Database for Global Atmospheric Research
EJ	Exajoule
EMIC	Earth System Model of Intermediate Complexity
ENSO	El Niño-Southern Oscillation
ES	Executive Summary
ESM	Earth System Model
ETS	Emissions Trading System
F-gases	Fluorinated gases
FAQ	Frequently Asked Question
FAR	First Assessment Report
FIT	Feed-in Tariff
FOLU	Forestry and Other Land Use
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GMI	Global Methane Initiative
Gt	Gigatonnes
GTP	Global Temperature change Potential
GWP	Global Warming Potential
H_2	Hydrogen
HadCRUT4	Hadley Centre Climatic Research Unit Gridded Surface Temperature Data Set 4
HDV	Heavy-Duty Vehicles
HFC	Hydrofluorocarbon
HFC-152a	Hydrofluorocarbon-152a, Difluoroethane
IAM	Integrated Assessment Model
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
IO	International Organization
LDV	Light-Duty Vehicles
LULUCF	Land Use, Land-Use Change and Forestry
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MEF	Major Economies Forum
MRV	Monitoring, Reporting and Verification
N_2O	Nitrous Oxide
NAMA	Nationally Appropriate Mitigation Action
NAP	National Adaptation Plan
NAPA	National Adaptation Programmes of Action

NGO	Non-Governmental Organization
O_2	Oxygen
OA	Ocean Acidification
OECD	Organisation for Economic Co-operation and Development
PFC	Perfluorocarbon
ppb	parts per billion
ppm	parts per million
PV	Photovoltaic
R&D	Research and Development
RCP	Representative Concentration Pathway
RE	Renewable Energy
REDD	Reducing Emissions from Deforestation and Forest Degradation
REEEP	Renewable Energy and Energy Efficiency Partnership
RES	Renewable Energy System
RFC	Reason For Concern
RPS	Renewable Portfolio Standard
SAR	Second Assessment Report
SM	Supplementary Material
SO_2	Sulfur Dioxide
SPM	Summary for Policymakers
SRES	Special Report on Emissions Scenarios
SREX	Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SRM	Solar Radiation Management
SRREN	Special Report on Renewable Energy Sources and Climate Change Mitigation
SYR	Synthesis Report
TCR	Transient Climate Response
TCRE	Transient Climate Response to Cumulative CO_2 Emissions
TFE	Thematic Focus Element
TS	Technical Summary
UHI	Urban Heat Island
UNFCCC	United Nations Framework Convention on Climate Change
W	Watt
WG	Working Group
WMGHG	Well-Mixed Greenhouse Gas

III

ANNEX IV

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ANNEX VI

Publications by the Intergovernmental Panel on Climate Change

Assessment Reports

Fifth Assessment Report

Climate Change 2013: The Physical Science Basis
Contribution of Working Group I to the Fifth Assessment Report

Climate Change 2014: Impacts, Adaptation, and Vulnerability
Contribution of Working Group II to the Fifth Assessment Report

Climate Change 2014: Mitigation of Climate Change
Contribution of Working Group III to the Fifth Assessment Report

Climate Change 2014: Synthesis Report
A Report of the Intergovernmental Panel on Climate Change

Fourth Assessment Report

Climate Change 2007: The Physical Science Basis
Contribution of Working Group I to the Fourth Assessment Report

Climate Change 2007: Impacts, Adaptation and Vulnerability
Contribution of Working Group II to the Fourth Assessment Report

Climate Change 2007: Mitigation of Climate Change
Contribution of Working Group III to the Fourth Assessment Report

Climate Change 2007: Synthesis Report
A Report of the Intergovernmental Panel on Climate Change

Third Assessment Report

Climate Change 2001: The Scientific Basis
Contribution of Working Group I to the Third Assessment Report

Climate Change 2001: Impacts, Adaptation, and Vulnerability
Contribution of Working Group II to the Third Assessment Report

Climate Change 2001: Mitigation
Contribution of Working Group III to the Third Assessment Report

Climate Change 2001: Synthesis Report
Contribution of Working Groups I, II and III to the Third Assessment Report

Second Assessment Report

Climate Change 1995: Science of Climate Change
Contribution of Working Group I to the Second Assessment Report

Climate Change 1995: Scientific-Technical Analyses of Impacts, Adaptations and Mitigation of Climate Change
Contribution of Working Group II to the Second Assessment Report

Climate Change 1995: Economic and Social Dimensions of Climate Change
Contribution of Working Group III to the Second Assessment Report

Climate Change 1995: Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change
A Report of the Intergovernmental Panel on Climate Change

Supplementary Reports to the First Assessment Report

Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment
Supplementary report of the IPCC Scientific Assessment Working Group I

Climate Change 1992: The Supplementary Report to the IPCC Impacts Assessment
Supplementary report of the IPCC Impacts Assessment Working Group II

Climate Change: The IPCC 1990 and 1992 Assessments
IPCC First Assessment Report Overview and Policymaker Summaries and 1992 IPCC Supplement

First Assessment Report

Climate Change: The Scientific Assessment
Report of the IPCC Scientific Assessment Working Group I, 1990

Climate Change: The IPCC Impacts Assessment
Report of the IPCC Impacts Assessment Working Group II, 1990

Climate Change: The IPCC Response Strategies
Report of the IPCC Response Strategies Working Group III, 1990

Special Reports

Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) 2012

Renewable Energy Sources and Climate Change Mitigation (SRREN) 2011

Carbon Dioxide Capture and Storage 2005

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Land Use, Land-Use Change, and Forestry 2000

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Aviation and the Global Atmosphere 1999

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Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios 1994

Methodology Reports and Technical Guidelines

2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (KP Supplement) 2014

2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement) 2014

2006 IPCC Guidelines for National Greenhouse Gas Inventories (5 Volumes) 2006

Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types 2003

Good Practice Guidance for Land Use, Land-use Change and Forestry 2003

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories 2000

Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (3 volumes) 1996

IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations 1994

IPCC Guidelines for National Greenhouse Gas Inventories (3 volumes) 1994

Preliminary Guidelines for Assessing Impacts of Climate Change 1992

Technical Papers

Climate Change and Water
IPCC Technical Paper VI, 2008

Climate Change and Biodiversity
IPCC Technical Paper V, 2002

Implications of Proposed CO_2 Emissions Limitations
IPCC Technical Paper IV, 1997

Stabilization of Atmospheric Greenhouse Gases: Physical, Biological and Socio-Economic Implications
IPCC Technical Paper III, 1997

An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report
IPCC Technical Paper II, 1997

Technologies, Policies and Measures for Mitigating Climate Change
IPCC Technical Paper I, 1996

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Methane emissions estimate from airborne measurements over a western United States natural gas field

Anna Karion,[1,2] Colm Sweeney,[1,2] Gabrielle Pétron,[1,2] Gregory Frost,[1,2] R. Michael Hardesty,[1,2] Jonathan Kofler,[1,2] Ben R. Miller,[1,2] Tim Newberger,[1,2] Sonja Wolter,[1,2] Robert Banta,[2] Alan Brewer,[2] Ed Dlugokencky,[2] Patricia Lang,[2] Stephen A. Montzka,[2] Russell Schnell,[2] Pieter Tans,[2] Michael Trainer,[2] Robert Zamora,[2] and Stephen Conley[3]

Received 12 June 2013; revised 18 July 2013; accepted 23 July 2013; published 27 August 2013.

[1] Methane (CH_4) emissions from natural gas production are not well quantified and have the potential to offset the climate benefits of natural gas over other fossil fuels. We use atmospheric measurements in a mass balance approach to estimate CH_4 emissions of $55 \pm 15 \times 10^3$ kg h^{-1} from a natural gas and oil production field in Uintah County, Utah, on 1 day: 3 February 2012. This emission rate corresponds to 6.2%–11.7% (1σ) of average hourly natural gas production in Uintah County in the month of February. This study demonstrates the mass balance technique as a valuable tool for estimating emissions from oil and gas production regions and illustrates the need for further atmospheric measurements to determine the representativeness of our single-day estimate and to better assess inventories of CH_4 emissions. **Citation:** Karion, A., et al. (2013), Methane emissions estimate from airborne measurements over a western United States natural gas field, *Geophys. Res. Lett.*, *40*, 4393–4397, doi:10.1002/grl.50811.

1. Introduction

[2] As concern grows over the climate impact of increasing greenhouse gas emissions and the actual and associated political costs of imported fuels, the U.S. is looking to exploit natural gas as a domestic energy source. Natural gas is an efficient energy source because its combustion produces more energy per carbon dioxide (CO_2) molecule formed than coal or oil (177% and 140%, respectively) [*U.S. Department of Energy Energy Information Administration*, 1999]. Despite this efficiency, leakage of natural gas to the atmosphere from the point of extraction to the point of consumption reduces its climate benefits because the major component of natural gas is CH_4, a greenhouse gas that is 25 times more potent than CO_2 over a 100 year time horizon [*Intergovernmental Panel on Climate Change*, 2007]. Although assessing the exact climate impact of natural gas has many complexities, a recent study has suggested that if more than 3.2% of natural gas leaks to the atmosphere on its way from the point of extraction to a gas-fired power plant, the electricity produced will have a larger immediate climate impact than that from a coal-fired plant [*Alvarez et al.*, 2012].

[3] A critical gap in determining the climate impact of the recent increase in U.S. natural gas production is the lack of accurate and reliable estimates of associated emissions. In particular, the methodology used to account for fugitive CH_4 emissions during production is in question. This is demonstrated by large year-to-year revisions in natural gas-related CH_4 emissions reported for 2008 by the U.S. Environmental Protection Agency (EPA), which caused the estimated national average production-sector leak rate for this year to increase from approximately 0.16% of production in the 2010 report to 1.42% in the 2011 and 2012 reports [*U.S. Environmental Protection Agency*, 2010, 2011, 2012]. This rate was revised back down to 0.88% in the 2013 report [*EPA*, 2013]. These changes were driven largely by changes in EPA's assumptions for calculating emissions from liquid unloading (removing the accumulation of fluids in gas wells), unconventional completions with hydraulic fracturing, and refracturing of natural gas wells. In particular, the main driver for the 2013 reduction in production emissions was a report prepared by the oil and gas industry, which contended that CH_4 emissions from liquid unloading were more than an order of magnitude lower than EPA's 2011 report estimate and that emissions from refracturing wells in tight sands or shale formations were less than half of EPA's 2011 report estimate [*Shires and Lev-On*, 2012]. The substantial changes in the CH_4 inventory between 2010 and 2013 have led the EPA's Office of Inspector General to release a report calling for the improvement of the agency's air emissions data for the natural gas production sector [*U.S. Environmental Protection Agency Office of Inspector General*, 2013].

[4] Such large revisions and differences in inventory-based emission estimates highlight an important point: most CH_4 emissions from oil and gas operations are estimated from the "bottom up," in which emission factors for multiple processes are multiplied by an inventory of activity data. Most of the 80 different EPA emission factors associated with oil and gas operations are based on a study done in the 1990s [*Harrison et al.*, 1996] and assume consistency throughout the industry in a variety of different regions. In reality, the distribution of emissions may be highly variable from region to region [*Rusco*, 2010], and the recent revisions have suggested uncertainties in activity data and emission factors. Thus, there is a need to assess the emission factors

Additional supporting information may be found in the online version of this article.

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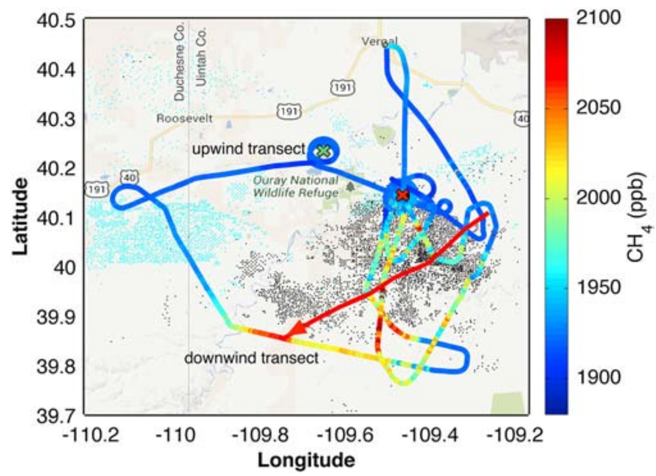

Figure 1. CH_4 measurements on 3 February 2012. Aircraft flight track overlaid on natural gas (black dots) and oil (blue dots) well locations along with color-coded CH_4 mole fraction. Bold red arrow shows the 3 h trajectory of the downwind air mass. The locations of two vertical profiles over Horse Pool (red X) and one northwest of Horse Pool (green X) are also indicated.

and extrapolation approaches used in bottom-up inventories with independent measurements and assessments of CH_4 emissions.

[5] Previous studies that have evaluated inventory estimates of oil and natural gas emissions [*Katzenstein et al.*, 2003; *Pétron et al.*, 2012] in a production basin with direct CH_4 measurements have concluded that CH_4 emissions from oil and gas production were likely underestimated by the available inventories. Because these studies took place in different U.S. regions (Oklahoma, Texas, and Kansas in *Katzenstein et al.* [2003] and Colorado in *Pétron et al.* [2012]) and over different time periods, it is difficult to assess to what extent this underestimate is found in all natural gas–producing regions or whether a trend is apparent. Here we present results from an oil and gas region not yet studied with atmosphere-based methods (the Uintah Basin) to the list of those that may have their CH_4 emissions underestimated by bottom-up inventories. The advantage of this study over previous ones is that the CH_4 emissions estimate does not require critical assumptions about either emission ratios using other trace gases or boundary layer flushing time.

2. Methods

2.1. Mass Balance Approach

[6] The mass balance approach is a measurement-based method for estimating the total emission of a trace gas released from a defined point [*Ryerson et al*., 2001] or area source [*Mays et al*., 2009; *Turnbull et al*., 2011; *White et al*., 1976], which allows for the direct assessment of uncertainties. The mass balance approach, as applied in this study, requires the assumption of steady horizontal winds, a well-developed convective planetary boundary layer (PBL), and measurements sufficiently downwind of the emission source; the uncertainties associated with these assumptions are identified and included in the uncertainty analysis (supplementary text section 4 in the supporting information). The Uintah County oil and gas field is well suited to this approach for deriving CH_4 fluxes using measurements from aircraft, because the majority of the 4800 gas wells and nearly 1000 oil wells are concentrated in a relatively small area ($40 \times 60\,km^2$, Figure 1) (State of Utah Department of Natural Resources Division of Oil Gas and Mining, Well Information Query, 2012, http://oilgas.ogm.utah.gov/Data_Center/LiveData_Search/well_information.htm.); an aircraft traveling at $60\,m\,s^{-1}$ is able to make several transects over the entire field and one to three vertical profiles during a 3–4 h flight.

[7] In the mass balance approach for flux estimation, the enhancement of the CH_4 mole fraction downwind of the source, relative to the upwind mole fraction, is integrated across the width of a horizontal plume in the planetary boundary layer (PBL) downwind of the source [*White et al*., 1976]. When the mean horizontal wind speed and direction are steady during the transit of an air mass across an area, the resulting calculated flux is equal to the surface flux between upwind and downwind measurements. The CH_4 flux is derived to be

$$\mathrm{flux}_{CH_4} = V\int_{-b}^{b} X_{CH_4}\left(\int_{z_{\mathrm{ground}}}^{z_{\mathrm{PBL}}} n_{\mathrm{air}}\mathrm{d}z\right)\cos\theta\,\mathrm{d}x \qquad (1)$$

[8] In equation (1), flux_{CH4} represents the molar flux (moles s^{-1}) of CH_4 from the basin. V is the mean horizontal wind speed over the region, averaged over the altitude between the ground and the top of the PBL, and over the time an air mass transits the basin. The angle θ is the angle between the mean wind direction and the direction normal to the aircraft track downwind, so that $\cos\theta dx$ is the flight track increment perpendicular to the mean horizontal wind direction. The CH_4 enhancement over the background mole fraction, i.e., ΔX_{CH4}, is integrated over the width of the plume ($-b$ to b) along the flight track and multiplied by the integral of the molar density of air (n_{air}) from the ground (z_{ground}, a function of path distance x) to the top of the PBL (z_{PBL}). In this calculation, ground-based heat flux measurements are used to characterize the mean time required to mix surface emissions from the ground to the top of the PBL (supplementary text section 4.3 in the supporting information).

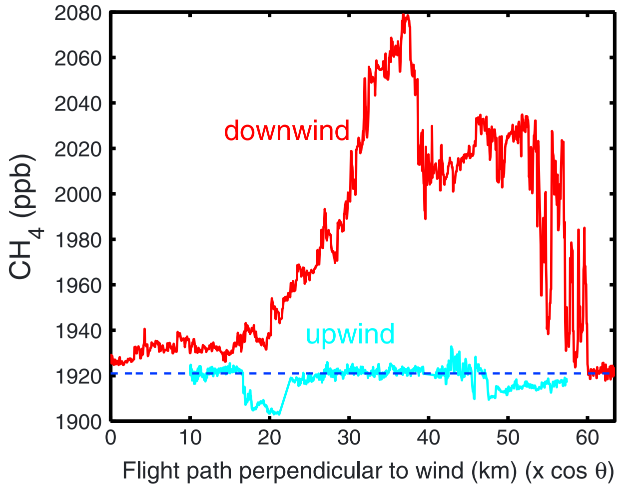

Figure 2. CH_4 mole fraction measured in the downwind plume (red line) as a function of distance perpendicular to the wind direction. The CH_4 mole fraction in the upwind transect is in light blue, and its average (1921 ppb) is represented by the dark blue dashed line. The lower upwind CH_4 measurements at ~20 km were made above the top of the PBL during a vertical profile.

2.2. 3 February 2012

[9] During 3 February 2012, moderate and steady horizontal winds and a well-defined PBL allowed us to use the mass balance approach to estimate the CH_4 emission flux from the Uintah County field. The CH_4 mole fraction was measured from an instrumented single-engine turboprop aircraft; and the PBL depth, wind speed, and wind direction were measured by high-resolution Doppler lidar (HRDL) (instrument details are in supplementary text sections 1–3 in the supporting information).

[10] Horizontal wind speeds on 3 February 2012 peaked during the night (2:00 local time (LT)) at 13 m s^{-1} (averaged throughout the PBL), flushing out the basin before decreasing to a steady 5–6 m s^{-1} from the northeast in the 3 h before the downwind transect was flown (at 15:30 LT). The PBL height (1700 ± 125 m meters above ground level (magl)) was determined from aircraft vertical profiles (Figure S1) and HRDL measurements. HRDL measurements showed the PBL height to be relatively constant throughout the time of the flight. Other than the vertical profiles, the rest of the flight measurements were made within the PBL between 100 and 1000 magl (Figure 1).

[11] The flight transect downwind of the natural gas field, along its southern and western edges and between 400 and 600 magl at 15:20–15:40 LT, showed elevated CH_4 mole fractions averaging 56 parts per billion (ppb) greater than the average upwind value of 1921 ± 5 ppb, with a peak enhancement of ~150 ppb. Horizontal winds from HRDL measurements averaged throughout the PBL were used to construct a back trajectory of the air mass sampled in this plume (Figure 1, red arrow). The trajectory indicates that the source of enhanced CH_4 was primarily the region containing the gas field in Uintah County and that the air mass traveled in a consistent southwesterly direction through the gas field in the ~3 h period prior to being sampled. Variability in the observed CH_4 mole fraction reflects the extent to which a point source emission is horizontally and vertically mixed, with individual narrow plumes likely originating from point sources closer to the flight path than the sources of wider plumes. We integrated the CH_4 enhancement above the background value of 1921 ppb, which was derived from measurements made upwind of the location of oil and gas wells, along the downwind flight path to calculate the flux from the oil and gas basin (Figure 2 and equation (1)). The altitude-averaged wind speed and direction were also averaged over the approximate transit time of the air mass through the basin, from 12:40 to 15:40 LT, corresponding to nine individual HRDL profiles (HRDL provided wind measurements as 20 min averages).

[12] Based on the variability and uncertainty in each term of the mass balance equation, we derived a total uncertainty of ±27% (1σ) on the total CH_4 flux estimate on 3 February of $56 \pm 15 \times 10^3$ kg h^{-1} (Table S1 and supplementary text section 4 in the supporting information). The relatively small uncertainty in the emission derived for this flight is the result of steady horizontal winds, consistent boundary layer height, and low measurement uncertainties.

2.3. Other Flight Days

[13] Twelve flights were made over the Uintah Basin in February 2012. Nonideal meteorological conditions (in particular, low, variable, and sometimes recirculating winds in the 0.5–1.5 m s^{-1} range) on the 11 other flight days made direct mass balance analysis of CH_4 emissions impossible. For example, horizontal wind speed and direction measured at the ground site could not be assumed to be representative of winds throughout the basin on the days with low and variable winds, given the complex terrain-driven meteorology of the basin. CH_4 enhancements measured on the other flight days were large, however, with average mole fractions from 2030 to 2650 ppb inside the PBL (Figure S3). Flight tracks passing over the field on 7 and 18 February show increased CH_4 over the locations of the gas and oil wells, with several large and distinct enhancements, in addition to more uniform enhancements over the remainder of the field; there is no evidence that a single, large point source is responsible for all of the CH_4 emissions (Figure S3).

[14] Although no hydrocarbon measurements were made on the 3 February 2012 flight, analyses of 67 discrete whole air samples collected over Uintah County aboard the aircraft throughout the month of February 2012 show excellent correlations of propane (C_3H_8) and butane (C_4H_{10}) with CH_4 ($R^2 > 0.85$, Figures 3a and 3b). Correlations of CH_4 with carbon monoxide (CO), a tracer for vehicle exhaust, are weaker ($R^2 = 0.28$, increasing to 0.52 when a single outlier with high CO is removed from the analysis (Figure 3c). The strong correlation of CH_4 with C_3H_8 and C_4H_{10} suggests that these CH_4 enhancements were primarily the result of emissions from oil and gas operations [*Pétron et al.*, 2012].

3. Results

[15] Because of the low uncertainty and the fact that the basin was so well cleaned out by the high winds prior to our flight on 3 February, the derived emissions estimate from this day is the focus of this study. A flux of $1.4 \pm 1.1 \times 10^3$ kg CH_4 h^{-1} (~2.5% of our 3 February estimate of 56×10^3 kg CH_4 h^{-1}) was subtracted from the total flux to account for emissions from cattle and natural seepage, as estimated from

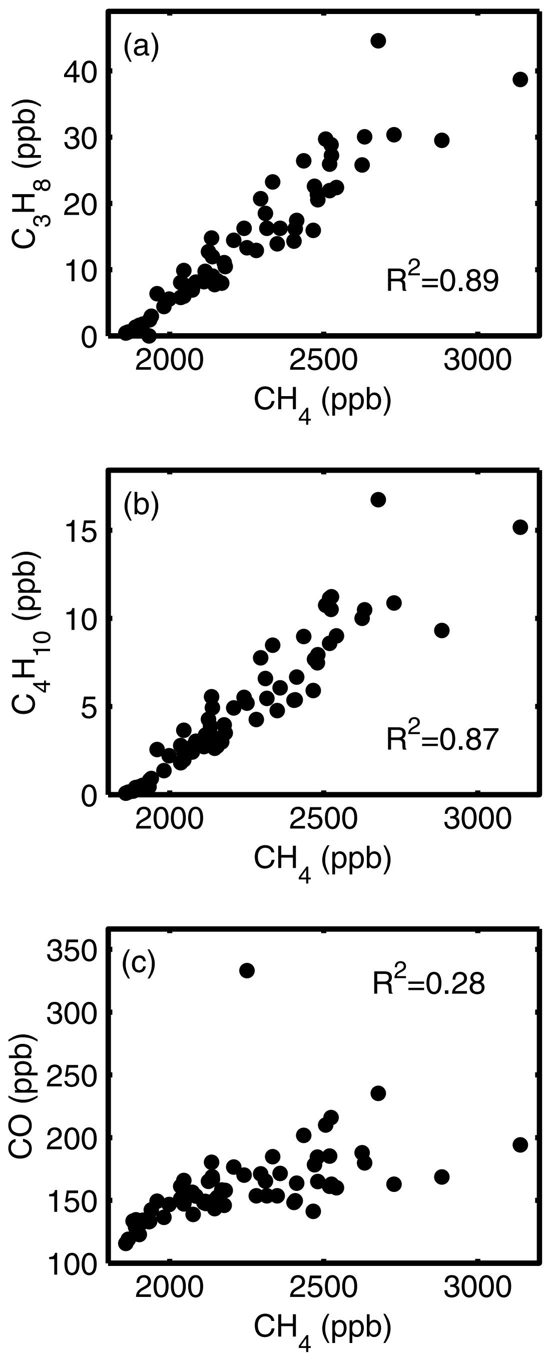

Figure 3. Mole fractions of (a) propane (C_3H_8), (b) butane (C_4H_{10}), and (c) carbon monoxide (CO) measured in discrete air samples collected over the Uintah Basin in February 2012, shown as functions of CH_4 mole fraction. Correlation coefficients (R^2) are shown in each panel.

inventories [*Griffith et al.*, 2008; *Klusman*, 2003; *U.S. Department of Agriculture*, 2009] (supplementary text section 5 in the supporting information), to give a total CH_4 emission of $54.6 \pm 15.5 \times 10^3$ kg CH_4 h^{-1} from oil and natural gas sources on 3 February 2012. The oil and gas wells whose emissions were estimated from our flight transect are almost entirely contained in Uintah County (Figure 1), so we calculate the amount of raw natural gas that would correspond to our estimated CH_4 emission and compare it to the average hourly natural gas production from Uintah County from both oil and gas wells (there is no coal bed CH_4 production in Uintah County). The total volume of natural gas produced from oil and gas wells in Uintah County in February 2012 was 7.1×10^8 m^3 (from the Utah Department of Natural Resources Division of Oil, Gas and Mining at https://fs.ogm.utah.gov/pub/Oil&Gas/Publications/Reports/Prod/County/), or 1.0×10^6 m^3 per hour on average. We convert our hourly CH_4 emissions estimate to natural gas units using a volume fraction of CH_4 in natural gas of 0.89 (composition profile for Uintah Basin raw natural gas from A. Bar-Ilan, personal communication, 2012) and the industry standard conditions (288.7 K and 101.3 kPa). Allowing for additional uncertainty on the production amount (estimated at 5% based on the average month-to-month variability in daily production) and on the composition of the emissions (estimated at 11% to encompass a realistic volume fraction of CH_4 from 0.79 to 0.99), the hourly emission rate we determined on 3 February 2012 corresponds to 6.2%–11.7% of the average hourly natural gas production from oil and gas wells in Uintah County during February 2012.

[16] Based on production data and publically available activity data, there is little evidence that emission magnitudes on 3 February were unusual relative to other days in January, February, or March 2012 (supplementary text section 6 in the supporting information and Figures S5 and S6). Furthermore, it should be noted that there are thousands of potential point sources (oil and gas wells, compressors, processing plants, etc.) in Uintah County and that there is no clear evidence in the data from our 12 flight days that a single point source is responsible for a large fraction of the emissions; we infer that it is unlikely that emissions differ drastically from one day to another. However, further work is needed to assess the variability of CH_4 emissions in this basin and to determine how representative our 1 day estimate is of Uintah's average natural gas leak rate.

4. Discussion

[17] Given the large global warming potential of CH_4, a natural gas leak rate of 6.2%–11.7% during production negates any short-term (<70 years) climate benefit of natural gas from this basin for electricity generation compared to coal and oil [*Alvarez et al.*, 2012; *Howarth et al.*, 2011]. This leakage also represents a potential economic loss and safety and air pollution hazard. An inventory analysis by the U.S. Government Accountability Office (GAO) suggests, however, that the fraction of natural gas emissions relative to production from the Uintah, a basin that produces approximately 1% of total U.S. natural gas, is atypical of many western U.S. basins. Using the Western Regional Air Partnership (WRAP) phase III [*Bar-Ilan et al.*, 2006] inventory and production numbers for 2006 from federal leases, the GAO estimates that the proportion of Uintah natural gas that is flared or vented is much greater (5% of production) than in surrounding regions, including the Denver-Julesburg (2.1%), Piceance (2.5%), N. San Juan (0.34%), and S. San Juan (1.13%) Basins [*Rusco*, 2010].

[18] The average leak rate we estimated from 3 February of $8.9 \pm 2.7\%$ is a factor of 1.8 greater than the GAO/WRAP bottom-up estimate (possibly more, as the GAO estimate of 5% included both flaring and venting; our measurements do not include CH_4 that is flared and converted to CO_2). Further measurements over several days and different

months and seasons would be necessary to evaluate the variability of emissions in Uintah County, because our result represents a snapshot of emissions from this region. Our result is consistent, however, with results from previous top-down studies of oil and gas production regions, which also found inventory estimates too low by similar factors [*Katzenstein et al*., 2003; *Pétron et al*., 2012]. More measurement-based evaluations of bottom-up inventories are needed to determine the consistency of results across different regions and determine trends in emissions that may result from increased production, new extraction techniques, or new regulations. Such independent verification of inventory-based estimates is essential for evaluating inventory methodologies, quantifying the effectiveness of future regulatory efforts, and accurately determining the climate impact of natural gas relative to other fossil fuels.

[19] **Acknowledgments.** This study would not have been possible without the support from participants of the 2012 Uintah Basin Winter Ozone and Air Quality Study, which was funded by Uintah Impact Mitigation Special Service District (UIMSSD), Western Energy Alliance, Bureau of Land Management (BLM), National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), National Science Foundation (NSF), and the State of Utah. We thank Ken Davis (Pennsylvania State University), Christopher Fairall (NOAA/PSD), Kelly Sours, Molly Crotwell, Jack Higgs, Don Neff, Doug Guenther, Carolina Siso, and Chris Carparelli (University of Colorado and NOAA/ESRL) for their assistance and contributions to this project.

[20] The Editor thanks Euan Nisbet and an anonymous reviewer for their assistance in evaluating this paper.

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Anthropogenic emissions of methane in the United States

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Edited by Mark H. Thiemens, University of California, San Diego, La Jolla, CA, and approved October 18, 2013 (received for review August 5, 2013)

This study quantitatively estimates the spatial distribution of anthropogenic methane sources in the United States by combining comprehensive atmospheric methane observations, extensive spatial datasets, and a high-resolution atmospheric transport model. Results show that current inventories from the US Environmental Protection Agency (EPA) and the Emissions Database for Global Atmospheric Research underestimate methane emissions nationally by a factor of ∼1.5 and ∼1.7, respectively. Our study indicates that emissions due to ruminants and manure are up to twice the magnitude of existing inventories. In addition, the discrepancy in methane source estimates is particularly pronounced in the south-central United States, where we find total emissions are ∼2.7 times greater than in most inventories and account for 24 ± 3% of national emissions. The spatial patterns of our emission fluxes and observed methane–propane correlations indicate that fossil fuel extraction and refining are major contributors (45 ± 13%) in the south-central United States. This result suggests that regional methane emissions due to fossil fuel extraction and processing could be 4.9 ± 2.6 times larger than in EDGAR, the most comprehensive global methane inventory. These results cast doubt on the US EPA's recent decision to downscale its estimate of national natural gas emissions by 25–30%. Overall, we conclude that methane emissions associated with both the animal husbandry and fossil fuel industries have larger greenhouse gas impacts than indicated by existing inventories.

climate change policy | geostatistical inverse modeling

Methane (CH_4) is the second most important anthropogenic greenhouse gas, with approximately one third the total radiative forcing of carbon dioxide (1). CH_4 also enhances the formation of surface ozone in populated areas, and thus higher global concentrations of CH_4 may significantly increase ground-level ozone in the Northern Hemisphere (2). Furthermore, methane affects the ability of the atmosphere to oxidize other pollutants and plays a role in water formation within the stratosphere (3).

Atmospheric concentrations of CH_4 [∼1,800 parts per billion (ppb)] are currently much higher than preindustrial levels (∼680–715 ppb) (1, 4). The global atmospheric burden started to rise rapidly in the 18th century and paused in the 1990s. Methane levels began to increase again more recently, potentially from a combination of increased anthropogenic and/or tropical wetland emissions (5–7). Debate continues, however, over the causes behind these recent trends (7, 8).

Anthropogenic emissions account for 50–65% of the global CH_4 budget of ∼395–427 teragrams of carbon per year $(TgC{\cdot}y)^{-1}$ (526–569 Tg CH_4) (7, 9). The US Environmental Protection Agency (EPA) estimates the principal anthropogenic sources in the United States to be (in order of importance) (*i*) livestock (enteric fermentation and manure management), (*ii*) natural gas production and distribution, (*iii*) landfills, and (*iv*) coal mining (10). EPA assesses human-associated emissions in the United States in 2008 at 22.1 TgC, roughly 5% of global emissions (10).

The amount of anthropogenic CH_4 emissions in the US and attributions by sector and region are controversial (Fig. 1). Bottom-up inventories from US EPA and the Emissions Database for Global Atmospheric Research (EDGAR) give totals ranging from 19.6 to 30 $TgC{\cdot}y^{-1}$ (10, 11). The most recent EPA and EDGAR inventories report lower US anthropogenic emissions compared with previous versions (decreased by 10% and 35%, respectively) (10, 12); this change primarily reflects lower, revised emissions estimates from natural gas and coal production Fig. S1. However, recent analysis of CH_4 data from aircraft estimates a higher budget of 32.4 ± 4.5 $TgC{\cdot}y^{-1}$ for 2004 (13). Furthermore, atmospheric observations indicate higher emissions in natural gas production areas (14–16); a steady 20-y increase in the number of US wells and newly-adopted horizontal drilling techniques may have further increased emissions in these regions (17, 18).

These disparities among bottom-up and top-down studies suggest much greater uncertainty in emissions than typically reported. For example, EPA cites an uncertainty of only ±13% for the for United States (10). Independent assessments of bottom-up inventories give error ranges of 50–100% (19, 20), and

Significance

Successful regulation of greenhouse gas emissions requires knowledge of current methane emission sources. Existing state regulations in California and Massachusetts require ∼15% greenhouse gas emissions reductions from current levels by 2020. However, government estimates for total US methane emissions may be biased by 50%, and estimates of individual source sectors are even more uncertain. This study uses atmospheric methane observations to reduce this level of uncertainty. We find greenhouse gas emissions from agriculture and fossil fuel extraction and processing (i.e., oil and/or natural gas) are likely a factor of two or greater than cited in existing studies. Effective national and state greenhouse gas reduction strategies may be difficult to develop without appropriate estimates of methane emissions from these source sectors.

Author contributions: S.M.M., S.C.W., and A.M.M. designed research; S.M.M., A.E.A., S.C.B., E.J.D., J.E., M.L.F., G.J.-M., B.R.M., J.B.M., S.A.M., T.N., and C.S. performed research; S.M.M. analyzed data; S.M.M., S.C.W., A.M.M., and E.A.K. wrote the paper; A.E.A., S.C.B., E.J.D., M.L.F., B.R.M., J.B.M., S.A.M., and C.S. collected atmospheric methane data; and J.E. and T.N. developed meteorological simulations using the Weather Research and Forecasting model.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1314392110/-/DCSupplemental.

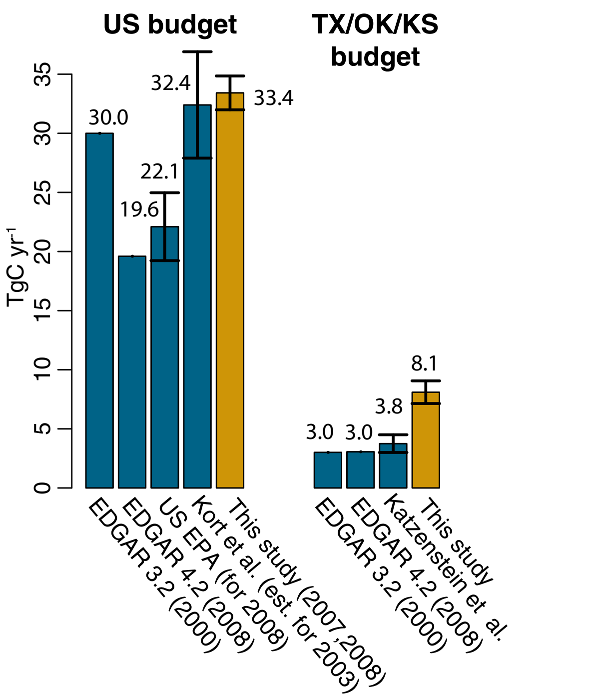

Fig. 1. US anthropogenic methane budgets from this study, from previous top-down estimates, and from existing emissions inventories. The south-central United States includes Texas, Oklahoma, and Kansas. US EPA estimates only national, not regional, emissions budgets. Furthermore, national budget estimates from EDGAR, EPA, and Kort et al. (13) include Alaska and Hawaii whereas this study does not.

values from Kort et al. are 47 ± 20% higher than EPA (13). Assessments of CH_4 sources to inform policy (e.g., regulating emissions or managing energy resources) require more accurate, verified estimates for the United States.

This study estimates anthropogenic CH_4 emissions over the United States for 2007 and 2008 using comprehensive CH_4 observations at the surface, on telecommunications towers, and from aircraft, combined with an atmospheric transport model and a geostatistical inverse modeling (GIM) framework. We use auxiliary spatial data (e.g., on population density and economic activity) and leverage concurrent measurements of alkanes to help attribute emissions to specific economic sectors. The work provides spatially resolved CH_4 emissions estimates and associated uncertainties, as well as information by source sector, both previously unavailable.

Model and Observation Framework

We use the Stochastic Time-Inverted Lagrangian Transport model (STILT) to calculate the transport of CH_4 from emission points at the ground to measurement locations in the atmosphere (21). STILT follows an ensemble of particles backward in time, starting from each observation site, using wind fields and turbulence modeled by the Weather Research and Forecasting (WRF) model (22). STILT derives an influence function ("footprint," units: ppb CH_4 per unit emission flux) linking upwind emissions to each measurement. Inputs of CH_4 from surface sources along the ensemble of back-trajectories are averaged to compute the CH_4 concentration for comparison with each observation.

We use observations for 2007 and 2008 from diverse locations and measurement platforms. The principal observations derive from daily flask samples on tall towers (4,984 total observations) and vertical profiles from aircraft (7,710 observations). Tower-based observations are collected as part of the National Oceanic and Atmospheric (NOAA)/Department of Energy (DOE) cooperative air sampling network, and aircraft-based data are obtained from regular NOAA flights (23), regular DOE flights (24), and from the Stratosphere-Troposphere Analyses of Regional Transport 2008 (START08) aircraft campaign (25); all data are publicly available from NOAA and DOE. These observations are displayed in Fig. 2 and discussed further in the *SI Text* (e.g., Fig. S2). We use a GIM framework (26, 27) to analyze the footprints for each of the 12,694 observations, and these footprints vary by site and with wind conditions. In aggregate, the footprints provide spatially resolved coverage of most of the continental United States, except the southeast coastal region (Fig. S3).

The GIM framework, using footprints and concentration measurements, optimizes CH_4 sources separately for each month of 2007 and 2008 on a 1° × 1° latitude–longitude grid for the United States. The contributions of fluxes from natural wetlands are modeled first and subtracted from the observed CH_4 (2.0 $TgC \cdot y^{-1}$ for the continental United States); these fluxes are much smaller than anthropogenic sources in the United States and thus would be difficult to independently constrain from atmospheric data (*SI Text*).

The GIM framework represents the flux distribution for each month using a deterministic spatial model plus a stochastic spatially correlated residual, both estimated from the atmospheric observations. The deterministic component is given by a weighted linear combination of spatial activity data from the EDGAR 4.2 inventory; these datasets include any economic or demographic data that may predict the distribution of CH_4 emissions (e.g., gas production, human and ruminant population densities, etc.). Both the selection of the activity datasets to be retained in the model and the associated weights (emission factors) are optimized to best match observed CH_4 concentrations. Initially, seven activity datasets are included from EDGAR 4.2, (*i*) population, (*ii*) electricity production from power plants, (*iii*) ruminant population count, (*iv*) oil and conventional gas production, (*v*) oil refinery production, (*vi*) rice production, and (*vii*) coal production.

We select the minimum number of datasets with the greatest predictive ability using the Bayesian Information Criterion (BIC) (*SI Text*) (28). BIC numerically scores all combinations of available datasets based on how well they improve goodness of fit and applies a penalty that increases with the number of datasets retained.

The stochastic component represents sources that do not fit the spatial patterns of the activity data (Fig. S4). GIM uses

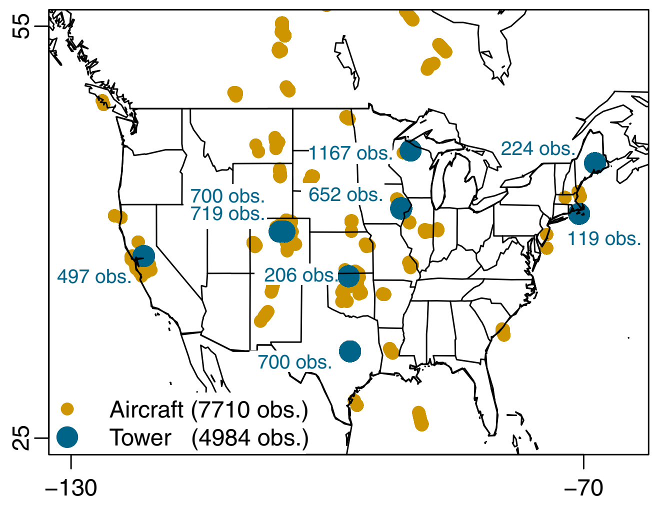

Fig. 2. CH_4 concentration measurements from 2007 and 2008 and the number of observations associated with each measurement type. Blue text lists the number of observations associated with each stationary tower measurement site.

a covariance function to describe the spatial and temporal correlation of the stochastic component and optimizes its spatial and temporal distribution simultaneously with the optimization of the activity datasets in the deterministic component (*SI Text*, Fig. S5) (26–28). Because of the stochastic component, the final emissions estimate can have a different spatial and temporal distribution from any combination of the activity data.

If the observation network is sensitive to a broad array of different source sectors and/or if the spatial activity maps are effective at explaining those sources, many activity datasets will be included in the deterministic model. If the deterministic model explains the observations well, the magnitude of CH_4 emissions in the stochastic component will be small, the assignment to specific sectors will be unambiguous, and uncertainties in the emissions estimates will be small. This result is not the case here, as discussed below (see *Results*).

A number of previous studies used top-down methods to constrain anthropogenic CH_4 sources from global (29–33) to regional (13–15, 34–38) scales over North America. Most regional studies adopted one of three approaches: use a simple box model to estimate an overall CH_4 budget (14), estimate a budget using the relative ratios of different gases (15, 37–39), or estimate scaling factors for inventories by region or source type (13, 34–36). The first two methods do not usually give explicit information about geographic distribution. The last approach provides information about the geographic distribution of sources, but results hinge on the spatial accuracy of the underlying regional or sectoral emissions inventories (40).

Here, we are able to provide more insight into the spatial distribution of emissions; like the scaling factor method above, we leverage spatial information about source sectors from an existing inventory, but in addition we estimate the distribution of emissions where the inventory is deficient. We further bolster attribution of regional emissions from the energy industry using the observed correlation of CH_4 and propane, a gas not produced by biogenic processes like livestock and landfills.

Results

Spatial Distribution of CH_4 Emissions. Fig. 3 displays the result of the 2-y mean of the monthly CH_4 inversions and differences from the EDGAR 4.2 inventory. We find emissions for the United States that are a factor of 1.7 larger than the EDGAR inventory. The optimized emissions estimated by this study bring the model closer in line with the observations (Fig. 4, Figs. S6 and S7). Posterior emissions fit the CH_4 observations [$R^2 = 0.64$, root mean square error (RMSE) = 31 ppb] much better than EDGAR v4.2 ($R^2 = 0.23$, RMSE = 49 ppb). Evidently, the spatial distribution of EDGAR sources is inconsistent with emissions patterns implied by the CH_4 measurements and associated footprints.

Several diagnostic measures preclude the possibility of major systematic errors in WRF–STILT. First, excellent agreement between the model and measured vertical profiles from aircraft implies little bias in modeled vertical air mixing (e.g., boundary-layer heights) (Fig. 4). Second, the monthly posterior emissions estimated by the inversion lack statistically significant seasonality (Fig. S8). This result implies that seasonally varying weather patterns do not produce detectable biases in WRF–STILT. *SI Text* discusses possible model errors and biases in greater detail.

CH_4 observations are sparse over parts of the southern and central East Coast and in the Pacific Northwest. Emissions estimates for these regions therefore rely more strongly on the deterministic component of the flux model, with weights constrained primarily by observations elsewhere. Therefore, emissions in these areas, including from coal mining, are poorly constrained (*SI Text*).

Contribution of Different Source Sectors. Only two spatial activity datasets from EDGAR 4.2 are selected through the BIC as meaningful predictors of CH_4 observations over the United States: population densities of humans and of ruminants (Table S1). Some sectors are eliminated by the BIC because emissions are situated far from observation sites (e.g., coal mining in West Virginia or Pennsylvania), making available CH_4 data insensitive to these predictors. Other sectors may strongly affect observed concentrations but are not selected, indicating that the spatial datasets from EDGAR are poor predictors for the distribution of observed concentrations (e.g., oil and natural gas extraction and oil refining). Sources from these sectors appear in the stochastic component of the GIM (*SI Text*).

The results imply that existing inventories underestimate emissions from two key sectors: ruminants and fossil fuel extraction and/or processing, discussed in the remainder of this section.

We use the optimized ruminant activity dataset to estimate the magnitude of emissions with spatial patterns similar to animal husbandry and manure. Our corresponding US budget of 12.7 ± 5.0 $TgC{\cdot}y^{-1}$ is nearly twice that of EDGAR and EPA (6.7 and 7.0, respectively). The total posterior emissions estimate over the northern plains, a region with high ruminant density but little fossil fuel extraction, further supports the ruminant estimate (Nebraska, Iowa, Wisconsin, Minnesota, and South Dakota). Our total budget for this region of 3.4 ± 0.7 compares with 1.5 $TgC{\cdot}y^{-1}$ in EDGAR. Ruminants and agriculture may also be

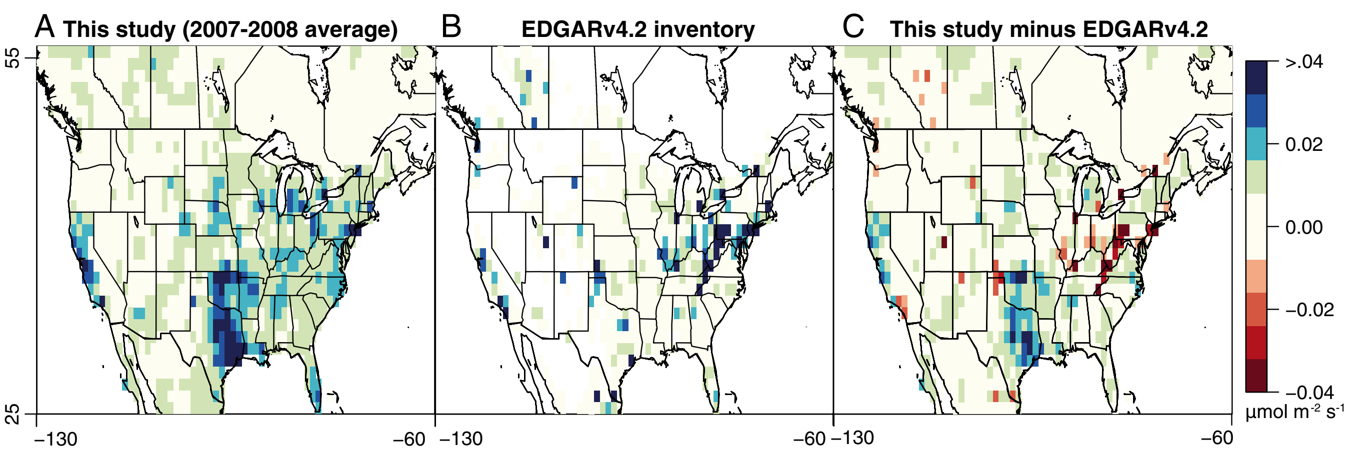

Fig. 3. The 2-y averaged CH_4 emissions estimated in this study (*A*) compared against the commonly used EDGAR 4.2 inventory (*B* and *C*). Emissions estimated in this study are greater than in EDGAR 4.2, especially near Texas and California.

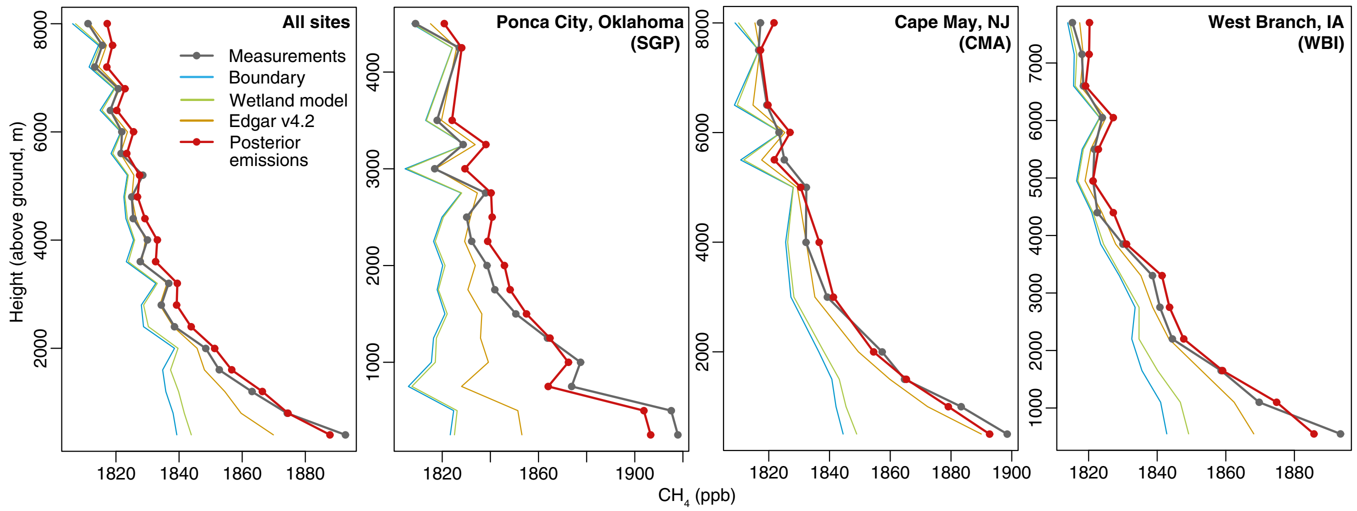

Fig. 4. A model–measurement comparison at several regular NOAA/DOE aircraft monitoring sites (averaged over 2007–2008). Plots include the measurements; the modeled boundary condition; the summed boundary condition and wetland contribution (from the Kaplan model); and the summed boundary, wetland, and anthropogenic contributions (from EDGAR v4.2 and the posterior emissions estimate).

partially responsible for high emissions over California (41). EDGAR activity datasets are poor over California (42), but several recent studies (34, 36–38, 41) have provided detailed top-down emissions estimates for the state using datasets from state agencies.

Existing inventories also greatly underestimate CH_4 sources from the south-central United States (Fig. 3). We find the total CH_4 source from Texas, Oklahoma, and Kansas to be 8.1 ± 0.96 TgC·y^{-1}, a factor of 2.7 higher than the EDGAR inventory. These three states alone constitute ~24 ± 3% of the total US anthropogenic CH_4 budget or 3.7% of net US greenhouse gas emissions [in CO_2 equivalents (10)].

Texas and Oklahoma were among the top five natural gas producing states in the country in 2007 (18), and aircraft observations of alkanes indicate that the natural gas and/or oil industries play a significant role in regional CH_4 emissions. Concentrations of propane (C_3H_8), a tracer of fossil hydrocarbons (43), are strongly correlated with CH_4 at NOAA/DOE aircraft monitoring locations over Texas and Oklahoma ($R^2 = 0.72$) (Fig. 5). Correlations are much weaker at other locations in North America ($R^2 = 0.11$ to 0.64).

We can obtain an approximate CH_4 budget for fossil-fuel extraction in the region by subtracting the optimized contributions associated with ruminants and population from the total emissions. The residual (Fig. S4*C*) represents sources that have spatial patterns not correlated with either human or ruminant density in EDGAR. Our budget sums to 3.7 ± 2.0 TgC·y^{-1}, a factor of 4.9 ± 2.6 larger than oil and gas emissions in EDGAR v4.2 (0.75 TgC·y^{-1}) and a factor of 6.7 ± 3.6 greater than EDGAR sources from solid waste facilities (0.55 TgC·y^{-1}), the two major sources that may not be accounted for in the deterministic component. The population component likely captures a portion of the solid waste sources so this residual methane budget more likely represents natural gas and oil emissions than landfills. *SI Text* discusses in detail the uncertainties in this sector-based emissions estimate. We currently do not have the detailed, accurate, and spatially resolved activity data (fossil fuel extraction and processing, ruminants, solid waste) that would provide more accurate sectorial attribution.

Katzenstein et al. (2003) (14) were the first to report large regional emissions of CH_4 from Texas, Oklahoma, and Kansas; they cover an earlier time period (1999–2002) than this study. They used a box model and 261 near-ground CH_4 measurements taken over 6 d to estimate a total Texas–Oklahoma–Kansas CH_4 budget (from all sectors) of 3.8 ± 0.75 TgC·y^{-1}. We revise their

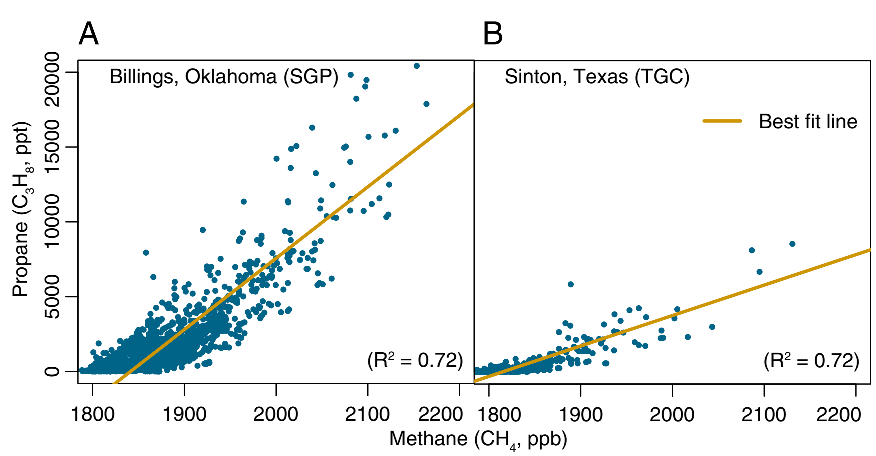

Fig. 5. Correlations between propane and CH_4 at NOAA/DOE aircraft observation sites in Oklahoma (*A*) and Texas (*B*) over 2007–2012. Correlations are higher in these locations than at any other North American sites, indicating large contributions of fossil fuel extraction and processing to CH_4 emitted in this region.

estimate upward by a factor of two based on the inverse model and many more measurements from different platforms over two full years of data. *SI Text* further compares the CH_4 estimate in Katzenstein et al. and in this study.

Discussion and Summary

This study combines comprehensive atmospheric data, diverse datasets from the EDGAR inventory, and an inverse modeling framework to derive spatially resolved CH_4 emissions and information on key source sectors. We estimate a mean annual US anthropogenic CH_4 budget for 2007 and 2008 of 33.4 ± 1.4 $TgC{\cdot}y^{-1}$ or ~7–8% of the total global CH_4 source. This estimate is a factor of 1.5 and 1.7 larger than EPA and EDGAR v4.2, respectively. CH_4 emissions from Texas, Oklahoma, and Kansas alone account for 24% of US methane emissions, or 3.7% of the total US greenhouse gas budget.

The results indicate that drilling, processing, and refining activities over the south-central United States have emissions as much as 4.9 ± 2.6 times larger than EDGAR, and livestock operations across the US have emissions approximately twice that of recent inventories. The US EPA recently decreased its CH_4 emission factors for fossil fuel extraction and processing by 25–30% (for 1990–2011) (10), but we find that CH_4 data from across North America instead indicate the need for a larger adjustment of the opposite sign.

ACKNOWLEDGMENTS. For advice and support, we thank Roisin Commane, Elaine Gottlieb, and Matthew Hayek (Harvard University); Robert Harriss (Environmental Defense Fund); Hanqin Tian and Bowen Zhang (Auburn University); Jed Kaplan (Ecole Polytechnique Fédérale de Lausanne); Kimberly Mueller and Christopher Weber (Institute for Defense Analyses Science and Technology Policy Institute); Nadia Oussayef; and Gregory Berger. In addition, we thank the National Aeronautics and Space Administration (NASA) Advanced Supercomputing Division for computing help; P. Lang, K. Sours, and C. Siso for analysis of National Oceanic and Atmospheric Administration (NOAA) flasks; and B. Hall for calibration standards work. This work was supported by the American Meteorological Society Graduate Student Fellowship/Department of Energy (DOE) Atmospheric Radiation Measurement Program, a DOE Computational Science Graduate Fellowship, and the National Science Foundation Graduate Research Fellowship Program. NOAA measurements were funded in part by the Atmospheric Composition and Climate Program and the Carbon Cycle Program of NOAA's Climate Program Office. Support for this research was provided by NASA Grants NNX08AR47G and NNX11AG47G, NOAA Grants NA09OAR4310122 and NA11OAR4310158, National Science Foundaton (NSF) Grant ATM-0628575, and Environmental Defense Fund Grant 0146-10100 (to Harvard University). Measurements at Walnut Grove were supported in part by a California Energy Commission Public Interest Environmental Research Program grant to Lawrence Berkeley National Laboratory through the US Department of Energy under Contract DE-AC02-05CH11231. DOE flights were supported by the Office of Biological and Environmental Research of the US Department of Energy under Contract DE-AC02-05CH11231 as part of the Atmospheric Radiation Measurement Program (ARM), ARM Aerial Facility, and Terrestrial Ecosystem Science Program. Weather Research and Forecasting–Stochastic Time-Inverted Lagrangian Transport model development at Atmospheric and Environmental Research has been funded by NSF Grant ATM-0836153, NASA, NOAA, and the US intelligence community.

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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, D04304, doi:10.1029/2011JD016360, 2012

Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study

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Received 3 June 2011; revised 19 December 2011; accepted 20 December 2011; published 21 February 2012.

[1] The multispecies analysis of daily air samples collected at the NOAA Boulder Atmospheric Observatory (BAO) in Weld County in northeastern Colorado since 2007 shows highly correlated alkane enhancements caused by a regionally distributed mix of sources in the Denver-Julesburg Basin. To further characterize the emissions of methane and non-methane hydrocarbons (propane, n-butane, i-pentane, n-pentane and benzene) around BAO, a pilot study involving automobile-based surveys was carried out during the summer of 2008. A mix of venting emissions (leaks) of raw natural gas and flashing emissions from condensate storage tanks can explain the alkane ratios we observe in air masses impacted by oil and gas operations in northeastern Colorado. Using the WRAP Phase III inventory of total volatile organic compound (VOC) emissions from oil and gas exploration, production and processing, together with flashing and venting emission speciation profiles provided by State agencies or the oil and gas industry, we derive a range of bottom-up speciated emissions for Weld County in 2008. We use the observed ambient molar ratios and flashing and venting emissions data to calculate top-down scenarios for the amount of natural gas leaked to the atmosphere and the associated methane and non-methane emissions. Our analysis suggests that the emissions of the species we measured are most likely underestimated in current inventories and that the uncertainties attached to these estimates can be as high as a factor of two.

Citation: Pétron, G., et al. (2012), Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study, *J. Geophys. Res.*, *117*, D04304, doi:10.1029/2011JD016360.

1. Introduction

[2] Since 2004, the National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA ESRL) has increased its measurement network density over North America, with continuous carbon dioxide (CO_2) and carbon monoxide (CO) measurements and daily collection of discrete air samples at a network of tall towers (A. E. Andrews et al., manuscript in preparation, 2012) and bi-weekly discrete air sampling along vertical aircraft profiles (C. Sweeney et al., manuscript in preparation, 2012). Close to 60 chemical species or isotopes are measured in the discrete air samples, including long-lived greenhouse gases (GHGs) such as CO_2, methane (CH_4), nitrous oxide (N_2O), and sulfur hexafluoride (SF_6), tropospheric ozone precursors such as CO and several volatile organic compounds (VOCs), and stratospheric-ozone-depleting substances. The NOAA multispecies regional data set provides unique information on how important atmospheric trace gases vary in space and time over the continent, and it can be used to quantify how different processes contribute to GHG burdens and/or affect regional air quality.

[3] In this study we focus our analysis on a very strong alkane atmospheric signature observed downwind of the Denver-Julesburg Fossil Fuel Basin (DJB) in the Colorado Northern Front Range (Figure 1 and auxiliary material

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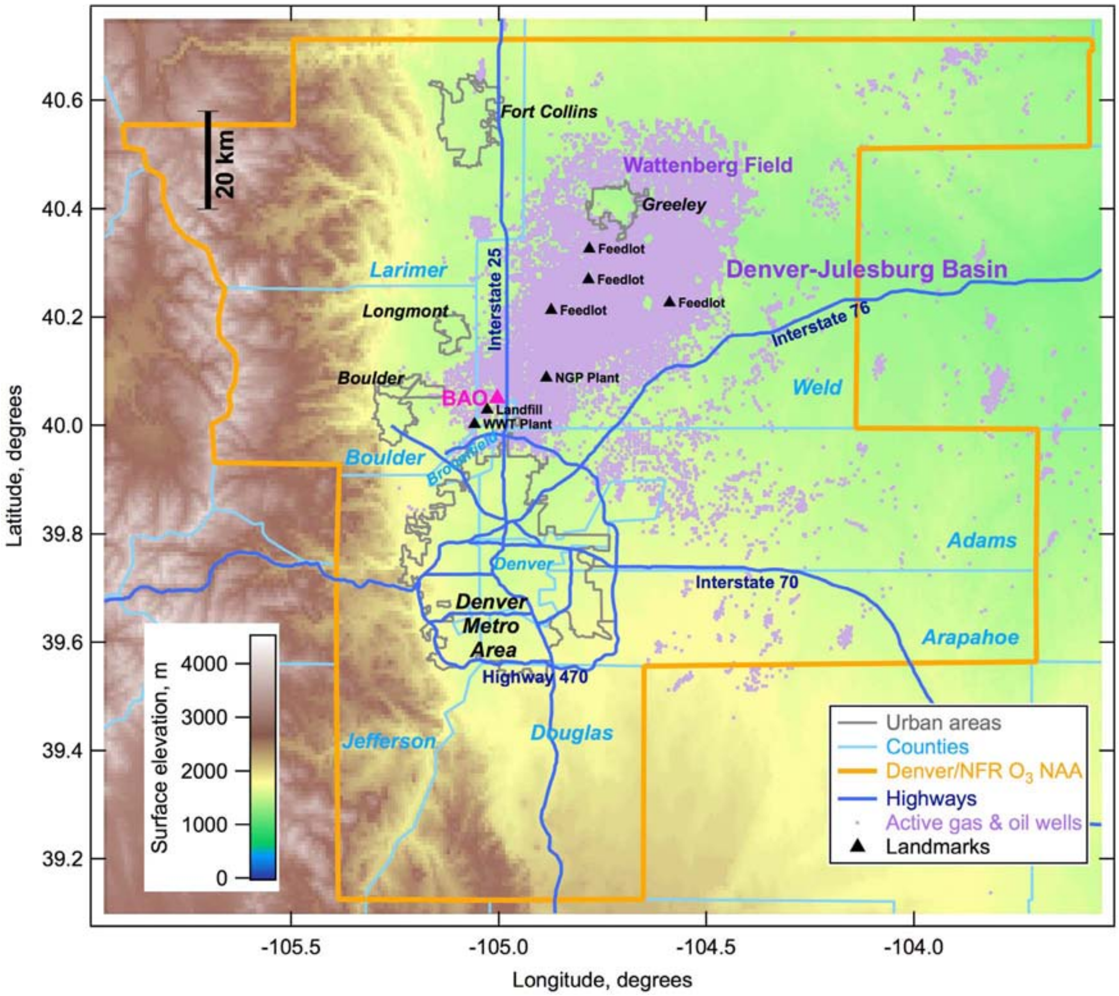

Figure 1. Map of the study area centered on the Boulder Atmospheric Observatory (BAO), located 25 km east-northeast of Boulder. Overlaid on this map are the locations of active oil and gas wells (light purple dots) as of April 2008 (data courtesy of SkyTruth, http://blog.skytruth.org/2008/06/colorado-all-natural-gas-and-oil-wells.html, based on COGCC well data). Also shown are the locations of landmarks used in the study, including selected point sources (NGP Plant = natural gas processing plant, WWT Plant = Lafayette wastewater treatment plant).

Figure S1).[1] In 2008, the DJB was home to over 20,000 active natural gas and condensate wells. Over 90% of the production in 2008 came from tight gas formations.

[4] A few recent studies have looked at the impact of oil and gas operations on air composition at the local and regional scales in North America. *Katzenstein et al.* [2003] reported results of two intensive surface air discrete sampling efforts over the Anadarko Fossil Fuel Basin in the southwestern United States in 2002. Their analysis revealed substantial regional atmospheric CH_4 and non-methane hydrocarbon (NMHC) pollution over parts of Texas, Oklahoma, and Kansas, which they attributed to emissions from the oil and gas industry operations. More recently, *Schnell et al.* [2009] observed very high wintertime ozone levels in the vicinity of the Jonah-Pinedale Anticline natural gas field in western Wyoming. *Ryerson et al.* [2003], *Wert et al.* [2003], *de Gouw et al.* [2009] and *Mellqvist et al.* [2010] reported elevated emissions of alkenes from petrochemical plants and refineries in the Houston area and studied their contribution to ozone formation. *Simpson et al.* [2010] present an extensive analysis of atmospheric mixing ratios for a long list of trace gases over oil sands mining operations in Alberta during one flight of the 2008 Arctic Research of the Composition of the Troposphere from Aircraft and Satellites campaign. Our study distinguishes itself from previous ones by the fact that it relies substantially on the analysis of daily air samples collected at a single tall-tower monitoring site between August 2007 and April 2010.

[5] Colorado has a long history of fossil fuel extraction [*Scamehorn*, 2002]. Colorado natural gas production has been increasing since the 1980s, and its share of national production jumped from 3% in 2000 to 5.4% in 2008. 1.3% of the nationally produced oil in 2008 also came from Colorado, primarily from the DJB in northeastern Colorado and from the Piceance Basin in western Colorado. As of

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011JD016360.

2004, Colorado also contained 43 natural gas processing plants, representing 3.5% of the conterminous U.S. processing capacity [*U.S. Energy Information Administration* (*EIA*), 2006], and two oil refineries, located in Commerce City, in Adams County just north of Denver.

[6] Emissions management requirements for both air quality and climate-relevant gases have led the state of Colorado to build detailed baseline emissions inventories for ozone precursors, including volatile organic compounds (VOCs), and for GHGs. Since 2004, a large fraction of the Colorado Northern Front Range, including Weld County and the Denver metropolitan area, has been in violation of the 8-h ozone national ambient air quality standard [*Colorado Department of Public Health and Environment* (*CDPHE*), 2008]. In December 2007, the Denver and Colorado Northern Front Range (DNFR) region was officially designated as a Federal Non-Attainment Area (NAA) for repeated violation in the summertime of the ozone National Ambient Air Quality Standard (see area encompassed by golden boundary in Figure 1). At the end of 2007, Colorado also adopted a Climate Action Plan, which sets greenhouse gas emissions reduction targets for the state [*Ritter*, 2007].

[7] Methane, a strong greenhouse gas with a global warming potential (GWP) of 25 over a 100 yr time horizon [*Intergovernmental Panel on Climate Change*, 2007], accounts for a significant fraction of Colorado GHG emissions, estimated at 14% in 2005 (*Strait et al.* [2007] and auxiliary material Table S1; note that in this report, the oil and gas industry CH_4 emission estimates were calculated with the EPA State Greenhouse Gas Inventory Tool). The natural gas industry (including exploration, production, processing, transmission and distribution) is the single largest source of CH_4 in the state of Colorado (estimated at 238 Gg/yr or ktonnes/yr), followed closely by coal mining (233 Gg/yr); note that all operating surface and underground coal mines are now in western Colorado. Emission estimates for oil production operations in the state were much lower, at 9.5 Gg/yr, than those from gas production. In 2005, Weld County represented 16.5% of the state's natural gas production and 51% of the state crude oil/ natural gas condensate production (auxiliary material Table S2). Scaling the state's total CH_4 emission estimates from *Strait et al.* [2007], rough estimates for the 2005 CH_4 source from natural gas production and processing operations and from natural gas condensate/oil production in Weld County are 19.6 Gg and 4.8 Gg, respectively. It is important to stress here that there are large uncertainties associated with these inventory-derived estimates.

[8] Other important sources of CH_4 in the state include large open-air cattle feedlots, landfills, wastewater treatment facilities, forest fires, and agriculture waste burning, which are all difficult to quantify. 2005 state total CH_4 emissions from enteric fermentation and manure management were estimated at 143 and 48 Gg/yr, respectively [*Strait et al.*, 2007]; this combined source is of comparable magnitude to the estimate from natural gas systems. On-road transportation is not a substantial source of methane [*Nam et al.*, 2004].

[9] In 2006, forty percent of the DNFR NAA's total anthropogenic VOC emissions were estimated to be due to oil and gas operations [*CDPHE*, 2008]. Over the past few years, the State of Colorado has adopted more stringent VOC emission controls for oil and gas exploration and processing activities. In 2007, the Independent Petroleum Association of Mountain States (IPAMS, now Western Energy Alliance), in conjunction with the Western Regional Air Partnership (WRAP), funded a working group to build a state-of-the-knowledge process-based inventory of total VOC and NOx sources involved in oil and gas exploration, production and gathering activities for the western United State's fossil fuel basins, hereafter referred to as the WRAP Phase III effort (http://www.wrapair.org/forums/ogwg/index.html). Most of the oil and gas production in the DJB is concentrated in Weld County. Large and small condensate storage tanks in the County are estimated to be the largest VOC fossil fuel production source category (59% and 9% respectively), followed by pneumatic devices (valve controllers) and unpermitted fugitives emissions (13% and 9% respectively). A detailed breakdown of the WRAP oil and gas source contributions is shown in auxiliary material Figure S2 for 2006 emissions and projected 2010 emissions [*Bar-Ilan et al.*, 2008a, 2008b]. The EPA NEI 2005 for Weld County, used until recently by most air quality modelers, did not include VOC sources from oil and natural gas operations (auxiliary material Table S3).

[10] Benzene (C_6H_6) is a known human carcinogen and it is one of the 188 hazardous air pollutants (HAPs) tracked by the EPA National Air Toxics Assessment (NATA). Benzene, like VOCs and CH_4, can be released at many different stages of oil and gas production and processing. Natural gas itself can contain varying amounts of aromatic hydrocarbons, including C_6H_6 [*U. S. Environmental Protection Agency* (*EPA*), 1998]. Natural gas associated with oil production (such sources are located in several places around the DJB) usually has higher C_6H_6 levels [*Burns*, 1999] than non-associated natural gas. Glycol dehydrators used at wells and processing facilities to remove water from pumped natural gas can vent large amounts of C_6H_6 to the atmosphere when the glycol undergoes regeneration [*EPA*, 1998]. Condensate tanks, venting and flaring at the wellheads, compressors, processing plants, and engine exhaust are also known sources of C_6H_6 [*EPA*, 1998]. C_6H_6 can also be present in the liquids used for fracturing wells [*EPA*, 2004].

[11] In this paper, we focus on describing and interpreting the measured variability in CH_4 and C_{3-5} alkanes observed in the Colorado Northern Front Range. We use data from daily air samples collected at a NOAA tall tower located in Weld County as well as continuous CH_4 observations and discrete targeted samples from an intensive mobile sampling campaign in the Colorado Northern Front Range. These atmospheric measurements are then used together with other emissions data sets to provide an independent view of methane and non-methane hydrocarbon emissions inventory results.

[12] The paper is organized as follows. Section 2 describes the study design and sampling methods. Section 3 presents results from the tall tower and the Mobile Lab surveys, in particular the strong correlation among the various alkanes measured. Based on the multispecies analysis in the discrete air samples, we were able to identify two major sources of C_6H_6 in Weld County. In section 4.1 we discuss the results and in section 4.2 we compare the observed ambient molar ratios with other relevant data sets, including raw natural gas composition data from 77 gas wells in the DJB. The last discussion section 4.3, is an attempt to shed new light on

Table 1. Locations of a Subset of the NOAA ESRL Towers and Aircraft Profile Sites Used in This Study[a]

Site Code	City	State	Latitude (°N)	Longitude (°E)	Elevation (Meters Above Sea Level)	Sampling Height (Meters Above Ground)
BAO	Erie	Colorado	40.05	105.01	1584	300
LEF	Park Falls	Wisconsin	45.93	90.27	472	396
NWF	Niwot Ridge	Colorado	40.03	105.55	3050	23
STR	San Francisco	California	37.755	122.45	254	232
WGC	Walnut Grove	California	38.26	121.49	0	91
WKT	Moody	Texas	31.32	97.33	251	457
SGP[b]	Southern Great Plains	Oklahoma	36.80	97.50	314	<650

[a]STR and WGC in Northern California are collaborations with Department of Energy Environmental Energy Technologies Division at Lawrence Berkeley National Laboratory (PI: Marc Fischer). The last column gives the altitudes of the quasi-daily flask air samples used in this study. We use midday data for all sites, but at Niwot Ridge Forest we used nighttime data to capture background air from summertime downslope flow. We also show the location information of SGP, a NOAA ESRL aircraft site in north central Oklahoma, for which we used samples taken below 650 m altitude.

[b]Aircraft discrete air samples.

methane and VOC emission estimates from oil and gas operations in Weld County. We first describe how we derived speciated bottom-up emission estimates based on the WRAP Phase III total VOC emission inventories for counties in the DJB. We then used (1) an average ambient propane-to-methane molar ratio, (2) a set of bottom-up estimates of propane and methane flashing emissions in Weld County and (3) three different estimates of the propane-to-methane molar ratio for the raw gas leaks to build top-down methane and propane emission scenarios for venting sources in the county. We also scaled the top-down propane (C_3H_8) estimates with the observed ambient alkane ratios to calculate top-down emission estimates for n-butane (n-C_4H_{10}), i- and n-pentane (i-C_5H_{12}, n-C_5H_{12}), and benzene. We summarize our main conclusions in section 5.

2. The Front Range Emissions Study: Sampling Strategy, Instrumentation, and Sample Analysis

2.1. Overall Experimental Design

[13] The Colorado Northern Front Range study was a pilot project to design and test a new measurement strategy to characterize GHG emissions at the regional level. The anchor of the study was a 300-m tall tower located in Weld County, 25 km east-northeast of Boulder and 35 km north of Denver, called the Boulder Atmospheric Observatory (BAO) [40.05°N, 105.01°W; base of tower at 1584 m above sea level] (Figure 1). The BAO is situated on the southwestern edge of the DJB. A large landfill and a wastewater treatment plant are located a few kilometers southwest of BAO. Interstate 25, a major highway going through Denver, runs in a north-south direction 2 km east of the site. Both continuous and discrete air sampling have been conducted at BAO since 2007.

[14] To put the BAO air samples into a larger regional context and to better understand the sources that impacted the discrete air samples, we made automobile-based on-road air sampling surveys around the Colorado Northern Front Range in June and July 2008 with an instrumented "Mobile Lab" and the same discrete sampling apparatus used at all the NOAA towers and aircraft sampling sites.

2.2. BAO and Other NOAA Cooperative Tall Towers

[15] The BAO tall tower has been used as a research facility of boundary layer dynamics since the 1970s [*Kaimal and Gaynor*, 1983]. The BAO tower was instrumented by the NOAA ESRL Global Monitoring Division (GMD) in Boulder in April 2007, with sampling by a quasi-continuous CO_2 non-dispersive infrared sensor and a CO Gas Filter Correlation instrument, both oscillating between three intake levels (22, 100 and 300 m above ground level) (Andrews et al., manuscript in preparation, 2012). Two continuous ozone UV-absorption instruments have also been deployed to monitor ozone at the surface and at the 300-m level.

[16] The tower is equipped to collect discrete air samples from the 300-m level using a programmable compressor package (PCP) and a programmable flasks package (PFP) described later in section 2.4. Since August 2007 one or two air samples have been taken approximately daily in glass flasks using PFPs and a PCP. The air samples are brought back to GMD for analysis on three different systems to measure a series of compounds, including methane (CH_4, also referred to as C_1), CO, propane (C_3H_8, also referred to as C_3), n-butane (n-C_4H_{10}, nC_4), isopentane (i-C_5H_{12}, iC_5), n-pentane (n-C_5H_{12}, nC_5), acetylene (C_2H_2), benzene, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). Ethane and i-butane were not measured.

[17] In this study, we use the results from the NOAA GMD multispecies analysis of air samples collected midday at the 300-m level together with 30- second wind speed and direction measured at 300-m. 30-min averages of the wind speed and direction prior to the collection time of each flask are used to separate samples of air masses coming from three different geographic sectors: the North and East (NE sector), where the majority of the DJB oil and gas wells are located; the South (S sector), mostly influenced by the Denver metropolitan area; and the West (W sector), with relatively cleaner air.

[18] In 2008, NOAA and its collaborators were operating a regional air sampling network of eight towers and 18 aircraft profiling sites located across the continental U.S. employing in situ measurements (most towers) and flask sampling protocols (towers and aircraft sites) that were similar to those used at BAO. Median mixing ratios for several alkanes, benzene, acetylene, and carbon monoxide from BAO and a subset of five other NOAA towers and from one aircraft site are presented in the Results (section 3). Table 1 provides the three letter codes used for each sampling site, their locations and sampling heights. STR is located in San Francisco. WGC is located 34 km south of downtown Sacramento in California's Central Valley where

Table 2. List of the Front Range Mobile Lab Measurement and Flasks Sampling Surveys[a]

Road Survey Number	Road Survey Date	Geographical Area/Target Sources	Measurements/Sampling Technique
1	June 4	Boulder	12 flasks
2	June 11	Boulder + Foothills	12 flasks
3	June 19	NOAA-Longmont-Fort Collins- Greeley (Oil and Gas Drilling, Feedlots)	24 flasks
4	July 1	NOAA - Denver	12 flasks
5	July 9	Around Denver	Picarro
6	July 14	NOAA - Greeley	12 flasks
7	July 15	NOAA-Greeley	Picarro
8	July 25	BAO surroundings - Natural Gas Processing Plant - Feedlot	Picarro + 8 flasks
9	July 31	"Regional" CH_4 enhancements, Landfill, Corn field	Picarro + 12 flasks

[a]Some trips (1, 2, 3, 4, 6) sampled air using the flask only. Surveys 5 and 7 used only the continuous analyzers on the Mobile Lab with no discrete flask collection. The last two trips targeted flask sampling close to known point or area sources based on the continuous methane measurement display in the Mobile Lab.

agriculture is the main economic sector. Irrigated crop fields and feedlots contribute to the higher CH_4 observed at WGC. The LEF tower in northern Wisconsin is in the middle of the Chequamegon National Forest which is a mix of temperate/boreal forest and lowlands/wetlands [*Werner et al.*, 2003]. Air samples from NWF (surface elevation 3050 m), in the Colorado Rocky Mountains, mostly reflect relatively unpolluted air from the free troposphere. The 457m tall Texas tower (WKT) is located between Dallas/Fort Worth and Austin. It often samples air masses from the surrounding metropolitan areas. In summer especially, it also detects air masses with cleaner background levels arriving from the Gulf of Mexico. The SGP NOAA aircraft sampling site (Sweeney et al., manuscript in preparation, 2012; http://www.esrl.noaa.gov/gmd/ccgg/aircraft/) in northern Oklahoma is also used in the comparison study. At each aircraft site, twelve discrete air samples are collected at specified altitudes on a weekly or biweekly basis. Oklahoma is the fourth largest state for natural gas production in the USA (EIA, Natural gas navigator, 2008, http://tonto.eia.doe.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_a.htm) and one would expect to observe signatures of oil and gas drilling operations at both SGP and BAO. Additional information on the tower and aircraft programs is available at http://www.esrl.noaa.gov/gmd/ccgg/. Median summer mixing ratios for several alkanes, C_2H_2, C_6H_6 and CO are presented in the Results section.

2.3. Mobile Sampling

[19] Two mobile sampling strategies were employed during this study. The first, the Mobile Lab, consisted of a fast response CO_2 and CH_4 analyzer (Picarro, Inc.), a CO gas-filter correlation instrument from Thermo Environmental, Inc., an O_3 UV-absorption analyzer from 2B Technologies and a Global Positioning System (GPS) unit. All were installed onboard a vehicle. A set of 3 parallel inlets attached to a rack on top of the vehicle brought in outside air from a few meters above the ground to the instruments. Another simpler sampling strategy was to drive around and collect flask samples at predetermined locations in the Front Range region. A summary of the on-road surveys is given in Table 2.

[20] The Mobile Lab's Picarro Envirosense $CO_2/CH_4/H_2O$ analyzer (model G1301, unit CFADS09) employs Wavelength-Scanned Cavity Ring-Down Spectroscopy (WS-CRDS), a time-based measurement utilizing a near-infrared laser to measure a spectral signature of the molecule. CO_2, CH_4, and water vapor were measured at a 5-s sampling rate (0.2 Hz), with a standard deviation of 0.09 ppm in CO_2 and 0.7 ppb for CH_4. The sample was not dried prior to analysis, and the CO_2 and CH_4 mole fractions were corrected for water vapor after the experiment based on laboratory tests. For water mole fractions between 1% and 2.5%, the relative magnitude of the CH_4 correction was quasi-linear, with values between 1 and 2.6%. CO_2 and CH_4 mole fractions were assigned against a reference gas tied to the relevant World Meteorological Organization (WMO) calibration scale. Total measurement uncertainties were 0.1 ppm for CO_2 and 2 ppb for CH_4 (Sweeney et al., manuscript in preparation, 2012). The CO and ozone data from the Mobile Lab are not discussed here. GPS data were also collected in the Mobile Lab at 1 Hz, to allow data from the continuous analyzers to be merged with the location of the vehicle.

[21] The excursions with the flask sampler (PFP) focused on characterizing the concentrations of trace gases in Boulder (June 4 and 11, 2008), the northeastern Front Range (June 19), Denver (July 1) and around oil and gas wells and feedlots in Weld County south of Greeley (July 14) (see Table 2). Up to 24 sampling locations away from direct vehicle emissions were chosen before each drive.

[22] Each Mobile Lab drive lasted from four to six hours, after a ~30 min warm-up on the NOAA campus for the continuous analyzer before switching to battery mode. The first two Mobile Lab drives, which did not include discrete air sampling, were surveys around Denver (July 9) and between Boulder and Greeley (July 15). The last two drives with the Mobile Lab (July 25 and 31) combined in situ measurements with discrete flask sampling to target emissions from specific sources: the quasi-real-time display of the data from the continuous CO_2/CH_4 analyzer was used to collect targeted flask samples at strong CH_4 point sources in the vicinity of BAO. Discrete air samples were always collected upwind of the surveying vehicle and when possible away from major road traffic.

2.4. Chemical Analyses of Flask Samples

[23] Discrete air samples were collected at BAO and during the road surveys with a two-component collection apparatus. One (PCP) includes pumps and batteries, along with an onboard microprocessor to control air sampling. Air was drawn through Teflon tubing attached to an expandable 3-m long fishing pole. The second package (PFP) contained a sampling manifold and twelve cylindrical, 0.7 L, glass flasks of flow-through design, fitted with Teflon O-ring on both

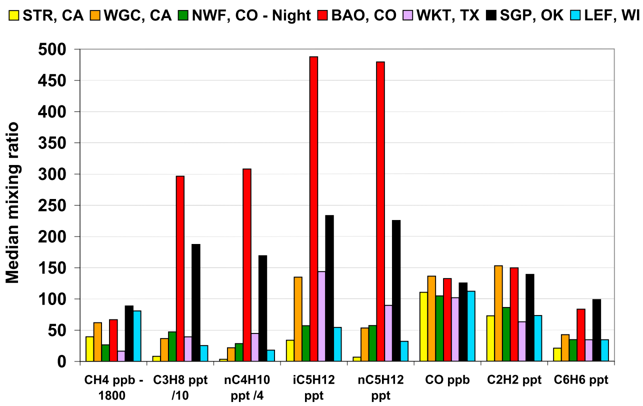

Figure 2. Observed median mixing ratios for several species measured in air samples taken at various sites at midday during June–August (2007–2010). The sites are described in Table 1. Only nighttime samples are shown for NWF to capture background air with predominantly downslope winds. Notice the different units with all columns and the different scaling applied to methane, propane and n-butane.

stopcocks. Before deployment, manifold and flasks were leak-checked then flushed and pressurized to ~1.4 atm with synthetic dry zero-air containing approximately 330 ppm of CO_2 and no detectable CH_4. During sampling, the manifold and flasks were flushed sequentially, at ~5 L min^{-1} for about 1 min and 10 L min^{-1} for about 3 min respectively, before the flasks were pressurized to 2.7 atm. Upon returning to the NOAA lab, the PFP manifold was leak-checked and metadata recorded by the PFP during the flushing and sampling procedures were read to verify the integrity of each air sample collected. In case of detected inadequate flushing or filling, the affected air sample is not analyzed.

[24] Samples collected in flasks were analyzed for close to 60 compounds by NOAA GMD (http://www.esrl.noaa.gov/gmd/ccgg/aircraft/analysis.html). In this paper, we focus on eight species: 5 alkanes (CH_4, C_3H_8, n-C_4H_{10}, i-C_5H_{12}, n-C_5H_{12}) as well as CO, C_2H_2 and C_6H_6. CH_4 and CO in each flask were first quantified on one of two nearly identical automated analytical systems (MAGICC 1 and 2). These systems consist of a custom-made gas inlet system, gas-specific analyzers, and system-control software. Our gas inlet systems use a series of stream selection valves to select an air sample or standard gas, pass it through a trap for drying maintained at ~−80°C, and then to an analyzer.

[25] CH_4 was measured by gas chromatography (GC) with flame ionization detection (±1.2 ppb = average repeatability determined as 1 s.d. of ~20 aliquots of natural air measured from a cylinder) [*Dlugokencky et al.*, 1994]. We use the following abbreviations for measured mole fractions: ppm = μmol mol^{-1}, ppb = nmol mol^{-1}, and ppt = pmol mol^{-1}. CO was measured directly by resonance fluorescence at ~150 nm (±0.2 ppb) [*Gerbig et al.*, 1999; *Novelli et al.*, 1998]. All measurements are reported as dry air mole fractions relative to internally consistent calibration scales maintained at NOAA (http://www.esrl.noaa.gov/gmd/ccl/scales.html).

[26] Gas chromatography/mass spectrometric (GC/MS) measurements were also performed on ~200 mL aliquots taken from the flask samples and pre-concentrated with a cryogenic trap at near liquid nitrogen temperatures [*Montzka et al.*, 1993]. Analytes desorbed at ~110°C were then separated by a temperature-programmed GC column (combination 25 m × 0.25 mm DB5 and 30 m × 0.25 mm Gaspro), followed by detection with mass spectrometry by monitoring compound-specific ion mass-to-charge ratios. Flask sample responses were calibrated versus whole air working reference gases which, in turn, are calibrated with respect to gravimetric primary standards (NOAA scales: benzene on NOAA-2006 and all other hydrocarbons (besides CH_4) on NOAA-2008). We used a provisional calibration for n-butane based on a diluted Scott Specialty Gas standard. Total uncertainties for analyses from the GC/MS reported here are <5% (accuracy) for all species except n-C_4H_{10} and C_2H_2, for which the total uncertainty at the time of this study was of the order of 15–20%. Measurement precision as repeatability is generally less than 2% for compounds present at mixing ratios above 10 ppt.

[27] To access the storage stability of the compounds of interest in the PFPs, we conducted storage tests of typically 30 days duration, which is greater than the actual storage time of the samples used in this study. Results for C_2H_2 and C_3H_8 show no statistically significant enhancement or degradation with respect to our "control" (the original test gas tank results) within our analytical uncertainty. For the remaining species, enhancements or losses average less than 3% for the 30 day tests. More information on the quality control of the flask analysis data is available at http://www.esrl.noaa.gov/gmd/ccgg/aircraft/qc.html.

[28] The flask samples were first sent to the GC/MS instrument for hydrocarbons, CFCs, and HFCs before being analyzed for major GHGs. This first step was meant to screen highly polluted samples that could potentially damage the greenhouse gas MAGICC analysis line with concentrations well above "background" levels. The time interval between flask collection and flask analysis spanned between 1 to 11 days for the GC/MS analysis and 3 to 12 days for MAGICC analysis.

3. Results

3.1. BAO Tall Tower: Long-Term Sampling Platform for Regional Emissions

3.1.1. Comparing BAO With Other Sampling Sites in the U.S.

[29] Air samples collected at BAO have a distinct chemical signature (Figure 2), showing enhanced levels of most alkanes (C_3H_8, n-C_4H_{10}, i-C_5H_{12} and n-C_5H_{12}) in comparison to results from other NOAA cooperative tall towers (see summary of site locations in Table 1 and data time series in auxiliary material Figure S1). The midday summer time median mixing ratios for C_3H_8 and n-C_4H_{10} at BAO were at least 6 times higher than those observed at most other tall tower sites. For i-C_5H_{12} and n-C_5H_{12}, the summertime median mixing ratios at BAO were at least 3 times higher than at the other tall towers.

[30] In Figure 2, we show nighttime measurements at the Niwot Ridge Forest tower (NWF) located at a high elevation site on the eastern slopes of the Rocky Mountains, 50 km west of BAO. During the summer nighttime, downslope flow brings clean air to the tower [*Roberts et al.*, 1984]. The median summer mixing ratios at NWF for all the species shown in Figure 2 are much lower than at BAO, as would be expected given the site's remote location.

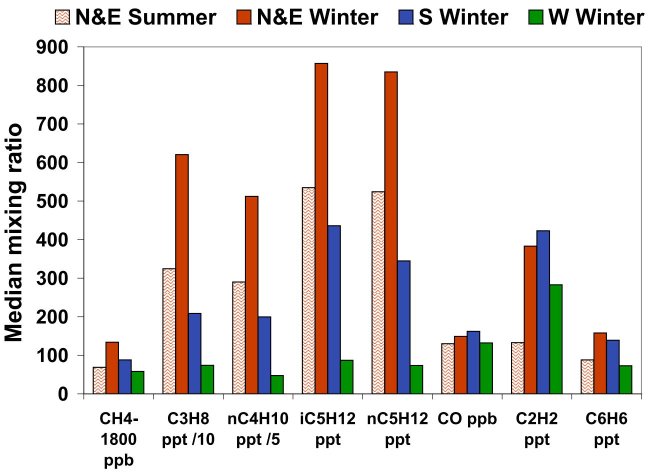

Figure 3. Summertime and wintertime median mixing ratios of several species measured in air samples from the 300-m level at the BAO tower for three wind sectors: North and East (NE) where the density of gas drilling operations is highest, South (S) with Denver 35 km away, and West (W) with mostly clean air. The time span of the data is from August 2007 to April 2010. Summer includes data from June to August and winter includes data from November to April. Due to the small number of data points (<15), we do not show summer values for the S and W wind sectors. Data outside of the 11am-3pm local time window were not used. Notice the different scales used for methane, propane and n-butane. The minimum number of data points used for each wind sector is: NE summer 33, NE winter 89, S winter 65 and W winter 111.

[31] Similarly to BAO, the northern Oklahoma aircraft site, SGP, exhibits high alkane levels in the boundary layer and the highest methane summer median mixing ratio of all sites shown in Figure 2 (1889 ppb at SGP versus 1867 ppb at BAO). As for BAO, SGP is located in an oil- and gas-producing region. Oklahoma, the fourth largest state in terms of natural gas production in the U.S., has a much denser network of interstate and intrastate natural gas pipelines compared to Colorado. *Katzenstein et al.* [2003] documented the spatial extent of alkane plumes around the gas fields of the Anadarko Basin in Texas, Oklahoma, and Kansas during two sampling intensives. The authors estimated that methane emissions from the oil and gas industry in that entire region could be as high as 4–6 Tg CH_4/yr, which is 13–20% of the U.S. total methane emission estimate for year 2005 reported in the latest EPA U.S. GHG Inventory (EPA, Inventory of U.S. Greenhouse Gas emissions and Sinks: 1990–2009, 2011, available at http://www.epa.gov/climatechange/emissions).

[32] Enhancements of CH_4 at BAO are not as striking in comparison to other sites. CH_4 is a long-lived gas destroyed predominantly by its reaction with OH radicals. CH_4 has a background level that varies depending on the location and season [*Dlugokencky et al.*, 1994], making it more difficult to interpret differences in median summer CH_4 mixing ratios at the suite of towers. Since we do not have continuous measurements of CH_4 at any of the towers except WGC, we cannot clearly separate CH_4 enhancements from background variability in samples with levels between 1800 and 1900 ppb if we only look at CH_4 mixing ratios by themselves (see more on this in the next section).

3.1.2. Influence of Different Sources at BAO

3.1.2.1. Median Mixing Ratios in the Three Wind Sectors

[33] To better separate the various sources influencing air sampled at BAO, Figure 3 shows the observed median mixing ratios of several species as a function of prevailing wind direction. For this calculation, we only used samples for which the associated 30-min average wind speed (prior to collection time) was larger than 2.5 m/s. We separated the data into three wind sectors: NE, including winds from the north, northeast and east (wind directions between 345° and 120°); S, including south winds (120° to 240°); and W, including winds from the west (240° to 345°).

[34] For the NE sector, we can further separate summer (June to August) and winter (November to April) data. For the other two wind sectors, only the winter months have enough data points. The species shown in Figure 3 have different photochemical lifetimes [*Parrish et al.*, 1998], and all are shorter-lived in the summer season. This fact, combined with enhanced vertical mixing in the summer, leads to lower mixing ratios in summer than in winter.

[35] Air masses from the NE sector pass over the oil and gas wells in the DJB and exhibit large alkane enhancements. In winter, median mole fractions of C_3-C_5 alkanes are 8 to 11 times higher in air samples from the NE compared to the samples from the W sector, while the median CH_4 value is 76 ppb higher. The NE wind sector also shows the highest median values of C_6H_6, but not CO and C_2H_2.

[36] C_3H_8, n-C_4H_{10} and the C_5H_{12} isomers in air samples from the NE wind sector are much higher than in air samples coming from the Denver metropolitan area in the South wind sector. Besides being influenced by Denver, southern air masses may pass over two operating landfills, the Commerce City oil refineries, and some oil and gas wells (Figure 1). The S sector BAO CO and C_2H_2 mixing ratios are higher than for the other wind sectors, consistent with the higher density of vehicular emission sources [*Harley et al.*, 1992; *Warneke et al.*, 2007; *Baker et al.*, 2008] south of BAO. There are also occasional spikes in CFC-11 and CFC-12 mixing ratios in the S sector (not shown). These are most probably due to leaks from CFC-containing items in the landfills. Air parcels at BAO coming from the east pass over Interstate Highway 25, which could explain some of the high mole fractions observed for vehicle combustion tracers such as CO, C_2H_2, and C_6H_6 in the NE sector data (see more discussion on C_6H_6 and CO in section 4.4 and Figure 4).

[37] The W wind sector has the lowest median mole fractions for all anthropogenic tracers, consistent with a lower density of emission sources west of BAO compared to the other wind sectors. However, the S and W wind sectors do have some data points with high alkane values, and these data will be discussed further below.

3.1.2.2. Strong Alkane Source Signature

[38] To detect if the air sampled at BAO has specific chemical signatures from various sources, we looked at correlation plots for the species shown in Figure 3. Table 3 summarizes the statistics for various tracer correlations for the three different wind sectors. Figure 4 (left) shows correlation plots of some of these BAO species for summer data in the NE wind sector.

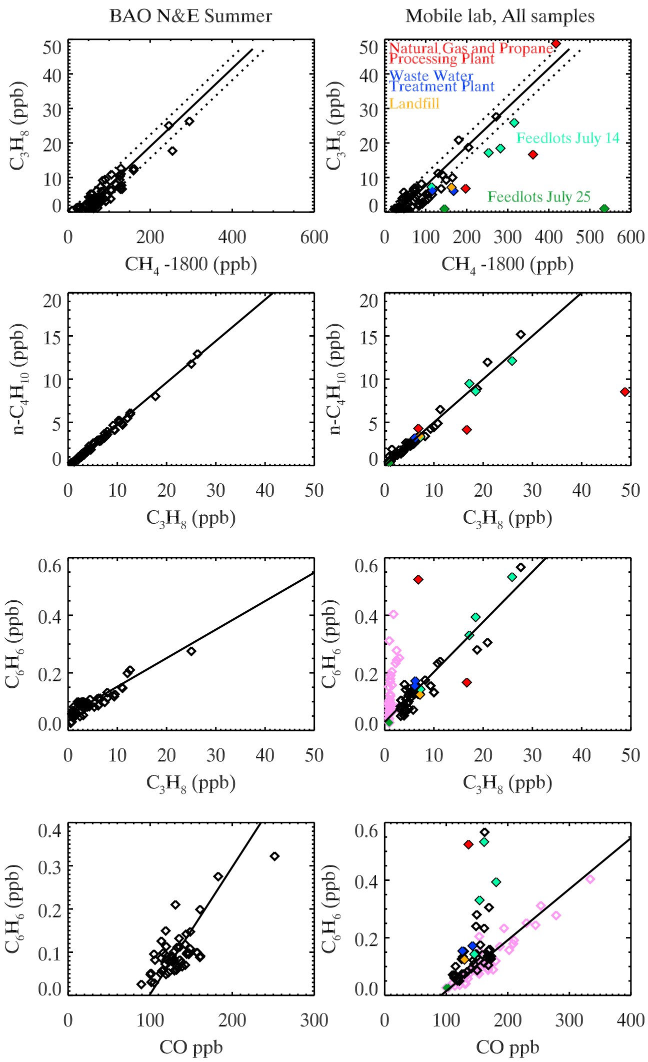

Figure 4. Correlation plots for various species measured in the (left) BAO summertime NE wind sector flask samples and (right) summer 2008 Mobile Lab samples. Data at BAO were filtered to keep only midday air samples collected between June and August over the time period spanning August 2007 to August 2009. See also Table 3.

[39] Even though BAO data from the NE winds show the largest alkane mixing ratios (Figure 3), all three sectors exhibit strong correlations between C_3H_8, n-C_4H_{10} and the C_5H_{12} isomers (Table 3). The r^2 values for the correlations between C_3H_8 and n-C_4H_{10} or the C_5H_{12} isomers are over 0.9 for the NE and W sectors. CH_4 is also well correlated with C_3H_8 in the NE wind sector for both seasons. For the NE wind sector BAO summertime data, a min/max range for the C_3H_8/CH_4 slope is 0.099 to 0.109 ppb/ppb.

[40] The tight correlations between the alkanes suggest a common source located in the vicinity of BAO. Since large alkane enhancements are more frequent in the NE wind sector, this common source probably has larger emissions north and east of the tower. This NE wind sector encompasses Interstate Highway 25 and most of the DJB oil and gas wells. The C_3-C_5 alkane mole fractions do not always correlate well with combustion tracers such as C_2H_2 and CO for the BAO NE wind sector (C_{3-5}/CO and C_{3-5}/C_2H_2: $r^2 < 0.3$ for 50 summer samples; C_{3-5}/CO: $r^2 < 0.4$ and C_{3-5}/C_2H_2: $r^2 \sim 0.6$ for 115 winter samples). These results indicate that the source responsible for the elevated alkanes at BAO is not the major source of CO or C_2H_2, which argues against vehicle combustion exhaust as being responsible. Northeastern Colorado is mostly rural with no big cities. The only operating oil refineries in Colorado are in the northern part of the Denver metropolitan area, south of BAO. The main industrial operations in the northeastern Front Range are oil and natural gas exploration and production and natural gas processing and transmission. We therefore hypothesize here that the oil and gas operations in the DJB, as noted earlier in section 2, are a potentially substantial source of alkanes in the region.

3.1.2.3. At Least Two Sources of Benzene in BAO Vicinity

[41] The median winter C_6H_6 mixing ratio at BAO is higher for the NE wind sector compared to the South wind sector, which comprises the Denver metropolitan area. The C_6H_6-to-CO winter correlation is highest for the S and W wind sectors BAO samples (r^2 = 0.85 and 0.83 respectively) compared to the NE wind sector data (r^2 = 0.69). The C_6H_6-to-CO correlation slope is substantially higher for the NE wind sector data compared to the other two wind sectors, suggesting that there may be a source of benzene in the NE

Table 3. Correlation Slopes and r^2 for Various Species Measured in the BAO Tower Midday Air Flask Samples for Summer (June to August, When More Than 25 Samples Exist) and Winter (November to April) Over the Time Period Spanning August 2007 to April 2010[a]

Sector		BAO North and East														
Season		Summer			Winter			BAO South Winter			BAO West Winter			Mobile Lab Summer		
Molar Ratios y/x	Units	Slope	r^2	n	Slope	r^2	n	Slope	r^2	n	Slope	r^2	n	Slope	r^2	n
C_3H_8/CH_4	ppb/ ppb	**0.104 ± 0.005**	0.85	81	**0.105 ± 0.004**	0.90	115	0.079 ±0.008	0.53	130	**0.085 ± 0.005**	0.73	148	**0.095 ± 0.007**	0.76	77
nC_4H_{10}/C_3H_8	ppb/ ppb	**0.447 ± 0.013**	1.00	81	**0.435 ± 0.005**	1.0	120	**0.449 ± 0.011**	0.98	131	**0.434 ± 0.006**	1.00	151	**0.490 ± 0.011**	1.00	85
iC_5H_{12}/C_3H_8	ppb/ ppb	**0.14 1 ± 0.004**	1.00	81	**0.134 ± 0.004**	0.98	120	**0.142 ± 0.009**	0.81	121	**0.130 ± 0.004**	0.94	151	**0.185 ± 0.011**	0.81	85
nC_5H_{12}/C_3H_8	ppb/ ppb	**0.150 ± 0.003**	1.00	81	**0.136 ± 0.004**	0.98	120	**0.142 ± 0.006**	0.90	131	**0.133 ± 0.003**	0.91	151	**0.186 ± 0.008**	0.92	85
C_6H_6/C_3H_8	ppt/ ppb	10.1 ± 1.2	0.67	49	**8.2 ± 0.5**	0.79	117	-	0.33	130	-	0.39	150	**17.9 ± 1.1**	0.95	46
C_6H_6/ CO	ppt/ ppb	2.89 ± 0.40	0.58	53	3.18 ± 0.24	0.69	112	**1.57 ± 0.08**	0.85	123	**1.81 ± 0.08**	0.83	148	**1.82 ± 0.12**	0.89	39
C_2H_2/ CO	ppt/ ppb	**3.15 ± 0.33**	0.85	81	**7.51 ± 0.39**	0.85	100	**5.03 ± 0.17**	0.92	110	**5.85 ± 0.25**	0.86	131	**4.32 ± 0.28**	0.89	39
C_6H_6/C_2H_2	ppt/ ppt	0.51 ± 0.09	0.55	50	**0.34 ± 0.02**	0.90	103	**0.27 ± 0.02**	0.90	111	**0.32 ± 0.02**	0.96	132	**0.37 ± 0.04**	0.75	39

[a]The three wind sectors used in Figure 3 are also used here with a 30-min average wind speed threshold of 2.5 m/s. Also shown are the slopes derived from flask samples collected by the Mobile Lab in summer 2008. The slope is in bold when r^2 is higher than 0.7 and the slope is not shown when r^2 is less than 0.4. The number of data points (n) used for the slope and r^2 calculations are provided. All slope units are ppb/ppb, except for C_6H_6/C_3H_8, C_6H_6/CO and C_2H_2/CO, which are in ppt/ppb. We used the IDL routine linmix_err.pro for the calculations with the following random measurement errors: 2ppb for CH_4 and CO and 5% for C_3H_8, n-C_4H_{10}, i-C_5H_{12}, n-C_5H_{12}, C_2H_2, and C_6H_6.

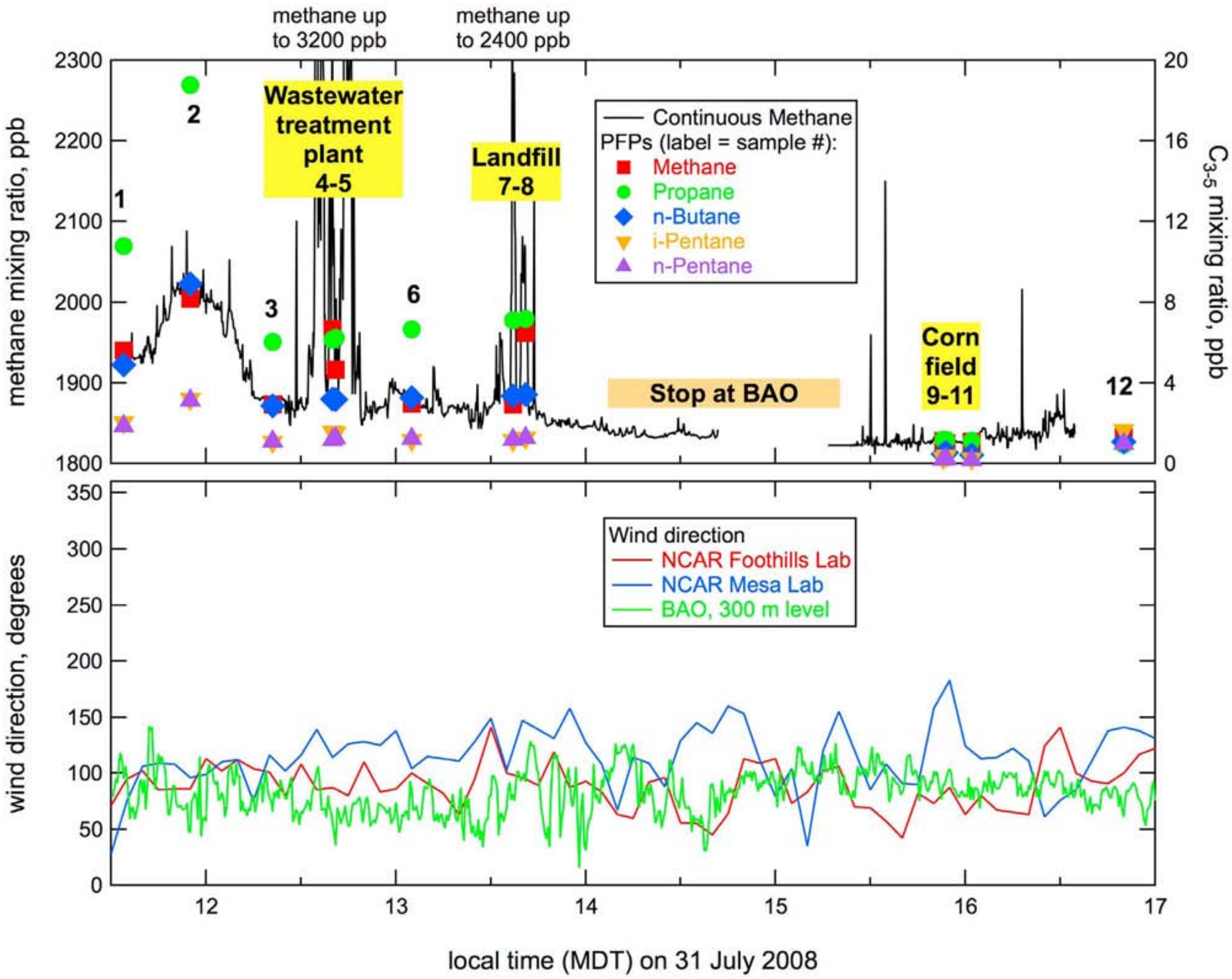

Figure 5. (top) Time series of the continuous methane measurements from Mobile Lab Survey 9 on July 31, 2008. Also shown are the mixing ratio data for the 12 flask samples collected during the road survey. The GC/MS had a faulty high energy dynode cable when these samples were analyzed, resulting in more noisy data for the alkanes and the CFCs ($\sigma < 10\%$ instead of 5%). However, the amplitudes of the C_{3-5} alkane signals are much larger than the noise here. The methane mixing ratio scale is shown on the left hand vertical axis. For all other alkanes, refer to the right hand vertical axis. (bottom) Time series of wind directions at the NCAR Foothills and Mesa Laboratories in Boulder (see Figure 6 for locations) and from the 300-m level at the BAO on July 31, 2008.

that is not a significant source of CO. The C_6H_6-to-C_2H_2 correlation slope is slightly higher for the NE wind sector data compared to the other two wind sectors. C_6H_6 in the BAO data from the NE wind sector correlates more strongly with C_3H_8 than with CO. The C_6H_6-to-C_3H_8 summer correlation slope for the NE wind sector is 10.1 ± 1.2 ppt/ppb (r^2 = 0.67).

[42] For the S and W wind sectors BAO data, the C_6H_6-to-C_2H_2 (0.27 - 0.32 ppt/ppt) and C_6H_6-to-CO (1.57 - 1.81 ppt/ppb) slopes are larger than observed emissions ratios for the Boston/New York City area in 2004: 0.171 ppt/ppt for C_6H_6-to-C_2H_2 ratio and 0.617 ppt/ppb for C_6H_6-to-CO ratio [*Warneke et al.*, 2007]. *Baker et al.* [2008] report an atmospheric molar C_6H_6-to-CO ratio of 0.9 ppt/ppb for Denver in summer 2004, which is in between the Boston/NYC emissions ratio value reported by *Warneke et al.* [2007] and the BAO S and W wind sectors correlation slopes.

[43] The analysis of the BAO C_6H_6 data suggests the existence of at least two distinct C_6H_6 sources in the vicinity of BAO: an urban source related mainly to mobile emissions, and a common source of alkanes and C_6H_6 concentrated in northeastern Colorado. We discuss C_6H_6 correlations and sources in more detail in section 4.4.

3.2. On-Road Surveys: Tracking Point and Area Source Chemical Signatures

[44] Road surveys with flask sampling and the Mobile Lab with the fast-response CH_4 analyzer were carried out in June–July 2008 (Table 2). The extensive chemical analysis of air samples collected in the Front Range provides a snapshot of a broader chemical composition of the regional boundary layer during the time of the study. The Mobile Lab surveys around the Front Range using the in situ CH_4 analyzer allowed us to detect large-scale plumes with long-

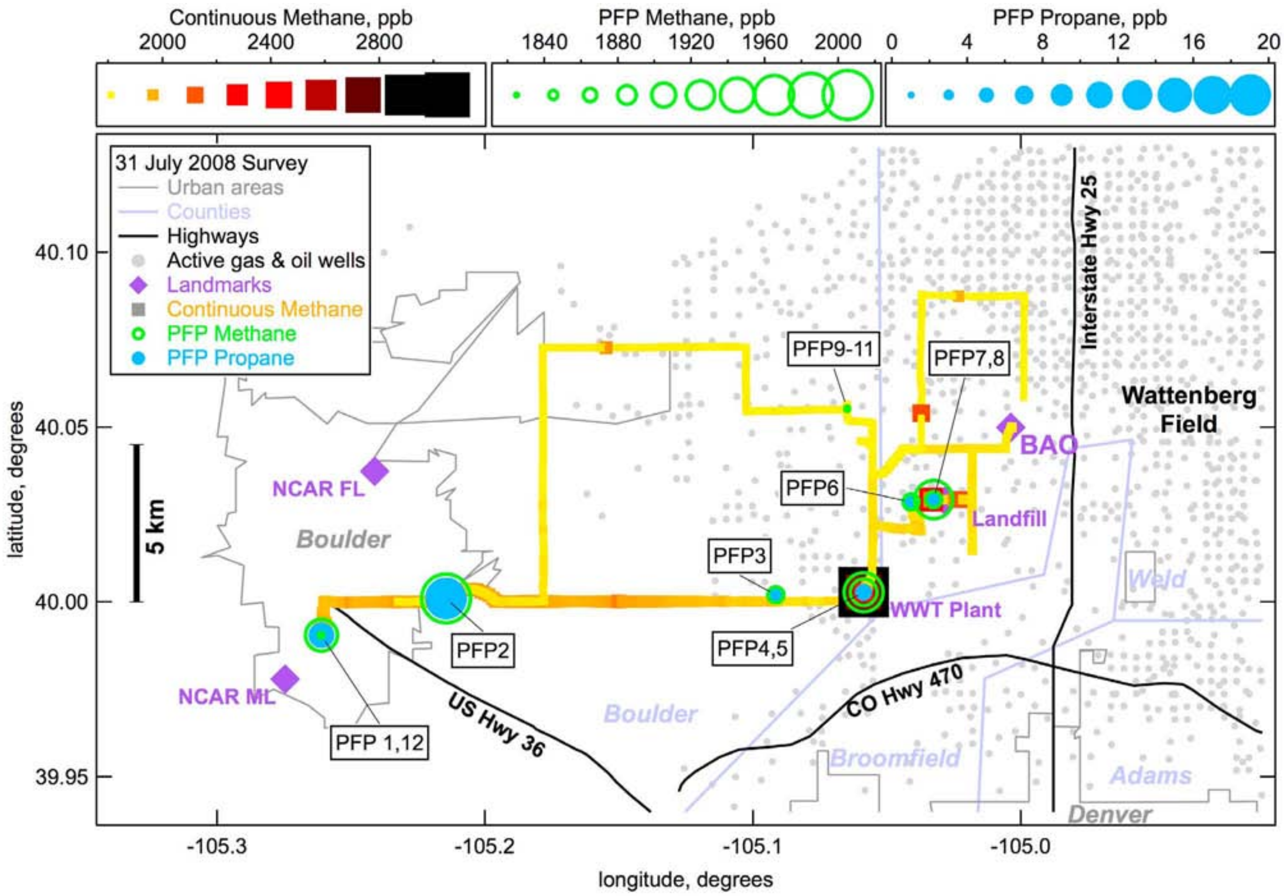

Figure 6. Continuous methane observations (colored squares) and flask (circles) samples collected during the July 31, 2008 Mobile Lab Survey 9 in Boulder and Weld County. The size of the symbols (and the symbol color for the continuous methane data) represents the mixing ratio of continuous/flask methane (squares, green circles) and flask propane (blue circles). The labels indicate the flask sample number (also shown in the time series in Figure 5). NCAR = National Center for Atmospheric Research, FL = NCAR Foothills Laboratory, ML = NCAR Mesa Laboratory, WWT Plant = Lafayette wastewater treatment plant.

lasting enhancements of CH_4 mixing ratios as well as small-scale plumes associated with local CH_4 point sources. In the last two Mobile Lab surveys (surveys 8 and 9), we combined the monitoring of the continuous CH_4 analyzer with targeted flask sampling, using the CH_4 data to decide when to collect flask samples in and out of plumes.

[45] The regional background CH_4 mixing ratio at the surface (interpreted here as the lowest methane level sustained for ~10 min or more) was between 1800 ppb and 1840 ppb for most surveys. Some of the highest "instantaneous" CH_4 mixing ratios measured during the Mobile Lab surveys were: 3166 ppb at a wastewater treatment plant, 2329 ppb at a landfill, 2825 ppb at a feedlot near Dacono, over 7000 ppb close to a feedlot waste pond near Greeley, and 4709 ppb at a large natural gas processing and propane plant in Fort Lupton (Figure 1).

[46] The analysis of the summer 2008 intensive data suggests that regional scale mixing ratio enhancements of CH_4 and other alkanes are not rare events in the Colorado Northern Front Range airshed. Their occurrence and extent depends on both emissions and surface wind conditions, which are quite variable and difficult to predict in this area. During the Mobile Lab road surveys, the high-frequency measurements of CO_2 and CH_4 did not exhibit any correlation. Unlike CO_2, the CH_4 enhancements were not related to on-road emissions. Below we present two examples of regional enhancements of CH_4 observed during the Front Range Mobile Lab surveys.

3.2.1. Survey 9: C_{3-5} Alkane Levels Follow Large-Scale Changes in Methane

[47] Figure 5 shows a time series of the continuous CH_4 mixing ratio data and alkane mixing ratios measured in twelve flask samples collected during the Front Range Mobile Lab survey on 31 July 2008 (flasks 1 to 12, sampled sequentially as shown in Figure 6). The wind direction on that day was from the ENE or E at the NCAR Foothills Lab and BAO tower. The Mobile Lab left the NOAA campus in Boulder around 11:40 A.M. and measured increasing CH_4 levels going east toward the BAO tower (Figure 6). An air sample was collected close to the peak of the CH_4 broad enhancement centered around 11:55 A.M. The CH_4 mixing ratio then decreased over the next 25 min and reached a local minimum close to 1875 ppb. The CH_4 level stayed around 1875 ppb for over one hour and then decreased again, more slowly this time, to ~1830 ppb over the next two hours.

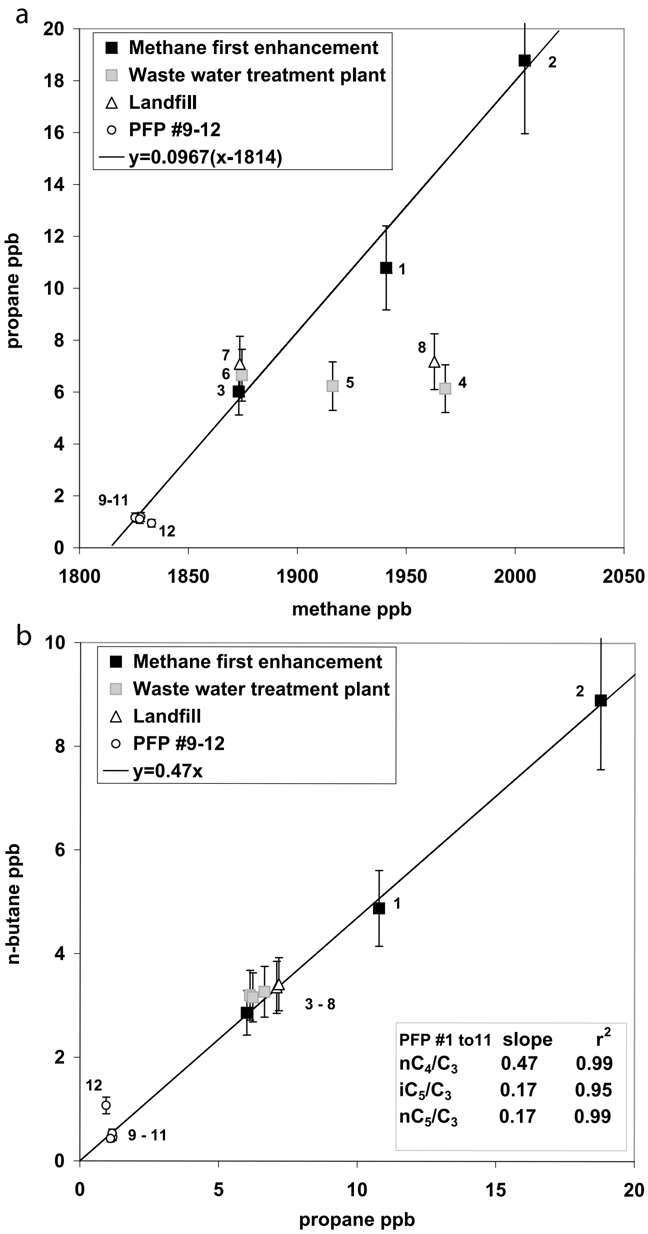

Figure 7. (a) Propane versus methane mixing ratios for air samples collected during Survey 9 on July 31, 2008. (b) The n-butane versus propane mixing ratios in the same air samples. The black line in Figure 7a shows the correlation line for samples not impacted by local sources of methane (all flasks except 4, 5, 8, and 12). The black line in Figure 7b shows the correlation line for all samples except flask 12. The flask sample number is shown next to each data point. The twelve samples were filled sequentially (see Figure 6).

[48] Flasks 1 to 3 were collected before, at the peak, and immediately after the broad CH_4 feature between 11:40 and 12:15. Flasks 4 and 5 were sampled close to a wastewater treatment plant and flasks 7 to 8 were sampled in a landfill. The in situ measurements showed that CH_4 was still elevated above background as these samples were collected. After a 90-min stop at BAO to recharge the Mobile Lab UPS batteries, flasks 9 to 11 were collected in a corn field while the in situ measurements showed lower CH_4 levels. The last flask sample was collected on the NOAA campus just before 17:00 MDT, about 5.5 h after the first flask sample was collected. The flask samples were always collected upwind of the Mobile Lab car exhaust.

[49] Sharp spikes in the continuous CH_4 data reflect local point sources (wastewater treatment plant, landfill). The highly variable signals in both the continuous and discrete CH_4 close to these sources are driven by the spatial heterogeneity of the CH_4 emissions and variations in wind speed and direction. Broader enhancements in the continuous CH_4 data reflect larger (regional) plumes. The last flask (12) sampled at NOAA has much higher levels of combustion tracers (CO, C_2H_2, C_6H_6) than the other samples.

[50] Figure 7 shows correlation plots for C_3H_8 versus CH_4 and n-C_4H_{10} versus C_3H_8 in the 12 flasks taken on 31 July. Air samples not directly influenced by identified point sources (flasks 1–3, 6–7, 9–12) show a very strong correlation between the various measured alkanes. Using the data from the air samples not directly influenced by identified point sources (flasks 1–3, 6–7, 9–12), we derive a C_3H_8-to-CH_4 (C_3/C_1) mixing ratio slope of 0.097 ± 0.005 ppb/ppb (Figure 7a). This slope is very similar to the one observed for the summertime NE wind sector data at BAO (0.104 ± 0.005; Table 3). Three air samples collected downwind of the wastewater treatment plant and the landfill (flasks 4–5 and 8) are off the C_3H_8-to-CH_4 correlation line and have higher CH_4 than air samples collected nearby but not under the influence of these local CH_4 sources (flasks 3 and 6). Flask 8 also has elevated CFC-11 (310 ppt) compared to the other samples collected that day (<255 ppt), probably related to leaks from old appliances buried in the landfill.

[51] The C_3-C_5 alkane mixing ratios in samples collected on 31 July are tightly correlated for flasks 1 to 11 with $r^2 > 0.95$ (Figure 7b). As concluded for the BAO alkane mixing ratio enhancements earlier, this tight correlation suggests that the non-methane alkanes measured during the surveys are coming from the same source types. The nC_4/C_3 correlation slope on 31 July (0.47 ppb/ppb; flasks 1–11) is similar to the summer slope in the BAO NE samples (0.45 ppb/ppb), while the 31 July iC_5/C_3 and nC_5/C_3 slopes are slightly higher (0.17 and 0.17 ppb/ppb, respectively) than for BAO (0.14 and 0.15 ppb/ppb, respectively).

3.2.2. Survey 6: Alkane Enhancements in the Denver-Julesburg Oil and Gas Production Zone and Cattle Feedlot Contributions to Methane

[52] The flask-sampling-only mobile survey on 14 July 2008 focused on the agricultural and oil and gas drilling region south of Greeley. Eleven of the twelve air samples collected on 14 July were taken over the Denver-Julesburg Basin (flasks 2–12 in auxiliary material Figure S3). Figure 8a shows a correlation plot of C_3H_8 versus CH_4 mixing ratios in these air samples. Flasks collected NE of BAO and not near feedlots (flasks 4, 6–8, and 10–12) fall on a line: y = 0.114(x-1830) (r^2 = 0.99). This slope and the correlation slope calculated for the BAO NE wind sector data are indistinguishable (within the 1-σ uncertainties in the slopes). Four samples collected in the vicinity of four different cattle feedlots (flasks 2, 3, 5, and 9) exhibit a lower C_3H_8-to-CH_4 correlation slope (0.083 ppb/ppb, r^2 = 0.93). The r^2 for the C_3H_8-to-CH_4 correlation using all the flasks is 0.91.

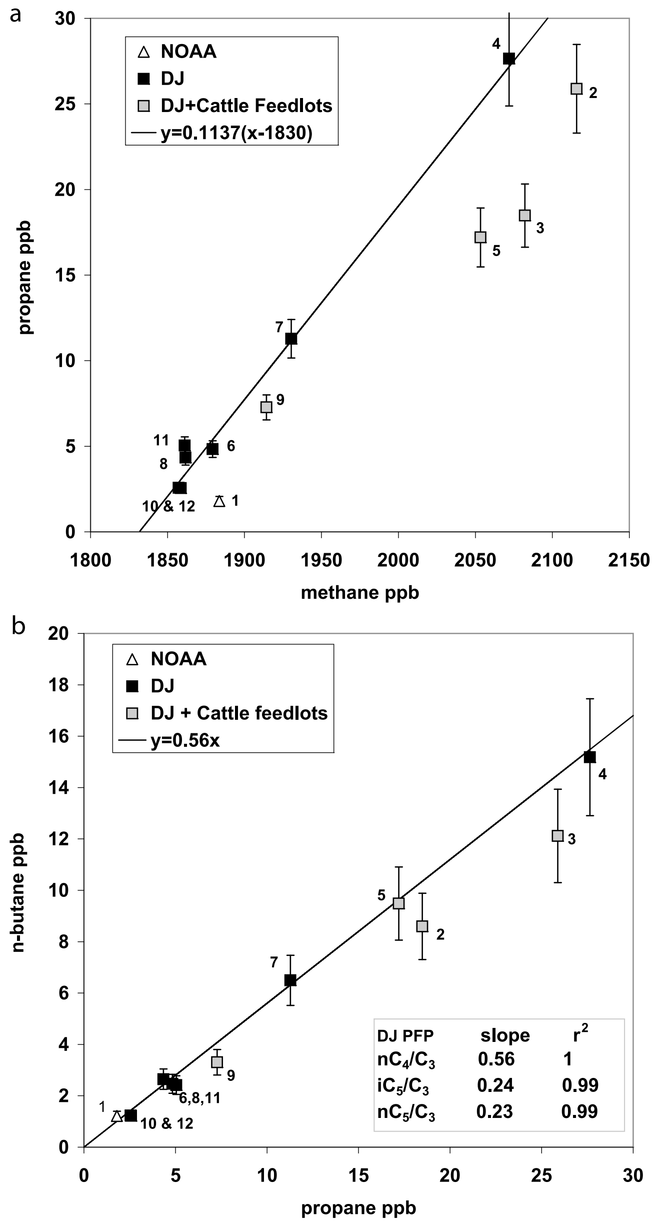

Figure 8. (a) Propane versus methane mixing ratios for air samples collected during Survey 6 on July 14, 2008. (b) The n-butane versus propane mixing ratios in the same air samples. The black line in Figure 8a shows the correlation line for samples not impacted by local sources of methane (all flasks except 1–3, 5, and 9). The black line in Figure 8b shows the correlation line for samples not impacted by local sources of propane.

[53] The n-C_4H_{10} versus C_3H_8 correlation plot and its slope, along with the n-C_4H_{10}–to-C_3H_8 and C_5H_{12}–to-C_3H_8 correlation slopes for air samples not collected downwind of feedlots are shown in Figure 8b. The r^2 for the n-C_4H_{10}-to-C_3H_8 correlation using all the flasks is 0.98, which is slightly higher than the r^2 for the C_3H_8-to-CH_4 correlation using all flasks (0.91). The r^2 for the i-C_5H_{12}-to-n-C_4H_{10} and n-C_5H_{12}-to-n-C_4H_{10} correlations using all the flasks are 0.96 ppb/ppb and 0.99 ppb/ppb, respectively. These results suggest that cattle feedlots have no substantial impact on n-C_4H_{10} and the C_5H_{12} levels.

[54] The strong correlation observed between the various alkane mixing ratios for air samples not collected downwind of feedlots once again suggests that a common source contributes to most of the observed alkanes enhancements. It is possible that some of the C_3H_8 enhancements seen near the feedlots are due to leaks of propane fuel used for farm operations (R. Klusman, personal communication, 2010). Two flask samples were collected downwind of a cattle feedlot near Dacono during Mobile Lab survey 8, on 25 July 2008. The analysis of these samples revealed large CH_4 enhancements (1946 and 2335 ppb), but no enhancement in C_3H_8 ($\sim$1ppb), n-C_4H_{10} (<300ppt), the C_5H_{12} (<130ppt) or C_6H_6 (<30ppt).

[55] For survey 6, the n-C_4H_{10}-to-C_3H_8 correlation slope (0.56 ppb/ppb) is 16% higher than the summer slope observed at BAO for the NE wind sector data, while the 14 July i-C_5H_{12}-to-C_3H_8 and n-C_5H_{12}-to-C_3H_8 correlation slopes (0.24 and 0.23 ppb/ppb, respectively) are 76% and 53% higher, respectively, than the summer NE BAO data. These slopes are higher than for flasks from survey 9. The difference in the C_5/C_3 slopes between the various Mobile Lab surveys data and the BAO NE summer data may reflect the spatial variability in the alkane source molar composition.

3.2.3. Benzene Source Signatures

[56] To look at the C_6H_6 correlations with other tracers, the 88 Mobile Lab flask samples have been divided into two subsets, none of which includes the three samples collected downwind of the natural gas and propane processing plant near Dacono, CO. In the summer, the lifetimes of C_6H_6 and C_3H_8 at 800 mbar and 40°N are close to 3 or 4 days and the lifetime of CO is about 10 days [*Finlayson-Pitts and Pitts*, 2000; *Spivakovsky et al.*, 2000].

[57] The first subset of 39 samples has C_3H_8 mixing ratios smaller than 3 ppb and it includes flasks collected mostly during surveys 2, 3 and 4. For this subset influenced mostly by urban and mobile emissions, C_6H_6 correlates well with CO (slope = 1.82 ppt/ppb, r^2 = 0.89) and C_2H_2 (slope = 0.37 ppt/ppt, r^2 = 0.75) but not with C_3H_8 (r^2 < 0.3). The C_6H_6-to-CO correlation slope for this subset is similar to the correlation slopes for the BAO S and W wind sector winter samples.

[58] The second subset of 46 samples corresponds to flasks with a C_3H_8 mixing ratio larger than 3ppb. These flasks were collected mostly during surveys 1, 6, 8 and 9. For this second subset influenced mostly by emissions from the DJB, C_6H_6 correlates well with C_3H_8 (slope = 17.9 ppt/ppb, r^2 = 0.95) but not with CO or C_2H_2 (r^2 < 0.3). The C_6H_6-to-C_3H_8 slope for these samples is almost twice as big as the slope calculated for the BAO NE wind sector data (10.1 ppt/ppb) (Table 3).

4. Discussion

4.1. Comparing the Alkane Enhancements in the BAO and Mobile Lab Data Sets

[59] In the previous section we showed two examples of enhanced alkanes in northeast Colorado using mobile sampling (surveys 6 and 9 on 14 and 31 July 2008, respectively). With lifetimes against OH removal on the order of 3.5, 1.7 and 1.0 days in the summer at 40°N [*Finlayson-Pitts and Pitts*, 2000; *Spivakovsky et al.*, 2000] respectively, C_3H_8,

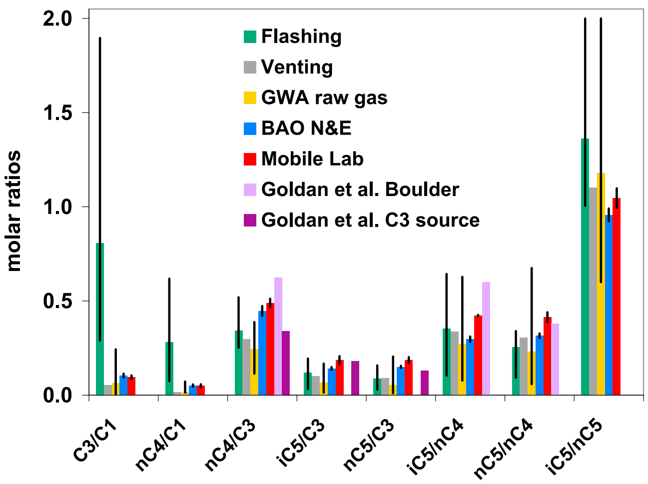

Figure 9. Alkane correlation slopes in air samples collected at BAO (NE wind sector, summer samples only, blue) and over the Denver-Julesburg Basin (red) during the Front Range Study (June–July 2008) are compared with VOC emissions molar ratios for flashing (green) and venting (gray) sources used by *Bar-Ilan et al.* [2008a] for the DJB WRAP Phase III emissions inventory. The error bars indicate the min and max values for the flashing emissions molar ratios. Also shown are the mean, min and max molar ratios derived from the composition analysis of gas samples collected in 2006 at 77 different gas wells in the Great Wattenberg Area (yellow) [*Colorado Oil and Gas Conservation Commission*, 2007]. *Goldan et al.* [1995] data are from a two week measurement campaign in the Foothills, west of Boulder, in February 1991 (light purple). Goldan et al. identified a "local" propane source (lower limit for correlation slope) with clear $C_{4–5}$ alkane ratios to propane (dark purple, see also text). The error bars on the observed atmospheric molar ratios are the 2-sigma calculated for the ratios with linmix_err.pro (http://idlastro.gsfc.nasa.gov/ftp/pro/math/linmix_err.pro).

n-C_4H_{10} and the C_5H_{12} isomers do not accumulate over the continent. Instead their atmospheric mixing ratios and the slopes of correlations between different alkanes reflect mostly local or regional sources within a few days of atmospheric transport.

[60] The source responsible for the alkane enhancements observed at BAO and in multiple surveys during the Front Range Study appears to be located in the northeastern part of the Front Range region within the Denver-Julesburg Basin, so we call it the DJB source. The small differences in alkane correlation slopes for the BAO and Mobile Lab samples likely reflect differences in the emitted alkane molar ratios across this distributed source, as well as the mix of chemical ages for the air samples collected at a variety of locations and on different days.

[61] In Table 3 and Figure 4, we compare the alkane correlation slopes in the Mobile Lab flask data set with the correlation slopes in the BAO data set. To calculate the DJB source C_3H_8-to-CH_4 correlation slope from the Mobile Lab data set, we have removed air samples collected downwind of feedlots, the wastewater treatment plant, and the natural gas and propane processing plant (Figure 1). The Mobile Lab flasks C_3H_8-to-CH_4 correlation slope is 0.095 ± 0.007 ppb/ppb (R^2 = 0.76, 77 samples), similar to the slope calculated for the BAO NE wind sector data. Samples collected downwind of the natural gas processing plant exhibit variable chemical signatures, reflecting a complex mix of contributions from leaks of gas and combustion exhaust from flaring units and compressor engines.

[62] To calculate the DJB source n-C_4H_{10}-to-C_3H_8, i-C_5H_{12}-to-C_3H_8 and n-C_5H_{12}-to-C_3H_8 correlation slopes from the Mobile Lab data set, we have removed the three air samples collected downwind of the natural gas and propane processing plant (Figure 1). The C_4/C_3, i-C_5/C_3 and n-C_5/C_3 correlation slopes in the Mobile Lab data are 0.49, 0.19 and 0.19 ppb/ppb, respectively (r^2 > 0.8, 85 samples). The i-C_5/C_3 and n-C_5/C_3 correlation slopes are 40% and 30% higher, respectively, than the BAO NE sector summer slopes. If we remove the 11 data points from survey 6 samples collected in the middle of the DJB, the C_5H_{12}-to-C_3H_8 ratios are only 15% higher than calculated for the NE sector at BAO.

[63] High correlations among various alkanes were reported in this region by *Goldan et al.* [1995]. In that study, hourly air samples were analyzed with an in situ gas chromatograph deployed on a mesa at the western edge of Boulder for two weeks in February 1991. CH_4 was not measured during that study. The correlation coefficient (r^2) between C_3H_8, n-C_4H_{10}, and the C_5H_{12} isomers was around 0.86, with a clear minimum slope for the abundance ratios [see *Goldan et al.*, 1995, Figure 4]. The authors proposed that the C_4-C_6 alkanes shared one common source with propane (called the "C_3 source" in the next section and in Figure 9), with additional emissions contributing to some C_4-C_6 alkane enhancements.

4.2. Comparing the Front Range Observed Alkane Signatures With VOC Emissions Profiles for Oil And Gas Operations in the Denver-Julesburg Basin

[64] In this section we compare the alkane ratios calculated from the BAO NE wind sector and the Mobile Lab samples to emissions profiles from the DJB oil and gas exploration and production sector. Most of these profiles were provided by the WRAP Phase III inventory team, who developed total VOC and NOx emission inventories for oil and gas production and processing operation in the DJB for 2006 [*Bar-Ilan et al.*, 2008a]. Emissions and activity data were extrapolated by the WRAP Phase III inventory team to derive emission estimates for 2010 based on projected production numbers and on state and federal emissions control regulations put in place in early 2008 for oil and gas permitted activities in the DNFR NAA [*Bar-Ilan et al.*, 2008b]. The VOCs included in the inventories are: C_3H_8, i,n-C_4H_{10}, i,n-C_5H_{12} and higher alkanes, C_6H_6, toluene, ethyl-benzene, xylenes and 224-trimethylpentane. The WRAP Phase III inventories for 2006 and 2010 were only provided as total VOC and NOx emitted at the county level for all the counties in the Colorado part of the DJB. The emission estimates are based on various activity data (including the number of new wells (spuds), the total number of wells, estimates of oil, condensate and gas production, and equipment counts) and measured/reported or estimated VOC speciation profiles for the different source categories. Auxiliary material Figure S2 and *Bar-Ilan et al.* [2008a, 2008b] present more details on how the inventory emission estimates are derived.

[65] We focus primarily on flashing and venting sources here, since the WRAP Phase III inventory indicates that these two sources are responsible for 95% of the total VOC emissions from oil and gas exploration and production operations in Weld County and in the NAA [*Bar-Ilan et al.*, 2008a, 2008b] (see auxiliary material Figure S2). In 2006, all the oil produced in the DJB was from condensate wells. Condensate tanks at well pads or processing plants store a mostly liquid mix of hydrocarbons and aromatics separated from the lighter gases in the raw natural gas. Flash losses or emissions happen for example when the liquid condensate is exposed to decreasing atmospheric pressure: gases dissolved in the liquid are released and some of the heavier compounds may be entrained with these gases. Flashing emissions from condensate storage tanks are the largest source of VOCs from oil and gas operations in the DJB. In the DNFR NAA, operators of large condensate tanks have to control and report emission estimates to the Colorado Department of Public Health and the Environment (CDPHE). In 2006 and 2010 flashing emissions represented 69% and 65% respectively of the total VOC source from oil and gas exploration, production and processing operations, for the nine counties in the NAA (see auxiliary material Figure S2 and *Bar-Ilan et al.* [2008a] for more details on how the estimates are derived).

[66] Venting emissions are related to loss of raw natural gas when a new oil or gas well is drilled or when an existing well is vented (blowdown), repaired or restimulated (recompletion). Equipment at active well sites (e.g., wellhead, glycol dehydrators and pumps) or in the midstream network of compressors and pipelines gathering the raw natural gas can also leak significant amounts of natural gas. In the WRAP Phase III inventory, venting emissions represented 27% and 21% respectively of the total VOC estimated source from the NAA oil and gas operations in 2006 and 2010 (see *Bar-Ilan et al.* [2008a, 2008b] and auxiliary material Figure S2).

[67] The molar compositions of venting and flashing emissions are quite different (see auxiliary material Figure S4). Emissions from flash losses are enriched in C_{2+} alkanes compared to the raw natural gas emissions. To convert the total VOC bottom-up source into speciated emission ratio estimates, we use molar ratio profiles for both flashing and venting emissions reported in three data sets: (1) *Bar-Ilan et al.* [2008a]: mean venting profile used for the 2006 DJB inventory, also called the "Venting-WRAP" profile; (2) *Colorado Oil and Gas Conservation Commission* (*COGCC*) [2007]: composition of 77 samples of raw natural gas collected at different wells in the Greater Wattenberg Area in December 2006, also called "Venting-GWA" profiles. Note that C_6H_6 was not reported in this data set; and (3) Colorado Department of Public Health and the Environment (C. LaPlante, CDPHE, personal communication, 2011): flashing emissions profiles based on condensate composition data from 16 different storage tanks in the DJB and EPA TANK2.0 (flashing emissions model) runs.

[68] Figure 9 shows a comparison of the alkane molar ratios for the raw natural gas and flash emissions data sets with the correlation slopes derived for the Mobile Lab 2008 samples and for air samples collected at BAO in the summer months only (between August 2007 and April 2010) for the NE wind sector (see auxiliary material Table S4 to get the plotted values). The alkane correlation slopes observed at BAO and across the Northern Front Range with the Mobile Lab are all within the range of ratios reported for flashing and/or venting emissions. The C_{3-5} alkane ratios for both flashing and venting emissions are too similar for their atmospheric ratios to be useful in distinguishing between the two source processes. The ambient C_3H_8-to-CH_4 and n-C_4H_{10}-to-CH_4 molar ratios are lower than what could be expected from condensate tank flashing emissions alone, indicating that most of the CH_4 observed came from the venting of raw natural gas. In the next section, we will describe how we derive bottom-up emission estimates for CH_4 and C_3H_8 as well as three top-down emissions scenarios consistent with the observed atmospheric slopes.

[69] Figure 9 also shows the correlation slopes calculated by *Goldan et al.* [1995] for the 1991 Boulder study. These slopes compare very well with the BAO and Mobile Lab results and the oil and gas venting and flashing emissions ratios. *Goldan et al.* [1995] compared the measured C_4/C_3 and C_5/C_3 ratios for the Boulder C_3 source (see definition in section 4.1) with the ratios reported in the locally distributed pipeline-quality natural gas for February 1991, and concluded that the common C_3H_8 and higher alkane source was not linked with the local distribution system of processed natural gas. However, the composition of the raw natural gas at the extraction well is quite different from the purified pipeline-quality natural gas distributed to end-users. Processed pipeline-quality natural gas delivered throughout the USA is almost pure CH_4 [*Gas Research Institute*, 1992]. Since *Goldan et al.* [1995] did not measure CH_4 in their 1991 study, they could not determine if the atmospheric C_{3+}/C_1 alkane ratios were higher than expected in processed natural gas.

4.3. Estimation of the Alkane Source in Weld County

4.3.1. Bottom-Up Speciated Emission Estimates

[70] In this section, we derive bottom-up and top-down estimates of alkane emissions from the DJB source for Weld County. We have averaged the 2006 and 2010 WRAP Phase III total VOC emissions data [*Bar-Ilan et al.*, 2008a, 2008b] to get bottom-up estimates for the year 2008, resulting in 41.3 Gg/yr for flashing emissions and 16.8 Gg/yr for venting emissions. There are no uncertainty estimates provided in the WRAP Phase III inventory. 2006 total VOC flashing emission estimates in Weld County are based on reported emissions for controlled large condensate tanks (34.8 Gg/yr) and calculated emissions for uncontrolled small condensate tanks (5.4 Gg/yr) (see *Bar-Ilan et al.* [2008a] for more details). Uncertainties attached to these estimates may be due to inaccurate emissions factors (number of pounds of VOC flashed per tons of condensate produced) and/or inaccurate estimate of the effectiveness of emission control systems.

[71] The WRAP Phase III total VOC emission from venting sources for Weld County was calculated by averaging industry estimates of the volume of natural gas vented or leaked to the atmosphere by various processes shown in auxiliary material Figure S2 (well blowdown, well completion, pneumatic devices…). A basin-wide average of gas composition analyses provided by oil and gas producers was then used to compute a bottom-up estimate of the total mass of VOC vented to the atmosphere by oil and gas exploration, production and processing operations. Uncertainties attached to the venting source can be related to

Table 4. Bottom-Up (Inventory-Derived) Emission Estimates and Top-Down Emissions Scenarios for CH_4 and C_3H_8 in Weld County

	Bottom-Up Estimates				Top-Down Scenarios: Venting[a] (Gg/yr)			Top-Down Scenarios: TOTAL Bottom-Up Flashing + Top-Down Venting[a] (Gg/yr)			Top-Down Scenarios: Percent Of Production Vented[a,b]		
	Flashing[c] (Gg/yr)	Venting[d] (Gg/yr)	Flashing + Venting (Gg/yr)	Percent of Production Vented[e]	1	2	3	1	2	3	1	2	3
Methane	**11.2**	53.1	64.3	**1.68%**	118.4	92.5	157	**129.6**	103.7	168.2	**4.0%**	3.1%	5.3%
Min[f]	**4**	42	46		86.5	67.6	114.7	90.5	**71.6**	118.7	2.9%	**2.3%**	3.8%
Max[f]	**23**	63	86		172.6	134.9	228.9	195.6	157.9	**251.9**	5.8%	4.5%	**7.7%**
Propane	**18.3**	7.8	26.1		17.4	10.2	28	**35.7**	28.5	46.3			
Min[f]	**14**	1	15		12.7	7.5	20.5	26.7	**21.5**	34.5			
Max[f]	**24**	28	52		25.3	14.9	40.8	49.3	38.9	**64.8**			

[a]The CH_4-to-C_3H_8 molar ratio for vented natural gas is 18.75 (WRAP report estimate) for scenario 1, 15.43 for scenario 2 (median of molar ratios in GWA data set) and 24.83 for scenario 3 (mean of molar ratios in GWA data set).

[b]Using the assumptions of a CH_4 molar ratio of 77% for the vented natural gas and a molar volume for the gas of 23.6 L/mol (Pressure = 14.73 pounds per square inch and Temperature = 60°F) as used by the *EIA* [2004].

[c]The bottom-up flashing emissions for methane and propane were calculated using the 2008 estimate of total VOC flash emissions derived by averaging the WRAP estimate for 2006 and the projection for 2010 (Cf. section 4.3).

[d]The bottom-up venting emissions for methane and propane were calculated using the WRAP Phase III inventory estimate for the total volume of natural gas vented and the GWA 77 natural gas composition profiles.

[e]Using the WRAP Phase III inventory data set and assumptions, including a CH_4 mean molar ratio of 77.44% for the vented natural gas and a molar volume for the gas of 22.4 L/mol.

[f]The minimum and maximum values reported here come from the ensemble of 16 condensate tank emissions speciation profiles provided by CDPHE.

uncertainties in leak rates or intensity of out-gassing events, as well to the variability in the composition of raw natural gas, none of which were quantitatively taken into account in the WRAP Phase III inventory.

[72] Next we describe the calculations, summarized in auxiliary material Figure S5, to derive bottom-up estimates of venting and flashing emissions for the various trace gases we measured using information from the WRAP Phase III inventory and the COGCC GWA raw natural gas composition data set (Table 4 and auxiliary material Figure S6). From the total annual vented VOC source and the average vented emission profile provided by *Bar-Ilan et al.* [2008a] (auxiliary material Table S2), we derived an estimate of the volume of natural gas that we assumed is vented to the atmosphere by the oil and gas production and processing operations in Weld County. Following *Bar-Ilan et al.* [2008a] inventory data and assumptions, we used the weight fraction of total VOC in the vented gas (18.74%), the molar mass of the vented gas (21.5g/mol) and standard pressure and temperature with the ideal gas law to assume that 1 mol of raw natural gas occupies a volume 22.4 L (as was done in the WRAP Phase III inventory). The total volume of vented gas we calculate for Weld County in 2008 is 3.36 billion cubic feet (Bcf), or the equivalent of 1.68% of the total natural gas produced in the county in 2008 (202.1 Bcf). We then use the estimate of the volume of vented gas and the molar composition profiles for the 77 raw natural gas samples reported in the COGCC GWA study to compute average, minimum, and maximum emissions for CH_4, each of the C_{3-5} alkanes we measured, and C_6H_6. Using this procedure, 2008 Weld County average venting CH_4 and C_3H_8 bottom-up source estimates are 53.1 Gg/yr and 7.8 Gg/yr, respectively (Table 4).

[73] For flashing emissions, we distributed the WRAP 2008 total annual VOC source estimate (41.3 Gg/yr) using the modeled flash loss composition profiles for 16 different condensate tanks provided by the CDPHE. Average CH_4 and C_3H_8 emissions as well as the minimum and maximum estimates are reported in Table 4. The 2008 average flashing CH_4 and C_3H_8 bottom-up emission estimates are 11.2 Gg/yr and 18.3 Gg/yr, respectively (Table 4). The total flashing + venting CH_4 and C_3H_8 bottom-up estimates range from 46 to 86 Gg/yr and from 15 to 52 Gg/yr, respectively.

4.3.2. Top-Down Emissions Scenarios

[74] Finally, we use our atmospheric measurements to bring new independent constraints for the estimation of venting and flashing emissions in Weld County in 2008. The exercise consists in calculating three top-down venting emission scenarios for CH_4 and C_3H_8 (x_m, x_p: mass of methane and propane vented respectively) consistent with a mean observed CH_4-to-C_3H_8 atmospheric molar ratio of 10 ppb/ppb (Table 4) in the DJB. We assume, as done earlier in the bottom-up calculations, that the observed C_3H_8-to-CH_4 ratio in the DJB results from a combination of flashing and venting emissions. The bottom-up information used here is (1) the set of speciated flashing emissions derived earlier for the 16 condensate tanks provided by CDPHE for CH_4 and C_3H_8 $(y_m, y_p)_{\mathrm{tank}=1,16}$, and (2) three scenarios for the basin-average raw (vented) natural gas CH_4-to-C_3H_8 molar ratio, denoted $\boldsymbol{v}_{m/p}$. The three values used for basin-average vented gas CH_4-to-C_3H_8 molar ratio are: 18.75, which is the WRAP Phase III inventory assumption (scenario 1); 15.43, which is the median of the molar ratios for the COGCC GWA 77 gas samples (scenario 2); and 24.83, which is the mean of the molar ratios for the COGCC GWA 77 gas samples (scenario 3). For each vented gas profile scenario, we use the set of 16 flash emission estimates to calculate an ensemble of venting emission estimates for CH_4 (x_m) and C_3H_8 (x_p) following the two equations below.

[75] The first equation formalizes the assumption for CH_4-to-C_3H_8 molar ratio of the vented raw natural gas, with M_m (16g/mol) and M_p (44g/mol) being the molar masses of CH_4 and C_3H_8 respectively.:

$$v_{m/p} = \frac{M_p}{M_m} \times \frac{x_m}{x_p} \quad (1)$$

[76] In the second equation, the mean observed atmospheric CH_4-to-C_3H_8 molar ratio ($a_{m/p}$ = 10 ppb/ppb)

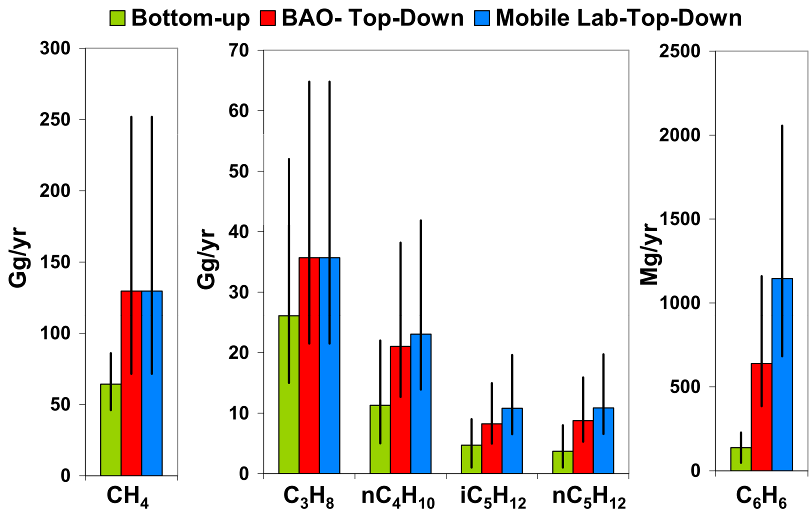

Figure 10. Bottom-up (inventory-derived) emission estimates and top-down emission scenarios for CH_4, C_3H_8, n-C_4H_{10}, i-C_5H_{12}, n-C_5H_{12} and C_6H_6 in Weld County. The vertical bars show scenario 1 average values and the error bars indicate the minimum and maximum values for the three scenarios described in Table 4.

constrains the overall ratio of methane versus propane emitted by both flashing and venting sources. Therefore, for each set of 16 bottom-up flashed emission estimates (y_m, y_p), we have:

$$\frac{M_p(x_m + y_m)}{M_m(x_p + y_p)} = a_{m/p} \tag{2}$$

[77] The analytical solutions to this set of equations are given by:

$$\begin{aligned} x_p &= \frac{1}{(v_{m/p} - a_{m/p})} \times \left(a_{m/p} \times y_p - \frac{M_p}{M_m} y_m \right) \\ x_m &= v_{m/p} \times \frac{M_m}{M_p} \times x_p \end{aligned} \tag{3}$$

[78] The average, minimum and maximum venting emission estimates, x_m and x_p, are reported for the three vented gas profile scenarios in Table 4 and Figure 10.

[79] The first goal of this top-down estimation exercise is to highlight the many assumptions required to build the bottom-up and top-down emission estimates. The choices made for the WRAP Phase III inventory or our top-down calculations are all reasonable, and the uncertainty attached to the values chosen (if available) should be propagated to calculate total uncertainty estimates for the final emission products. When the error propagation is done conservatively, the emission uncertainty is close to a factor of 2 for both CH_4 and C_3H_8. This number is much higher than the 30% uncertainty reported by the EPA for the 2009 national CH_4 source estimate from natural gas systems [*EPA*, 2011].

[80] The scenario 1 mean top-down vented CH_4 source (118.4 Gg/yr) is twice as large as the bottom-up estimate of 53.1 Gg/yr (Table 4). If we assume that 77% (by volume) of the raw gas is CH_4, an average estimate of 118.4 Gg/yr of CH_4 vented would mean that the equivalent of 4% of the 2008 natural gas gross production in Weld County was vented. It is important to note that the top-down scenarios cover a large range (67–229 Gg/yr), corresponding to between 2.3% and 7.7% of the annual production being lost to the atmosphere through venting (Table 4). The lowest estimate is, however, larger than what we derived from the WRAP Phase III bottom-up inventory (1.68%). If instead of using the *EIA* [2004] convention for the molar volume of gas (23.6 L/mol), we used the standard molar volume used by WRAP (22.4 L/mol), our top-down calculations of the volume of gas vented would be 5% lower than reported in Table 4.

[81] Emissions for the other alkanes measured are all derived from the C3H8 total sources scaled with the atmospheric molar ratios observed in the BAO NE summer samples and the Mobile Lab samples. Figure 10 shows a comparison of the bottom-up estimates and the top-down emission scenarios (mean of scenario 1 and overall minimum and maximum of the three scenarios).

[82] The main result of this exercise is that for each of the three top-down total emissions scenarios, the mean estimates for CH_4, n-C_4H_{10} and the C_5H_{12} isomers are at least 60% higher than the bottom-up mean estimates. The minimum top-down emissions scenarios are lower than (in the case of C_3H_8) or higher than (for CH_4, nC_4H_{10}, i-C_5H_{12}, n-C_5H_{12}) the bottom-up mean estimates.

[83] To put the top-down CH_4 source estimate from oil and gas exploration, production and processing operations in perspective, we compare it with an estimate of the passive "geological" CH_4 flux over the entire DJB. *Klusman and Jakel* [1998] reported an average flux of 0.57 mg $CH_4/m^2/$day in the DJB due to natural microseepage of light alkanes. Multiplied by a rough upper boundary estimate of the DJB surface area (Figure 1), the estimated annual natural flux is 0.66 Gg CH_4 /yr, or less than 1% of the top-down venting source estimated for active exploration and production of natural gas in Weld County.

4.4. Benzene Sources in the Northern Front Range

[84] On-road vehicles are estimated to be the largest source of C_6H_6 in the U.S. (EPA, 2008 report on the environment,

2009, www.epa.gov/roe). Emissions from on-road and off-road vehicles and from large point sources (including chemical plants and refineries) have been regulated by the EPA for over thirty years [*Fortin et al.*, 2005; *Harley et al.*, 2006]. When motor vehicle combustion dominates emissions, such as in the BAO S and W wind sectors, C_6H_6 correlates well with CO and C_2H_2.

[85] Crude oil and natural gas production and processing emitted an estimated 8333 tonnes of benzene nationally in 2005, which represented 2% of the national total C_6H_6 source (EPA, 2008 report on the environment, 2009, www.epa.gov/roe). C_6H_6 and C_3H_8 have similar photochemical lifetimes (~3–4 days in the summer), so the observed atmospheric ratios we report in Table 3 should be close to their emission ratio if they are emitted by a common source. The strong correlation between C_6H_6 and C_3H_8 (Figure 4 and Table 3) for the BAO NE wind sector and in the DJB Mobile Lab air samples suggests that oil and gas operations could also be a non-negligible source of C_6H_6 in the Northern Colorado Front Range.

[86] The C_6H_6-to-C_3H_8 molar ratios in the flash losses from 16 condensate tanks simulated with the EPA TANK model are between 0.4 to 5.6 ppt/ppb. The C_6H_6-to-C_3H_8 molar ratio reported for vented emissions in the WRAP Phase III inventory is 5.3 ppt/ppb, based on regionally averaged raw gas speciation profiles provided by local companies [*Bar-Ilan et al.*, 2008a] (only an average profile was provided, other data is proprietary). These emission ratios are at least a factor of two lower than the atmospheric ratios measured in the Front Range air samples influenced by the DJB source (Table 3).

[87] If we use the mean C_3H_8 emission estimate for scenario 1 described in section 4.3 (35.7 Gg/yr), together with the C_6H_6-to-C_3H_8 correlation slope for the summer BAO NE wind sector data and that from the Mobile Lab samples (10.1 ppt/ppb and 17.9 ppt/ppb respectively), we derive a C_6H_6 emission estimate for the DJB source in Weld County in 2008 of 639 tonnes/yr (min/max range: 478/883 tonnes/yr) and 1145 tonnes/yr (min/max range: 847/1564 tonnes/yr), respectively. As expected, these numbers are much higher than what we derived for the bottom-up flashing and venting emissions (total of 139 tonnes/yr, min/max range of 49–229 tonnes/yr). For comparison, C_6H_6 emissions from facilities in Colorado reporting to the U.S. EPA for the Toxics Release Inventory amounted to a total of 3.9 tonnes in 2008 (EPA, Toxics Release Inventory program, 2009, data available at http://www.epa.gov/triexplorer/chemical.htm) and on–road emissions in Weld County were estimated at 95.4 tonnes/yr in 2008 (C. LaPlante, CDPHE, personal communication, 2011). Based on our analysis, oil and gas operations in the DJB could be the largest source of C_6H_6 in Weld County.

[88] More measurements are needed to further evaluate the various potential sources associated with oil and gas operations (for example, glycol dehydrators and condensate tank flash emissions). The past two iterations of the C_6H_6 emissions inventory developed by the State of Colorado for the National Emissions Inventory and compiled by the EPA do not show much consistency from one year to another. The 2008 and 2005 NEI reported very different C_6H_6 emission estimates for condensate tanks in Weld County (21.5 Mg/yr versus 1120 Mg/yr, respectively; see also auxiliary material Table S3). Estimates in the 2008 NEI are much closer to estimates provided by CDPHE (C. LaPlante, personal communication, 2011) for 2008 (21.3 Mg/yr), suggesting the 2005 NEI estimate may be flawed, even though it is in the range of our top-down estimation. We conclude that the current level of understanding of emissions of C_6H_6 from oil and gas operations cannot explain the top-down range of estimates we derive in our study, suggesting that, once again, more field measurements are needed to understand and quantify oil and gas operation sources.

5. Conclusion

[89] This study provides a regional overview of the processes impacting ambient alkane and benzene levels in northeastern Colorado in the late 2000s. We report atmospheric observations collected by two sampling platforms: a 300-m tall tower located in the SW corner of Weld County (samples from 2007 to 2010), and road surveys by a Mobile Lab equipped with a continuous methane analyzer and discrete canister sampling (June–July 2008). The analysis of the tower data filtered by wind sector reveals a strong alkane and benzene signature in air masses coming from northeastern Colorado, where the main activity producing these compounds is related to oil and gas operations over the Denver–Julesburg Fossil Fuel Basin. Using the Mobile Lab platform, we sampled air directly downwind of different methane sources (oil and gas wells, a landfill, feedlots, and a wastewater treatment plant) and collected targeted air samples in and out of plumes. The tall tower and Mobile Lab data both revealed a common source for air masses with enhanced alkanes. In the data from both platforms, the alkane mixing ratios were strongly correlated, with slight variations in the correlation slopes depending on the location and day of sampling. The alkanes did not correlate with combustion tracers such as carbon monoxide and acetylene. We hypothesize that the observed alkanes were emitted by the same source located over the Denver-Julesburg Basin, "the DJB source."

[90] The second part of the study brings in information on VOC emissions from oil and gas activities in the DJB from the detailed bottom-up WRAP Phase III inventory [*Bar Ilan et al.*, 2008a, 2008b]. We have used the total VOC emission inventory and associated emissions data for DJB condensate and gas production and processing operations to calculate annual emission estimates for CH_4, C_3H_8, n-C_4H_{10}, i-C_5H_{12}, n-C_5H_{12} and C_6H_6 in Weld County. The main findings are summarized below:

1. The emissions profiles for flashing and venting losses are in good agreement with the atmospheric alkane enhancement ratios observed during this study and by *Goldan et al.* [1995] in Boulder in 1991. This is consistent with the hypothesis that the observed alkane atmospheric signature is due to oil and gas operations in the DJB.

2. The three top-down emission scenarios for oil and gas operations in Weld County in 2008 give a rather large range of potential emissions for CH_4 (71.6–251.9 Gg/yr) and the higher alkanes. Except for propane, the lowest top-down alkanes emission estimates are always larger than the inventory-based mean estimate we derived based on the WRAP Phase III inventory data and the COGCC GWA raw gas composition data set.

3. There are notable inconsistencies between our results and state and national regulatory inventories. In 2008 gas wells in Weld County represented 15% of the state's production. Based on our top-down analysis, Weld County methane emissions from oil and gas production and processing represent at least 30% of the state total methane source from natural gas systems derived by *Strait et al.* [2007] using the EPA State Inventory Tool. The methane source from natural gas systems in Colorado is most likely underestimated by at least a factor of two. Oil and gas operations are the largest source of alkanes in Weld County. They were included as a source of "total VOC" in the 2008 EPA NEI for Weld County but not in the 2005 NEI.

4. There are at least two main sources of C_6H_6 in the region: one related to combustion processes, which also emit CO and C_2H_2 (engines and mobile vehicles), and one related to the DJB alkane source. The C_6H_6 source we derived based on flashing and venting VOC emissions in the WRAP inventory (143 Mg/yr) most likely underestimates the actual total source of C_6H_6 from oil and gas operations. Our top-down source estimates for C_6H_6 from oil and gas operations in Weld County cover a large range: 385–2056 Mg/yr. Again, the lowest figure is much higher than reported in the 2008 CDPHE inventory for Weld County oil and gas total point sources (61.8 Mg/yr).

5. Samples collected at the BAO tall tower or while driving around the Front Range reflect the emissions from a complex mix of sources distributed over a large area. Using a multispecies analysis including both climate and air quality relevant gases, we can start unraveling the contributions of different source types. Daily multispecies measurements from the NOAA collaborative network of tall towers in the U.S. provide a unique opportunity to understand source chemical signatures in different airsheds and how these emissions may change over time.

6. More targeted multispecies well-calibrated atmospheric measurements are needed to evaluate current and future bottom-up inventory emissions calculations for the fossil fuel energy sector and to reduce uncertainties on absolute flux estimates for climate and air quality relevant trace gases.

[91] **Acknowledgments.** The authors thank John Grant (ENVIRON) and Kathleen Sgamma (Western Energy Alliance) for their expertise and support in interpreting the WRAP Phase III inventory public data. Special thanks are extended to the NOAA personnel and collaborators responsible for flask preparation, sample collection and sample analysis, data quality control and database management.

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UNEP

The Emissions Gap Report 2013

A UNEP Synthesis Report

Published by the United Nations Environment Programme (UNEP), November 2013

ISBN: 978-92-807-3353-2
DEW/1742/NA

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Citation

This document may be cited as:
UNEP 2013. The Emissions Gap Report 2013. United Nations Environment Programme (UNEP), Nairobi

A digital copy of this report along with supporting appendices are available at http://www.unep.org/emissionsgapreport2013/

This project is part of the International Climate Initiative. The Federal Ministry for the Environment, Nature Conservation and Nuclear Safely supports this initiative on the basis of a decision adopted by the German Bundestag.

Supported by:

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

Based on a decision of the Parliament of the Federal Republic of Germany

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The Emissions Gap Report 2013

A UNEP Synthesis Report

November 2013

Acknowledgements

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Thanks also to:

Keith Alverson (UNEP, Kenya), Stuart Crane (UNEP, Kenya), David Crossley (Regulatory Assistance Project, Australia), Davide D'Ambrosio (International Energy Agency, France), Shyamasree Dasgupta (Jadavpur University, India), Justine Garrett (International Energy Agency, France), Antonia Gawel (Independent Consultant, Bhutan), Michael Grubb (University of Cambridge, United Kingdom), James Arthur Haselip (UNEP Risø Centre, Denmark), Michael Mendelsohn (National Renewable Energy Laboratory, USA), Pedro Filipe Paralta Carqueija (UNEP Risø Centre, Denmark), Daniel Perczyk (Instituto Torcuato Di Tella, Argentina), Lynn Price (Lawrence Berkeley National Laboratory, USA), Wilson Rickerson (Meister Consultants Group, USA), Joyashree Roy (Jadavpur University, India), Misato Sato (London School of Economics, United Kingdom), Janet Sawin (Sunna Research, USA), Andrew Scott (Overseas Development Institute, United Kingdom), Jacob Krog Søbygaard (Ministry of Climate, Energy and Buildings, Denmark), Geng Yong (National Academy of Sciences, China), Changhua Wu (The Climate Group, China).

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Contents

Glossary

The entries in this glossary are adapted from definitions provided by authoritative sources, such as the Intergovernmental Panel on Climate Change.

Additionality A criterion sometimes applied to projects aimed at reducing greenhouse gas emissions. It stipulates that the emission reductions accomplished by the project would not have happened anyway had the project not taken place.

Aerosols Airborne solid or liquid particles, with a typical size of between 0.01 and 10 micrometer (a millionth of a meter) that reside in the atmosphere for at least several hours. They may influence the climate directly through scattering and absorbing radiation, and indirectly by modifying the optical properties and lifetime of clouds.

Agroforestry Farming management practice characterized by the deliberate inclusion of woody perennials on farms, which usually leads to significant economic and/or ecological benefits between woody and non-woody system components. In most documented cases of successful agroforestry, tree-based systems are more productive, more sustainable and more attuned to people's cultural or material needs than treeless alternatives. Agroforestry also provides significant mitigation benefits by sequestering carbon from the atmosphere in the tree biomass.

Annex I countries The industrialised countries (and those in transition to a market economy) that took on obligations to reduce their greenhouse gas emissions under the United Nations Framework Convention on Climate Change.

Biomass plus carbon capture and storage (BioCCS) Use of energy produced from biomass where the combustion gases are then captured and stored underground or used, for example, in industrial processes. Gases generated through, for example, a fermentation process (as opposed to combustion) can also be captured.

Black carbon The substance formed through the incomplete combustion of fossil fuels, biofuels, and biomass, which is emitted in both anthropogenic and naturally occurring soot. It consists of pure carbon in several linked forms. Black carbon warms the Earth by absorbing heat in the atmosphere and by reducing albedo, the ability to reflect sunlight, when deposited on snow and ice.

Bottom-up model In the context of this report, a model that represents a system by looking at its detailed underlying parts. For example, a bottom-up model of emissions would compute the various sources of emissions, sector-by-sector, and then add these components together to get a total emissions estimate.

Business-as-usual In the context of this report, a scenario used for projections of future emissions that assumes that no new action will be taken to mitigate emissions.

Carbon credits Tradable permits which aim to reduce greenhouse gas emissions by giving them a monetary value.

Carbon dioxide equivalent (CO_2e) A simplified way to place emissions of various radiative forcing agents on a common footing by accounting for their effect on climate. It describes, for a given mixture and amount of greenhouse gases, the amount of carbon dioxide that would have the same global warming ability, when measured over a specified time period. For the purpose of this report, greenhouse gas emissions (unless otherwise specified) are the sum of the basket of greenhouse gases listed in Annex A of the Kyoto Protocol, expressed as carbon dioxide equivalents assuming a 100-year global warming potential.

Carbon leakage The increase in greenhouse gas emissions occurring outside countries taking domestic mitigation action.

Conditional pledge Pledges made by some countries that are contingent on the ability of national legislatures to enact the necessary laws, ambitious action from other countries, realization of finance and technical support, or other factors.

Double counting In the context of this report, double counting refers to a situation in which the same emission reductions are counted towards meeting two countries' pledges.

Emission pathway The trajectory of annual global greenhouse gas emissions over time.

Greenhouse gases covered by the Kyoto Protocol These include the six main greenhouse gases, as listed in Annex A of the Kyoto Protocol: carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); hydrofluorocarbons (HFCs); perfluorocarbons (PFCs); and sulphur hexafluoride (SF_6).

Integrated assessment models Models that seek to combine knowledge from multiple disciplines in the form of equations and/or algorithms in order to explore complex environmental problems. As such, they describe the full chain of climate change, including relevant links and feedbacks between socio-economic and biophysical processes.

International cooperative initiatives Initiatives outside of the United Nations Framework Convention on Climate Change aimed at reducing emissions of greenhouse gases by promoting actions that are less greenhouse gas intensive, compared to prevailing alternatives.

Kyoto Protocol The international environmental treaty intended to reduce greenhouse gas emissions. It builds upon the United Nations Framework Convention on Climate Change.

Later-action scenarios Climate change mitigation scenarios in which emission levels in the near term, typically up to 2020 or 2030, are higher than those in the corresponding least-cost scenarios.

Least-cost scenarios Climate change mitigation scenarios assuming that emission reductions start immediately after the model base year, typically 2010, and are distributed optimally over time, such that aggregate costs of reaching the climate target are minimized.

Lenient rules Pledge cases with maximum Annex I land use, land-use change and forestry (LULUCF) credits and surplus emissions units, and maximum impact of double counting.

Likely chance A likelihood greater than 66 percent. Used in this report to convey the probabilities of meeting temperature limits.

Medium chance A likelihood of 50–66 percent. Used in this report to convey the probabilities of meeting temperature limits.

Montreal Protocol The Montreal Protocol on Substances that Deplete the Ozone Layer is an international treaty that was designed to reduce the production and consumption of ozone-depleting substances in order to reduce their abundance in the atmosphere, and thereby protect the Earth's ozone layer.

Non-Annex I countries A group of developing countries that have signed and ratified the United Nations Framework Convention on Climate Change. They do not have binding emission reduction targets.

No-tillage agriculture Farming practice characterized by the elimination of soil ploughing by seeding a crop directly under the mulch layer from the previous crop. It relies on permanent soil cover by organic amendments, and the diversification of crop species grown in sequences and/or association. This approach avoids emissions caused by soil disturbances related to ploughing, and from burning fossil fuels to run farm machinery for ploughing.

Pledge For the purpose of this report, pledges include Annex I targets and non-Annex I actions, as included in Appendix I and Appendix II of the Copenhagen Accord, and subsequently revised and updated in some instances.

Radiative forcing Change in the net, downward minus upward, irradiance, expressed in watts per square meter (W/m^2), at the tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun. For the purposes of this report, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value.

Scenario A description of how the future may unfold based on if-then propositions. Scenarios typically include an initial socio-economic situation and a description of the key driving forces and future changes in emissions, temperature or other climate change-related variables.

Strict rules Pledge cases in which the impact of land use, land-use change and forestry (LULUCF) credits and surplus emissions units are set to zero.

Top-down model A model that applies macroeconomic theory, econometric and optimisation techniques to aggregate economic variables. Using historical data on consumption, prices, incomes, and factor costs, top-down models assess final demand for goods and services, and supply from main sectors, such as energy, transportation, agriculture and industry.

Transient climate response Measure of the temperature rise that occurs at the time of a doubling of CO_2 concentration in the atmosphere.

Transient climate response to cumulative carbon emissions Measure of temperature rise per unit of cumulative carbon emissions.

Unconditional pledges Pledges made by countries without conditions attached.

20^{th}–80^{th} percentile range Results that fall within the 20–80 percent range of the frequency distribution of results in this assessment.

Acronyms

AAU	Assigned Amount Unit
ADP	Ad Hoc Working Group on the Durban Platform
AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
AWD	Alternate Wetting and Drying
BaU	Business-as-Usual
BC	black carbon
BioCCS	Bio-energy combined with Carbon Capture and Storage
BP	British Petroleum
BRT	Bus Rapid Transit
CCAC	Climate and Clean Air Coalition to Reduce Short-lived Climate Pollutants
CCS	Carbon Capture and Storage
CDIAC	Carbon Dioxide Information Analysis Center
CDM	Clean Development Mechanism
CEM	Clean Energy Ministerial
CER	Certified Emission Reduction
CFC	chlorofluorocarbon
CO_2e	Carbon Dioxide Equivalent
COP	Conference of the Parties to the United Nations Framework Convention on Climate Change
CP1	First Commitment Period of the Kyoto Protocol
CP2	Second Commitment Period of the Kyoto Protocol
EDGAR	Emissions Database for Global Atmospheric Research
EIA	Energy Information Administration
ERU	Emission Reduction Unit
EU-ETS	EU Emissions Trading System
GDP	Gross Domestic Product
GEA	Global Energy Assessment
GHG	greenhouse gas
Gt	gigatonne
GWP	Global Warming Potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
IAM	Integrated Assessment Model
ICAO	International Civil Aviation Organization
ICI	International Cooperative Initiative
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-Use Change and Forestry
NAMA	Nationally Appropriate Mitigation Action
NGO	Non-Governmental Organization
OC	organic carbon
ODS	ozone depleting substances
PAM	policies and measures
PPP	Purchasing Power Parity
PV	photovoltaic
RD&D	research, development and demonstration
REDD+	Reduced Emissions from Deforestation and Forest Degradation
RPS	Renewable Portfolio Standards
SO_2	sulphur dioxide
SOC	soil organic carbon
TCR	transient climate response
TCRE	transient climate response to cumulative carbon emissions
UDP	urea deep placement
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

Foreword

The latest assessment by Working Group I of the Intergovernmental Panel on Climate Change, released earlier this year, concluded that climate change remains one of the greatest challenges facing society. Warming of the climate system is unequivocal, human-influenced, and many unprecedented changes have been observed throughout the climate system since 1950. These changes threaten life on Earth as we know it. Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. But how much reduction is needed?

Further to the Copenhagen Accord of 2009 and the Cancún agreements in 2010, international efforts under the United Nations Framework Convention on Climate Change are focused on keeping the average rise in global temperature to below 2° C, compared to pre-industrial levels. Current commitments and pledges by developed and developing nations can take the world part of the way towards achieving this 2° C target, but this assessment shows that the there is still a significant gap between political ambition and practical reality. In short, additional emission reductions are needed.

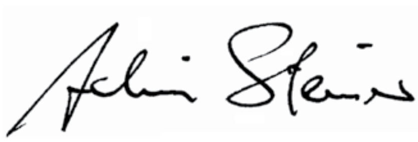
With this fourth assessment of the gap between ambitions and needs, the United Nations Environment Programme seeks to inform governments and the wider public on how far the response to climate change has progressed over the past year, and thus whether the world is on track to meet the 2° C target. In addition to reviewing national pledges and actions, this year's assessment, for the first time, also reviews international cooperative initiatives which, while potentially overlapping, serve to complement national pledges and actions.

From a technical standpoint, meeting the 2° C target remains possible: it will take a combination of full implementation of current national pledges and actions, a scaling up of the most effective international cooperative initiatives, and additional mitigation efforts at the country level. All these efforts will require strengthened policies aimed at curbing greenhouse gas emissions. Crucially, they also require the promotion of development pathways that can concomitantly reduce emissions.

As in the previous assessment, this year's report provides updated analyses of a number of tried and tested sector-specific policy options to achieve this goal. Specifically, we show that actions taken in the agricultural sector can lower emissions and boost the overall sustainability of food production. Replicating these successful policies, and scaling them up, would provide one option for countries to go beyond their current pledges and help close the 'emissions gap'.

The challenge we face is neither a technical nor policy one – it is political: the current pace of action is simply insufficient. The technologies to reduce emission levels to a level consistent with the 2° C target are available and we know which policies we can use to deploy them. However, the political will to do so remains weak. This lack of political will has a price: we will have to undertake steeper and more costly actions to potentially bridge the emissions gap by 2020.

This report is a call for political action. I hope that, by providing high quality evidence and analysis, it will achieve its goal of supporting international climate change negotiations.



Achim Steiner
UN Under-Secretary-General,
UNEP Executive Director

Executive summary

The emissions gap in 2020 is the difference between emission levels in 2020 consistent with meeting climate targets, and levels expected in that year if country pledges and commitments are met. As it becomes less and less likely that the emissions gap will be closed by 2020, the world will have to rely on more difficult, costlier and riskier means after 2020 of keeping the global average temperature increase below 2° C. If the emissions gap is not closed, or significantly narrowed, by 2020, the door to many options limiting the temperature increase to 1.5° C at the end of this century will be closed.

Article 2 of the United Nations Framework Convention on Climate Change ('Climate Convention') declares that its "*ultimate objective*" is to "*[stabilize] greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*". The parties to the Climate Convention have translated this objective into an important, concrete target for limiting the increase in global average temperature to 2° C, compared to its pre-industrial levels. With the aim of meeting this target, many of the parties have made emission reduction pledges, while others have committed to reductions under the recent extension of the Kyoto Protocol.

Since 2010, the United Nations Environment Programme has facilitated an annual independent analysis of those pledges and commitments, to assess whether they are consistent with a least-cost approach to keep global average warming below 2° C [1]. This report confirms and strengthens the conclusions of the three previous analyses that current pledges and commitments fall short of that goal. It further says that, as emissions of greenhouse gases continue to rise rather than decline, it becomes less and less likely that emissions will be low enough by 2020 to be on a least-cost pathway towards meeting the 2° C target[2].

As a result, after 2020, the world will have to rely on more difficult, costlier and riskier means of meeting the target – the further from the least-cost level in 2020, the higher these costs and the greater the risks will be. If the gap is not closed or significantly narrowed by 2020, the door to many options to limit temperature increase to 1.5° C at the end of this century will be closed, further increasing the need to rely on accelerated energy-efficiency increases and biomass with carbon capture and storage for reaching the target.

[1] For this report, a least-cost approach means that emissions are reduced by the cheapest means available.

[2] For this report, a least-cost pathway or a least-cost emissions pathway or least-cost emission scenarios mean the same thing – the temporal pathway of global emissions that meets a climate target and that also takes advantage of the lowest-cost options available for reducing emissions.

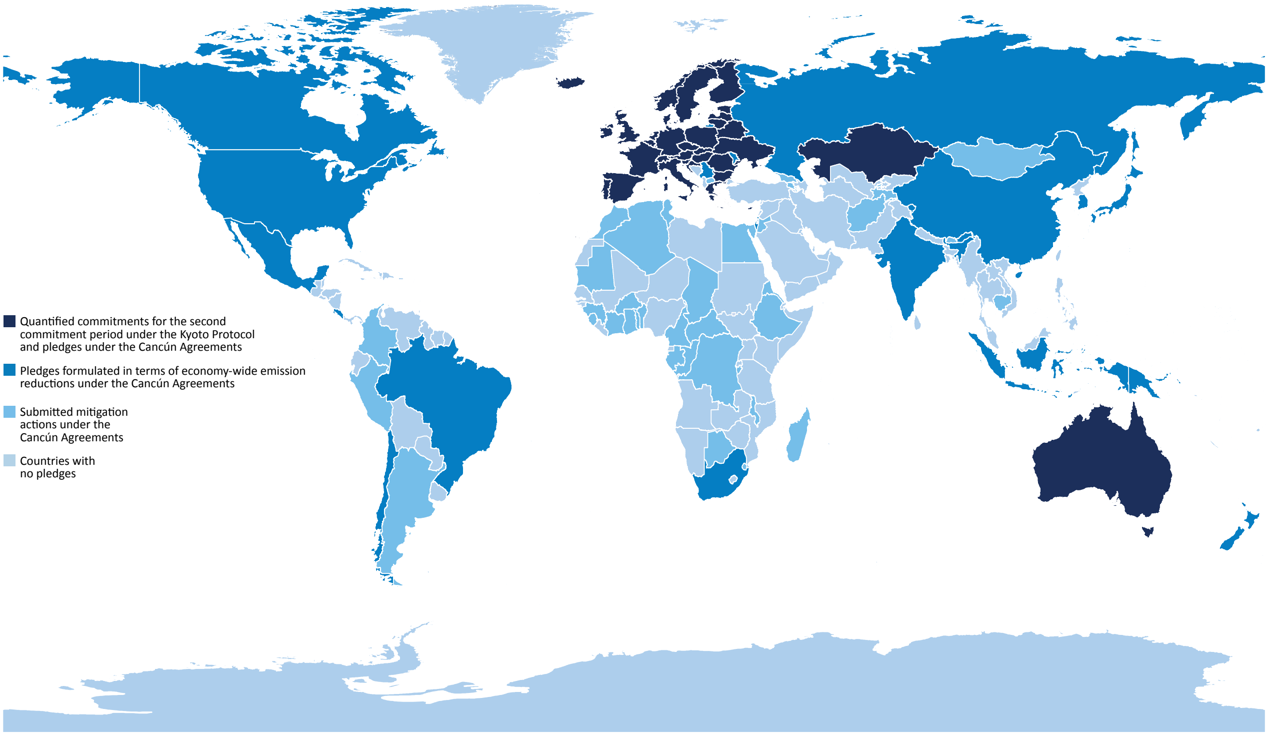
1. What are current global emissions?

Current global greenhouse gas emission levels are considerably higher than the levels in 2020 that are in line with meeting the 1.5° C or 2° C targets, and are still increasing. In 2010, in absolute levels, developing countries accounted for about 60 percent of global greenhouse gas emissions.

The most recent estimates of global greenhouse gas emissions are for 2010 and amount to 50.1 gigatonnes of carbon dioxide equivalent ($GtCO_2e$) per year (range: 45.6–54.6 $GtCO_2e$ per year). This is already 14 percent higher than the median estimate of the emission level in 2020 with a likely chance of achieving the least cost pathway towards meeting the 2° C target (44 $GtCO_2e$ per year)[3]. With regards to emissions in 2010, the modelling groups report a median value of 48.8 $GtCO_2e$, which is within the uncertainty range cited above. For consistency with emission scenarios, the figure of 48.8 $GtCO_2e$ per year is used in the calculation of the pledge case scenarios.

Relative contributions to global emissions from developing and developed countries changed little from 1990 to 1999. However, the balance changed significantly between 2000 and 2010 – the developed country share decreased from 51.8 percent to 40.9 percent, whereas developing country emissions increased from 48.2 percent to 59.1 percent. Today developing and developed countries are responsible for roughly equal shares of cumulative greenhouse gas emissions for the period 1850-2010.

[3] See footnote 2.



Note:
Following the 2012 conference of the parties to the Climate Convention in Doha, a group of countries has adopted reduction commitments for the second commitment period under the Kyoto Protocol
Source: United Nations Framework Convention on Climate Change

2. What emission levels are anticipated for 2020?

Global greenhouse gas emissions in 2020 are estimated at 59 GtCO$_2$e per year under a business-as-usual scenario. If implemented fully, pledges and commitments would reduce this by 3–7 GtCO$_2$e per year. It is only possible to confirm that a few parties are on track to meet their pledges and commitments by 2020.

Global greenhouse gas emissions in 2020 are estimated at 59 GtCO$_2$e per year (range: 56–60 GtCO$_2$e per year) under a business-as-usual scenario – that is, a scenario that only considers existing mitigation efforts. This is about 1 GtCO$_2$e higher than the estimate in the 2012 emissions gap report.

There have been no significant changes in the pledges and commitments made by parties to the Climate Convention since the 2012 assessment. However, both rules of accounting for land-use change and forestry, and rules for the use of surplus allowances from the Kyoto Protocol's first commitment period have been tightened.

Implementing the pledges would reduce emissions by 3–7 GtCO$_2$e, compared to business-as-usual emission levels.

A review of available evidence from 13 of the parties to the Climate Convention that have made pledges or commitments indicates that five – Australia, China, the European Union, India and the Russian Federation – appear to be on track to meet their pledges. Four parties – Canada, Japan, Mexico and the U.S. – may require further action and/or purchased offsets to meet their pledges, according to government and independent estimates of projected national emissions in 2020. A fifth party – the Republic of Korea – may also require further action but this could not be verified based on government estimates. However, new actions now being taken by all five of these parties many enable them to meet their pledges, although the impact of these actions have not been analyzed here. Not enough information is available concerning Brazil, Indonesia and South Africa. It is worth noting that being on track to implement pledges does not equate to being on track to meet the 1.5° C or 2° C temperature targets.

3. What is the latest estimate of the emissions gap in 2020?

Even if pledges are fully implemented, the emissions gap in 2020 will be 8–12 GtCO$_2$e per year, assuming least-cost emission pathways. Limited available information indicates that the emissions gap in 2020 to meet a 1.5° C target in 2020 is a further 2–5 GtCO$_2$e per year wider.

Least-cost emission pathways consistent with a likely chance of keeping global mean temperature increases below 2° C compared to pre-industrial levels have a median level of 44 GtCO$_2$e in 2020 (range: 38–47 GtCO$_2$e)[4]. Assuming full implementation of the pledges, the emissions gap thus amounts to between 8–12 GtCO$_2$e per year in 2020 (Table 1).

Governments have agreed to more stringent international accounting rules for land-use change and surplus allowances for the parties to the Kyoto Protocol. However, it is highly uncertain whether the conditions currently attached to the high end of country pledges will be met. Therefore, it is more probable than not that the gap in 2020 will be at the high end of the 8–12 GtCO$_2$e range.

Limiting increases in global average temperature further to 1.5° C compared to pre-industrial levels requires emissions in 2020 to be even lower, if a least-cost path towards achieving this objective is followed. Based on a limited number of new studies, least-cost emission pathways consistent with the 1.5° C target have emission levels in 2020 of 37–44 GtCO$_2$e per year, declining rapidly thereafter.

[4] See footnote 2.

4. What emission levels in 2025, 2030 and 2050 are consistent with the 2° C target?

Least-cost emission pathways consistent with a likely chance of meeting a 2° C target have global emissions in 2050 that are 41 and 55 percent, respectively, below emission levels in 1990 and 2010.

Given the decision at the 17th Conference of the Parties to the Climate Convention in 2011 to complete negotiations on a new binding agreement by 2015 for the period after 2020, it has become increasingly important to estimate global emission levels in 2025 and thereafter that are likely to meet the 2° C target. In the scenarios assessed in this report, global emission levels in 2025 and 2030 consistent with the 2° C target amount to approximately 40 $GtCO_2e$ (range: 35–45 $GtCO_2e$) and 35 $GtCO_2e$ (range: 32–42 $GtCO_2e$), respectively. In these scenarios, global emissions in 2050 amount to 22 $GtCO_2e$ (range: 18–25 $GtCO_2e$). These levels are all based on the assumption that the 2020 least-cost level of 44 $GtCO_2e$ per year will be achieved.

5. What are the implications of least-cost emission pathways that meet the 1.5° C and 2° C targets in 2020?

The longer that decisive mitigation efforts are postponed, the higher the dependence on negative emissions in the second half of the 21st century to keep the global average temperature increase below 2° C. The technologies required for achieving negative emissions may have significant negative environmental impacts.

Scenarios consistent with the 1.5° C and 2° C targets share several characteristics: higher-than-current emission reduction rates throughout the century; improvements in energy efficiency and the introduction of zero- and low-carbon technologies at faster rates than have been experienced historically over extended periods; greenhouse gas emissions peaking around 2020; net negative carbon dioxide emissions from the energy and industrial sectors in the second half of the century[5] and an accelerated shift toward electrification[6].

The technologies required for achieving negative emissions in the energy and industrial sectors have not yet been deployed on a large scale and their use may have significant impacts, notably on biodiversity and water supply. Because of this, some scenarios explore the emission reductions required to meet temperature targets without relying on negative emissions. These scenarios require maximum emissions in 2020 of 40 $GtCO_2e$ (range: 36–44 $GtCO_2e$), as compared to a median of 44 $GtCO_2e$ for the complete set of least-cost scenarios.

6. What are the implications of later action scenarios that still meet the 1.5° C and 2° C targets?

Based on a much larger number of studies than in 2012, this update concludes that so-called later-action scenarios have several implications compared to least-cost scenarios, including: (i) much higher rates of global emission reductions in the medium term; (ii) greater lock-in of carbon-intensive infrastructure; (iii) greater dependence on certain technologies in the medium-term; (iv) greater costs of mitigation in the medium- and long-term, and greater risks of economic disruption; and (v) greater risks of failing to meet the 2° C target. For these reasons later-action scenarios may not be feasible in practice and, as a result, temperature targets could be missed.

The estimates of the emissions gap in this and previous reports are based on least-cost scenarios, which characterize trends in global emissions up to 2100 under the assumption that climate targets will be met by the cheapest combination of policies, measures and technologies. But several new studies using a different type of scenario are now available – later-action scenarios, which assume that a least-cost trajectory is not followed immediately, but rather forwards from a specific future date. Like least-cost scenarios, later-action scenarios chart pathways that are consistent with the 2° C target. Contrary to least-cost scenarios, later-action scenarios assume higher global emissions in the near term, which are compensated by deeper reductions later, typically, after 2020 or 2030.

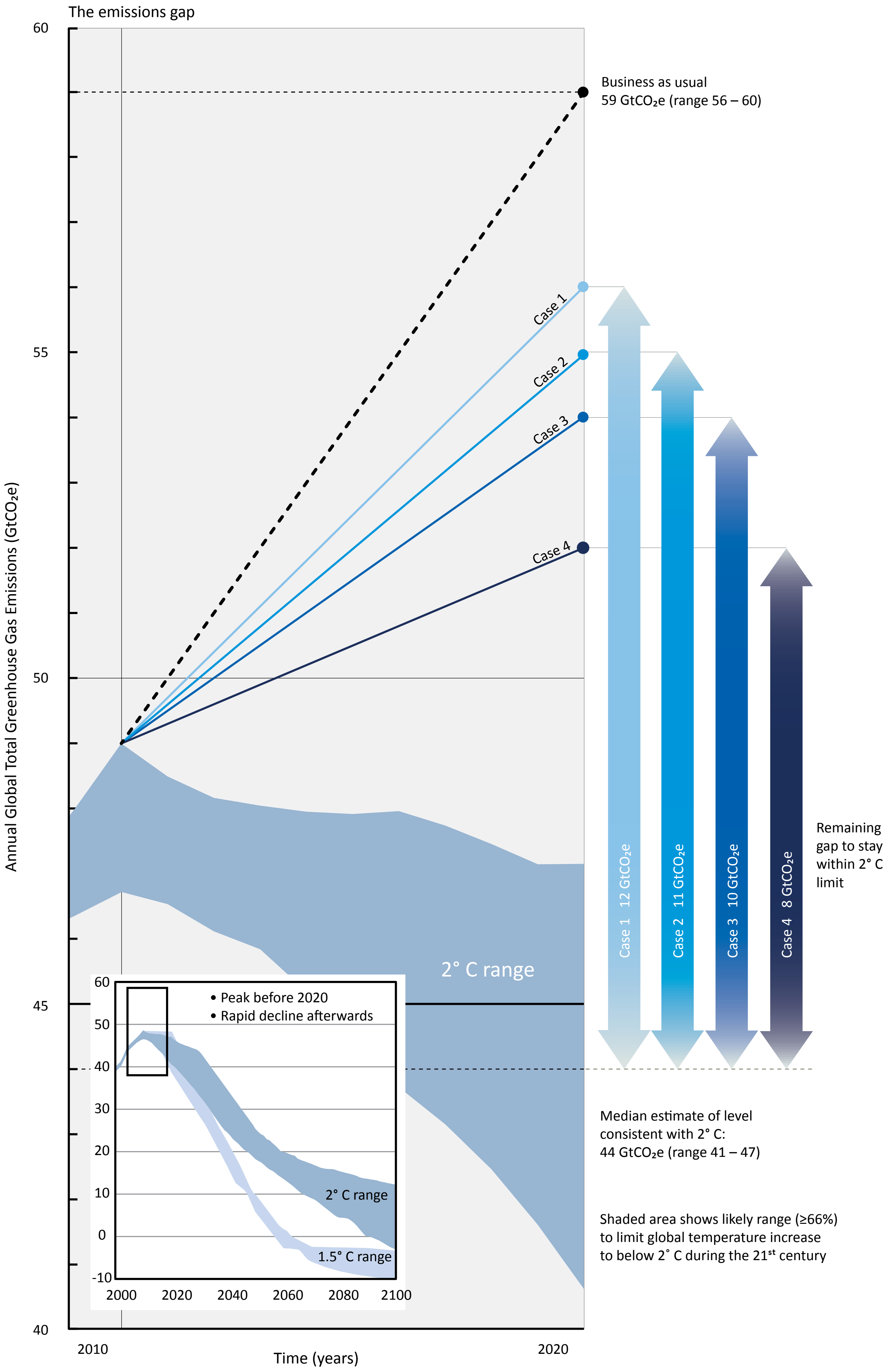
For least-cost scenarios, emission reduction rates for 2030–2050 consistent with a 2° C target are 2–4.5 percent per year. Historically, such reductions have been achieved in a small number of individual countries, but not globally. For later-action scenarios, the corresponding emission reduction rates would have to be substantially higher, for example, 6–8.5 percent if emission reductions remain modest until 2030. These emission reduction rates are without historic precedent over extended periods of time. Furthermore, and because of the delay between policy implementation and actual emission reductions, achieving such high rates of change would require mitigation policies to be adopted several years before the reductions begin.

Apart from assuming higher global emissions in the near term, later-action scenarios also have fewer options for reducing emissions when concerted action finally begins after 2020 or 2030. This is because of carbon lock-in – the continued construction of high-emission fossil-fuel infrastructure unconstrained by climate policies. Because technological infrastructure can have life-times of up to several decades, later-action scenarios effectively lock-in in these high-emission alternatives for a long period of time.

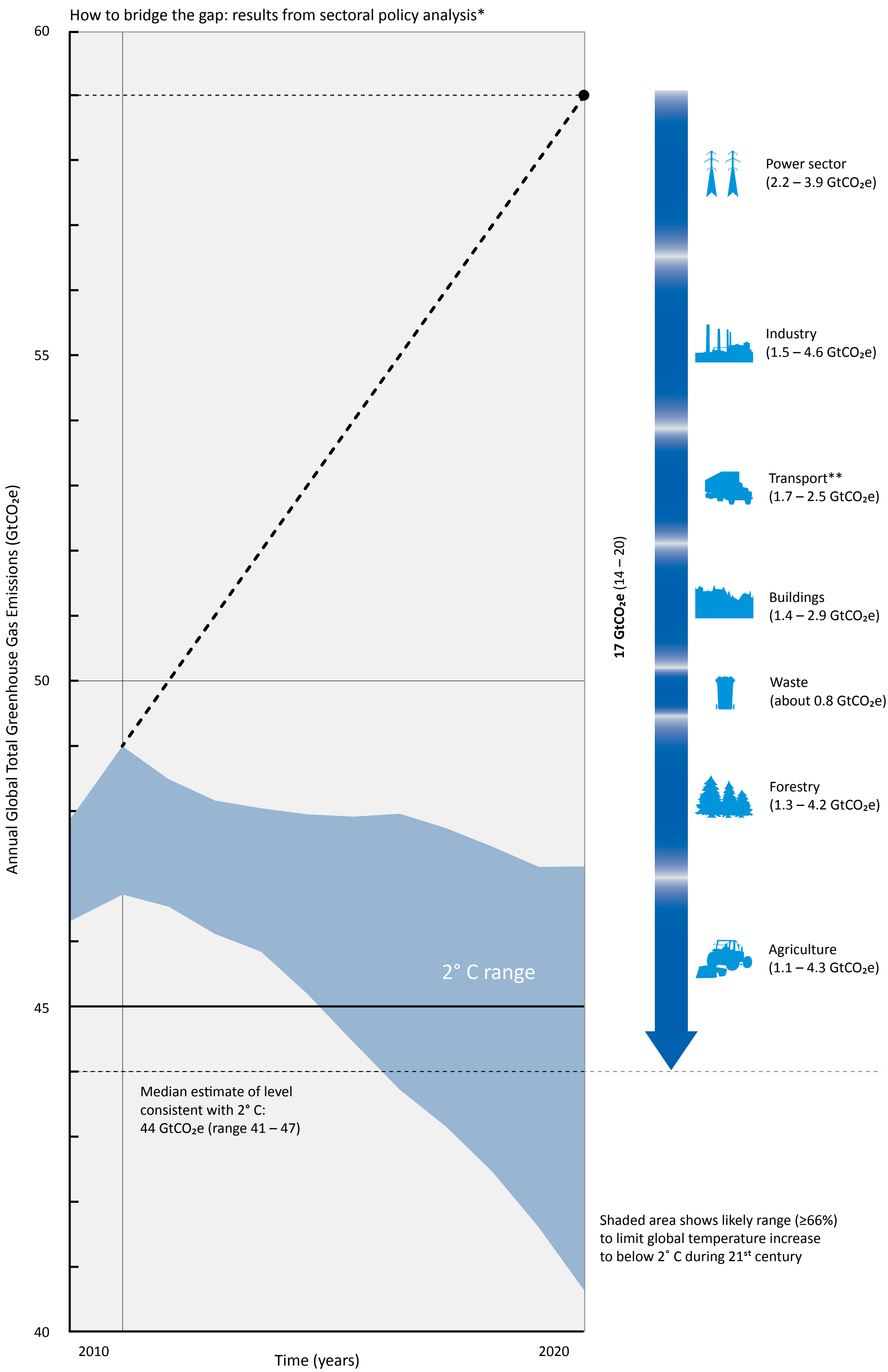
By definition, later-action scenarios are more expensive than least-cost scenarios. The actual cost penalty of later action depends on the future availability of technologies when comprehensive mitigation actions finally begin, as well as on the magnitude of emission reductions up to that point. Finally, although later-action scenarios might reach the same temperature targets as their least-cost counterparts, later-action scenarios pose greater risks of climate impacts for four reasons. First, delaying action allows more greenhouse gases to build-up in the atmosphere in the near term, thereby increasing the risk that later emission reductions will be unable to compensate for this build up. Second, the risk of overshooting climate targets for both atmospheric concentrations of greenhouse gases and global temperature increase is higher with later-action scenarios.

[5] For most scenarios.

[6] Net negative carbon dioxide emissions from the energy and industrial sectors refers to the potential to actively remove more carbon dioxide from the atmosphere than is emitted within a given period of time. Negative emissions can be achieved through, among other means, bioenergy in combination with carbon capture and storage.



The emissions gap
60
55
50
45
40
Annual Global Total Greenhouse Gas Emissions ($GtCO_2e$)
2010
2020
Time (years)
Business as usual
59 $GtCO_2e$ (range 56 – 60)
Case 1
Case 2
Case 3
Case 4
Case 1 12 $GtCO_2e$
Case 2 11 $GtCO_2e$
Case 3 10 $GtCO_2e$
Case 4 8 $GtCO_2e$
Remaining gap to stay within 2° C limit
2° C range
Median estimate of level consistent with 2° C:
44 $GtCO_2e$ (range 41 – 47)
Shaded area shows likely range (≥66%) to limit global temperature increase to below 2° C during the 21st century
• Peak before 2020
• Rapid decline afterwards
60
50
40
30
20
10
0
-10
2000
2020
2040
2060
2080
2100
2° C range
1.5° C range



*based on results from Bridging the Emissions Gap Report 2011
**including shipping and aviation

Third, the near-term rate of temperature increase is higher, which implies greater near-term climate impacts. Lastly, when action is delayed, options to achieve stringent levels of climate protection are increasingly lost.

7. Can the gap be bridged by 2020?

The technical potential for reducing emissions to levels in 2020 is still estimated at about 17 ± 3 $GtCO_2e$. This is enough to close the gap between business-as-usual emission levels and levels that meet the 2° C target, but time is running out.

Sector-level studies of emission reductions reveal that, at marginal costs below US $50–100 per tonne of carbon dioxide equivalent, emissions in 2020 could be reduced by 17 ± 3 $GtCO_2e$, compared to business-as-usual levels in that same year. While this potential would, in principle, be enough to reach the least-cost target of 44 $GtCO_2e$ in 2020, there is little time left.

There are many opportunities to narrow the emissions gap in 2020 as noted in following paragraphs, ranging from applying more stringent accounting practices for emission reduction pledges, to increasing the scope of pledges. To bridge the emissions gap by 2020, all options should be brought into play.

8. What are the options to bridge the emissions gap?

The application of strict accounting rules for national mitigation action could narrow the gap by 1–2 $GtCO_2e$. In addition, moving from unconditional to conditional pledges could narrow the gap by 2–3 $GtCO_2e$, and increasing the scope of current pledges could further narrow the gap by 1.8 $GtCO_2e$. These three steps can bring us halfway to bridging the gap. The remaining gap can be bridged through further national and international action, including international cooperative initiatives. Much of this action will help fulfil national interests outside of climate policy.

Minimizing the use of lenient land-use credits and of surplus emission reductions, and avoiding double counting of offsets could narrow the gap by about 1–2 $GtCO_2e$. Implementing the more ambitious conditional pledges (rather than the unconditional pledges) could narrow the gap by 2–3 $GtCO_2e$. A range of actions aimed at increasing the scope of current pledges could narrow the gap by an additional 1.8 $GtCO_2e$. (These include covering all emissions in national pledges, having all countries pledge emission reductions, and reducing emissions from international transport). Adding together the more stringent accounting practices, the more ambitious pledges, and the increased scope of current pledges, reduces the gap around 6 $GtCO_2e$ or by about a half.

The remaining gap can be bridged through further national and international action, including international cooperative initiatives (see next point). Also important is the fact that many actions to reduce emissions can help meet other national and local development objectives such as reducing air pollution or traffic congestion, or saving household energy costs.

9. How can international cooperative initiatives contribute to narrowing the gap?

There is an increasing number of international cooperative initiatives, through which groups of countries and/or other entities cooperate to promote technologies and policies that have climate benefits, even though climate change mitigation may not be the primary goal of the initiative. These efforts have the potential to help bridge the gap by several $GtCO_2e$ in 2020.

International cooperative initiatives take the form of either global dialogues (to exchange information and understand national priorities), formal multi-lateral processes (addressing issues that are relevant to the reduction of GHG emissions), or implementation initiatives (often structured around technical dialogue fora or sector-specific implementation projects). Some make a direct contribution to climate change mitigation, by effectively helping countries reduce emissions, while others contribute to this goal indirectly, for example through consensus building efforts or the sharing of good practices among members.

The most important areas for international cooperative initiatives appear to be:

- Energy efficiency (up to 2 $GtCO_2e$ by 2020): covered by a substantial number of initiatives.
- Fossil fuel subsidy reform (0.4–2 $GtCO_2e$ by 2020): the number of initiatives and clear commitments in this area is limited.
- Methane and other short-lived climate pollutants (0.6–1.1 $GtCO_2e$ by 2020); this area is covered by one overarching and several specific initiatives. (Reductions here may occur as a side effect of other climate mitigation.)
- Renewable energy (1–3 $GtCO_2e$ by 2020): several initiatives have been started in this area.

Based on limited evidence, the following provisions could arguably enhance the effectiveness of International Cooperative Initiatives: (i) a clearly defined vision and mandate with clearly articulated goals; (ii) the right mix of participants appropriate for that mandate, going beyond traditional climate negotiators; (iii) stronger participation from developing country actors; (iv) sufficient funding and an institutional structure that supports implementation and follow-up, but maintains flexibility; and (v) and incentives for participants.

10. How can national agricultural policies promote development while substantially reducing emissions?

Agriculture now contributes about 11 percent to global greenhouse gas emissions. The estimated emission reduction potential for the sector ranges from 1.1 $GtCO_2e$ to 4.3 $GtCO_2e$ in 2020. Emission reductions achieved by these initiatives may partly overlap with national pledges, but in some cases may also be additional to these.

Not many countries have specified action in the agriculture sector as part of implementing their pledges. Yet, estimates of emission reduction potentials for the sector are high, ranging from 1.1 $GtCO_2e$ to 4.3 $GtCO_2e$ – a wide range, reflecting uncertainties in the estimate. In this year's update we describe policies that have proved to be effective

Table 1 Emissions reductions with respect to business-as-usual and emissions gap in 2020, by pledge case

Case	Pledge type	Rule type	Median emission levels and range ($GtCO_2e$ per year)	Reductions with respect to business-as-usual in 2020 ($GtCO_2e$ per year)	Emissions gap in 2020 ($GtCO_2e$ per year)
Case 1	Unconditional	Lenient	56 (54–56)	3	12
Case 2	Unconditional	Strict	55 (53–55)	4	11
Case 3	Conditional	Lenient	54 (52–54)	5	10
Case 4	Conditional	Strict	52 (50–52)	7	8

Note: In this report, an unconditional pledge is one made without conditions attached. A conditional pledge might depend on the ability of a national legislature to enact necessary laws, or may depend on action from other countries, or on the provision of finance or technical support. Strict rules means that allowances from land use, land-use change and forestry accounting and surplus emission credits will not be counted as part of a country's meeting their emissions reduction pledges. Under lenient rules, these elements can be counted.

in reducing emissions and increasing carbon uptake in the agricultural sector.

In addition to contributing to climate change mitigation, these measures enhance the sector's environmental sustainability and, depending on the measure and situation, may provide other benefits such as higher yields, lower fertilizer costs or extra profits from wood supply. Three examples are:

– Usage of no-tillage practices: no-tillage refers to the elimination of ploughing by direct seeding under the mulch layer of the previous season's crop. This reduces greenhouse gas emissions from soil disturbance and from fossil-fuel use of farm machinery.
– Improved nutrient and water management in rice production: this includes innovative cropping practices such as alternate wetting and drying and urea deep placement that reduce methane and nitrous oxide emissions.
– Agroforestry: this consists of different management practices that all deliberately include woody perennials on farms and the landscape, and which increase the uptake and storage of carbon dioxide from the atmosphere in biomass and soils.

Chapter 1

Introduction

In December of 2009, 114 parties to the United Nations Framework Convention on Climate Change (the 'Climate Convention') agreed to the Copenhagen Accord[1]. Among the important provisions of the accord was the call to parties to submit voluntary emission reduction pledges for the year 2020. To date, 42 developed countries have responded to this call and submitted economy-wide greenhouse gas emission reduction pledges, 16 developing countries have submitted multi-sector expected emission reductions, and in addition 39 other developing countries have submitted pledges related to sectoral goals[2]. Another important provision was the setting of a target to keep the increase in global average temperature below 2°C relative to pre-industrial levels. In the wake of these two provisions, some very critical questions arose:

– Are the pledges for 2020 enough to keep the world on track to meet the 2° C target?
– Will there be a gap between where we need to be in 2020 versus where we expect to be?

UNEP, together with the scientific community, took on these questions in a report published just ahead of the Climate Convention meeting in Cancún in late 2010 (UNEP, 2010). This "emissions gap" report synthesized the latest scientific knowledge about the possible gap between the global emissions levels in 2020 consistent with the 2° C target versus the expected levels if countries fulfil their emission reduction pledges. Many parties to the Climate Convention found this analysis useful as a reference point for establishing the level of ambition that countries needed to pursue in controlling their greenhouse gas emissions. As a result they asked UNEP to produce annual follow-ups, with updates of the gap and advice on how to close it.

Besides updating the estimates of the emissions gap, the 2011 report also looked at feasible ways of bridging the gap from two perspectives (UNEP, 2011). The first was from the top-down viewpoint of integrated models, which showed that feasible transformations in the energy system and other sectors would lower global emissions enough to meet the 2° C target. The second was a bottom-up perspective, which examined the emissions reduction potential in each of the main emissions-producing sectors of the economy. These bottom-up estimates showed that enough total potential exists to bridge the emissions gap in 2020.

The 2012 report presented an update of the gap but also good examples of best-practice policy instruments for reducing emissions. Among these were actions such as implementing appliance standards and vehicle fuel-efficiency guidelines, which are working successfully in many parts of the world and are ready for application elsewhere to help reduce emissions.

The current report reviews the latest estimates of the emissions gap in 2020 and provides plentiful additional information relevant to the climate negotiations. Included are the latest estimates of:

– the current level of global greenhouse gas emissions based on authoritative sources;
– national emission levels, both current (2010) and projected (2020), consistent with current pledges and other commitments;
– global emission levels consistent with the 2° C target in 2020, 2030 and 2050;
– progress being made in different parts of the world to achieve substantial emission reductions.

New to this fourth report is an assessment of the extent to which countries are on track to meet their national pledges. Also new is a description of the many cooperative climate initiatives being undertaken internationally among many different actors – public, private, and from civil society.

Special attention is given to analysing new scenarios that assume later action for mitigation, compared to those used earlier to compute the emissions gap. The report also describes new findings from scientific literature about the impacts of later action to reduce global emissions.

This year the report reviews best practices in reducing emissions in an often-overlooked emissions-producing sector – agriculture. Innovative ideas are described for transforming agriculture into a more sustainable, low-emissions form.

As in previous years, this report has been prepared by a wide range of scientists from around the world. This year

[1] Since then, the number of parties agreeing to the Accord has risen to 141 (see https://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php).
[2] With the 28 member states of the European Union counted as one party.

70 scientists from 44 scientific groups in 17 countries have contributed to the assessment.

The information contained in the report provides invaluable inputs to the current debate on global climate policy and the actions needed to meet international climate targets. Meeting these targets is instrumental for limiting the adverse impacts of climate change and associated 'adaptation gaps' as illustrated in Box 1.1. UNEP hopes that this fourth update will help catalyse action in the forthcoming climate negotiations.

Box 1.1 From emissions gap to adaptation gap

This report's definition of the emissions gap is based on the internationally agreed limit to the increase in global average temperature of 2° C (or possibly 1.5°C). Chapter 3 summarizes the latest scientific findings regarding both least-cost and later-action scenarios for meeting that 1.5 or 2° C target. The chapter concludes that, with later-action scenarios, the cost and risk of not meeting the target increases significantly, compared to least-cost scenarios.

The 2° C target has become associated with what the Intergovernmental Panel on Climate Change (IPCC) termed "*dangerous anthropogenic interference with the climate system*", even though the IPCC has thus far never attached a specific temperature threshold to the concept. Nevertheless, the IPCC has characterised "*dangerous anthropogenic interference*" through five "*reasons for concern*", namely risk to unique and threatened systems, risk of extreme weather events, disparities of impacts and vulnerabilities, aggregate damage and risks of large-scale discontinuities.

These reasons for concern would thus gain particular relevance in the event that the world followed a later-action scenario emissions trajectory that in the end failed to meet the 1.5 or 2° C target. Today, when the choice between least-cost and later-action scenarios is still available to us, later-action scenarios highlight a growing adaptation problem which, by analogy with the emissions gap, could be termed an adaptation gap.

The adaptation gap is more of a challenge to assess than the emissions gap. Whereas carbon dioxide and its equivalents provide a common metric for quantifying the emissions gap, we lack a comparable metric for quantifying the adaptation gap and assessing the impacts of efforts to close it. While the emissions gap indicates the quantity of greenhouse gas emissions that need to be abated, the adaptation gap could measure vulnerabilities which need to be reduced but are not accounted for in any funded programme for reducing adaptation risks. Alternatively, it could estimate the gap between the level of funding needed for adaptation and the level of funding actually committed to the task. Developing countries needs for adaptation are believed to cost in the range of US $100 billion per year (UNFCCC, 2007; World Bank, 2010). By comparison the funds made available by the major multilateral funding mechanisms that generate and disperse adaptation finance add up to a total of around US $3.9 billion to date. From a funding perspective therefore, the adaptation gap is significant[3].

The concept of the adaptation gap is in line with the IPCC's Working Group II's use of the term *adaptation deficit*, which is used to describe the deficit between the current state of a country or management system and a state that would minimize the adverse impacts of current climate conditions.

Framing the adaptation gap in a way useful for policy making also requires a better understanding of how the costs of adaptation vary with different temperature projections. Data on the costs of adaptation under business-as-usual, and best- and worst-case emission scenarios could help policy makers better understand the relationship between adaptation to, and mitigation of climate change. Adaptation cost estimates also put the true costs of climate change, as opposed to only looking at the costs of mitigating it, into a broader and clearer perspective.

There is also a knowledge gap between what we know and what we need to know to successfully adapt to climate change. It is true that we already have enough knowledge to act on adaptation, but not enough to act well. For example, we lack information about how much existing and planned policies can reduce people's vulnerability. Evaluating the effectiveness of various interventions would arguably be a very effective way of measuring progress towards adaptation.

[3] The US $3.9 billion figure is a rough estimate based on information from the following major multilateral funding mechanisms for adaptation: an equivalent of US $399 million has been committed by the EU's Global Climate Change Alliance from 2008 to 2013 (GCCA, 2013). (It should be noted that part of these funds have supported clean energy, Reducing Emissions from Deforestation and Forest Degradation (REDD) and Disaster Risk Reduction programme); cumulative pledges to the Least Developed Countries Fund and the Special Climate Change Fund amounted to a total of US $863 million from their inception to May 2013, (GEF, 2013); US $2.3 billion has been pledged to the Strategic Climate Fund Trust fund as of December 31, 2012 (World Bank, 2013); and the Adaptation Fund had received resources amounting to US $324 billion as of 30 November, 2012 (Adaptation Fund, 2012).

Chapter 2

Emission trends, pledges and their implementation

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2.1 Introduction

This chapter presents an update, based on the scientific literature, of the following critical topics:

- current (2010 global) emissions of greenhouse gases;
- projected emissions (to 2020) of greenhouse gases under a business-as-usual (BaU) scenario;
- projections (to 2020) of greenhouse gas emissions under four different sets of assumptions regarding implementation of national pledges to reduce emissions;
- the extent to which parties are positioned to implement their pledges, in light of their current policy portfolios and plausible assumptions regarding macroeconomic trends and offsets.

The estimated emission level in 2020 under a business-as-usual scenario is 1 gigatonne of carbon dioxide equivalent ($GtCO_2e$) higher compared to last year's emissions gap report[1]. While the emission levels in 2020 for the strict-rules cases are higher by roughly 1 $GtCO_2e$ (unconditional) and are comparable to last year's emission level (conditional), the emission levels associated with the two lenient-rules cases are lower by roughly 1 $GtCO_2e$, as compared to last year's estimates. These changes are mainly due to decisions on surpluses made by countries during the Doha climate negotiations and downward revisions to the assumptions on double counting of offsets. They illustrate that increasing stringency through the climate negotiations can help reduce emission levels in 2020 under lenient-rules cases. However, they do not reflect an increase in ambition or action, but represent a move towards stricter accounting rules. To illustrate, in last year's emissions gap report, emission levels associated with the strict-rules cases were 3 $GtCO_2e$ lower than those of the lenient-rules cases, whereas this year they are lower by around 1 $GtCO_2e$ (unconditional) and 2 $GtCO_2e$ (conditional).

While previous reports assumed full pledge implementation, this year we also explore the extent to which 13 parties, accounting for 72 percent of global greenhouse gas emissions, are already on track to implement their pledges, and where further policy implementation or offsets are likely to be required.

2.2 Current global emissions

Last year's report estimated total global greenhouse gas emissions in 2010 at 50.1 $GtCO_2e$, with a 95 percent uncertainty range of 45.6–54.6 $GtCO_2e$[2]. This bottom-up estimate from the EDGAR database (JRC/PBL, 2012) has not been updated since and is considered a comprehensive assessment of global greenhouse gas emissions in 2010[3]. Figure 2.1 shows emission levels by major economic grouping for the period 1970–2010, using this database[4]. These may differ from data derived from the National Inventory Reports, which are the latest estimate of emissions for most developed countries. The latest global estimates of energy-related carbon dioxide emissions show a continued increase for the years 2011 and 2012, although at a lower pace than the average since the beginning of the 21st century (Olivier *et al.*, 2013)[5].

[1] Unless otherwise stated, all emissions in this report are expressed in $GtCO_2e$. This is the sum of six of the greenhouse gases covered by the Kyoto Protocol (that is CO_2, CH_4, N_2O, HFCs, PFCs and SF_6), weighted by their global warming potential (GWP) (UNFCCC, 2002). Not included are ozone depleting substances (ODS), black carbon (BC), and organic carbon (OC). While nitrogen trifluoride (NF_3) has recently been added to the Kyoto Protocol, it has not been included in this analysis. Unless otherwise stated, data include emissions from land use, land-use change and forestry (LULUCF).

[2] This estimate included all six Kyoto gases and also takes into account emissions from land use, land-use change and forestry.

[3] Another comprehensive assessment of global GHG emissions is WRI's CAIT database that estimated total global GHG emissions in 2010 at 47.2 $GtCO_2e$.

[4] The reader is referred to last year's report (UNEP 2012a) for a breakdown by gas.

[5] The reader is referred to Appendix 2A for further details.

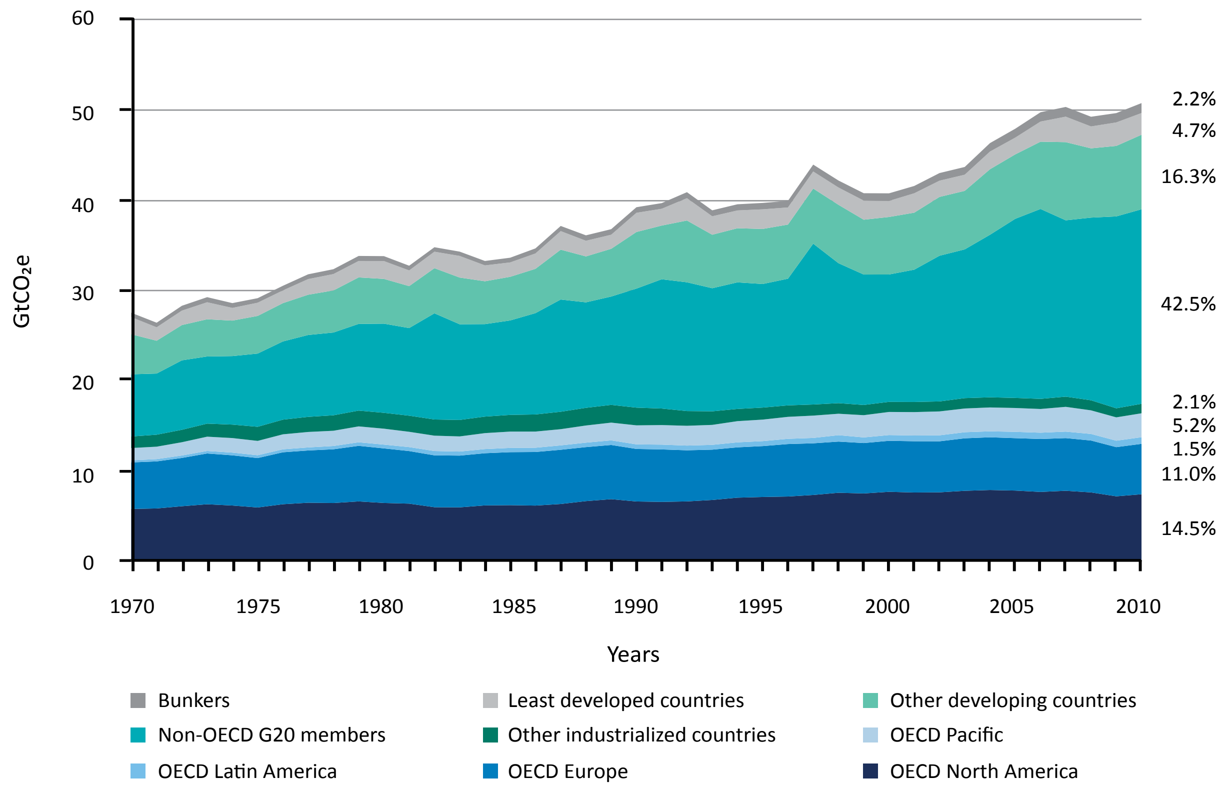

Figure 2.1 Trend in global greenhouse gas emissions 1970–2010 by major economic grouping.
Note: The data plotted has been calculated using global warming potential values as used for UNFCCC/Kyoto Protocol reporting. The graph shows emissions of 50.1 $GtCO_2e$ in 2010, as derived from bottom-up emission inventories.
Source: EDGAR 4.2 FT2010 (JRC/PBL, 2012. Percentages refer to shares in global emissions in 2010.

While the last decade of the 20th century saw little change in the relative regional contributions to annual global greenhouse gas emissions, this changed drastically during the first decade of the 21st century. Between 2000 and 2010, the developed country share decreased from 51.8 percent to 40.9 percent, whereas developing country emissions increased from 48.2 percent to 59.1 percent (JRC/PBL, 2012). Referring to Figure 2.1, between 2000 and 2010 the share of global emissions of the non-OECD G20 countries (i.e. Argentina, China, Brazil, India, Indonesia, the Russian Federation, Saudi Arabia and South Africa) increased by 8.7 percent, while the share of all OECD countries and other industrialized countries declined by 9.0 percent, and the share of the remaining developing countries changed little. Today developing and developed countries are responsible for roughly equal shares of cumulative greenhouse gas emissions for the period 1850-2010 (den Elzen et al., 2013b).

Greenhouse gas emission estimates are uncertain due to differences in definitions and in the accounting of national emissions. To produce a statistically significant assessment of the uncertainty associated with those emission estimates, a large number of independent but consistent datasets is required, which at present is not the case (Appendix 2.A). It is nonetheless clear that energy-related carbon dioxide emissions have the lowest uncertainty (UNEP, 2012a), while land use and land-use change emissions of different greenhouse gases have the highest.

2.3 Projected global emissions under business-as-usual scenarios

Business-as-usual scenarios of future developments are generally based on an extrapolation of current economic, social and technological trends. They usually reflect policies that have taken effect as of a recent cut-off date, for example, 2010[8]. However, in some cases they may include policies that, while approved, will only enter into force at a future date (DEA/OECD/URC, 2013).

Business-as-usual scenarios of greenhouse gases are benchmarks against which the effectiveness of mitigation policies and measures can be tested. They are also used in this report to assess the extent to which parties' pledges can meet the 2° C or 1.5° C targets.

Business-as-usual emissions for 2020 were derived from estimates by 12 modelling groups that analyzed the reduction proposals of parties, as described in Section 2.4 [9]. Most of the modelling groups followed the same approach with regards to the types of policies included in the BaU scenario – they did not include new policies with a potential effect on greenhouse gas emissions beyond those in effect at the cut-off date[10]. Some of the modelling groups used the BaU scenarios that the parties provided.

Based on the analysis by these 12 modelling groups, global greenhouse gas emissions for 2020 are estimated at 59 $GtCO_2e$ (range 56–60 $GtCO_2e$) in 2020 under BaU assumptions, which is about 1 $GtCO_2e$ higher than the figure in the 2012 emissions gap report[11]. Two key factors explain

[8] BaU scenarios typically vary with regard to which policies they take into account for a variety of reasons, including: the cut-off year for their inclusion; whether policies have to be planned, adopted, and/or implemented if they are to be included; methodologies for quantifying the effect of included policies; and the determination of whether a policy will have a significant effect that warrants inclusion.
[9] See Table B.1 in Appendix 2.B for a listing of the modelling groups.
[10] The cut-off date for exclusion of policies varies among the modelling groups.
[11] Unless stated otherwise, all ranges in the report are expressed as 20th–80th percentiles.

this increase: using the BaU numbers from China's second national communication to UNFCCC (Government of China, 2012), and moving the base year from 2005 to 2010 in more model studies[12].

To test the robustness of the 59 $GtCO_2e$ BaU estimate, we compare our estimates with those of several international modelling groups, including six that are participating in the studies discussed in Section 2.4 (Kriegler *et al.*, 2013)[13]. The BaU scenarios with which we compared our estimates (24 scenarios, developed by 12 different models) give a median of 58 $GtCO_2e$, with a range of 55–60 $GtCO_2e$. In spite of the different lower bound, this median, 58 $GtCO_2e$, is consistent with that obtained by the modelling groups contributing to this report.

2.4 Projected global emissions under pledge assumptions

Under the 2010 Cancún Agreements of the Climate Convention, 42 developed-country parties have submitted quantified economy-wide emission reduction proposals for 2020. Since November 2012, when the last emissions gap report was released, only New Zealand has significantly changed its pledge[14]. Some countries, notably Mexico, have changed underlying assumptions that effectively change their pledge[15].

At the latest Conference of the Parties (COP) to the Climate Convention, held in in Doha in late 2012, parties agreed on a second commitment period of the Kyoto Protocol. This period will run from 2013 to 2020 and provides for quantified emission reduction targets for the following Annex I parties: Australia, Belarus, the European Union and its member states, Kazakhstan, Monaco, Norway, Switzerland and Ukraine. No binding emission reduction targets were set for any other Climate Convention parties, neither Annex-I nor non-Annex I.

To date 55 developing country parties and the African group have submitted nationally appropriate mitigation actions (NAMAs) to Climate Convention (UNFCCC, 2013). Of these, 16 have been framed in terms of multi-sector expected greenhouse gas emission reductions[16]. The remaining 39 are expressed as sectoral goals or, in fewer instances, specific mitigation projects. In this assessment only the former 16 are considered[17]. Together, the 42 developed country parties with reduction targets and the 16 developing country parties accounted for about 75 percent of global emissions in 2010.

Box 2.1 Current and projected emission levels for 13 UNFCCC parties with a pledge

Figure 2.2 shows past (1990, 2005 and 2010) as expected and future (2020) emission levels for 13 Climate Convention parties that have submitted quantitative emission reduction pledges. Four different projections to 2020 are presented: the national BaU scenario, the median BaU value from several international modelling studies, and the emission levels resulting from implementation of two emission reduction pledge cases (see the next section for a description of the different pledge cases).

Annex I parties have defined their commitments in terms of emission reductions in 2020 relative to historical emission levels, typically emission levels in 1990. Conversely, non-Annex I parties have defined them in terms of emission reductions in 2020 relative to hypothetical future emission levels, typically against BaU levels in 2020, or in terms of greenhouse gas emission intensity. In this second case, the uncertainty about actual emission levels in 2020 is carried over into the estimate of the emission reductions commitment.

Most national BaU scenarios from non-Annex I parties are relatively high compared to the range in the corresponding scenario by 12 modelling studies. The reasons for this are numerous, including differences in definitions, notably as to which policies are considered in the baseline, as well in the nature of the assumptions made (DEA/OECD/URC, 2013). Crucially, some developing countries are increasingly clarifying those assumptions and the methods used to calculate the baseline[18].

[12] This resulted in higher emission levels, as economic activity – and thus emission levels – was higher in the period 2005–2010, compared to the previous base year.
[13] The estimates in this report do not include new policies affecting greenhouse gas emissions after the cut-off year.
[14] In August 2013, New Zealand announced a single 5 percent reduction target with respect to its 1990 emission levels, replacing its initial 10–20 percent target.
[15] The Mexican government recently updated the country's BaU scenario for 2020. This updated scenario leads to 960 $MtCO_2e$ emissions, which is above the previous BaU estimate, and also affects the 2020 emissions resulting from the pledge (see Box 2.1).
[16] China and India have expressed their mitigation goals in terms of emission reductions per unit of GDP; Brazil, Indonesia, Mexico, South Africa and the Republic of Korea, in terms of deviations below their respective BaU emission scenarios; Antigua and Barbuda, Marshall Islands and Republic of Moldova, in terms of absolute greenhouse gas emission reductions; and Costa Rica and the Maldives, in terms of a carbon neutrality goal. The reader is referred to Appendix 2.C for additional details on these goals.
[17] Quantifying the emission reductions resulting from these 39 actions is difficult. For this reason, this assessment assumes no reductions below BaU emission scenarios for these countries. This might be a conservative assumption.
[18] For example, in November 2012, as a part of the country's second national communication to the Climate Convention, the Chinese government released national BaU and mitigation scenarios for the first time (Government of China, 2012). The BaU scenario excludes all climate-related policies implemented since 2005, which leads to energy-related carbon dioxide emissions of 14.4 $GtCO_2$ in 2020. The mitigation scenario reflects both domestic policies and the country's international emission-intensity target and results in emissions levels of 4.5 $GtCO_2$ below BaU levels. Similarly, the Mexican government recently updated the country's BaU scenario for 2020.

Box 2.1 Current and projected emission levels for 13 UNFCCC parties with a pledge *(continued)*

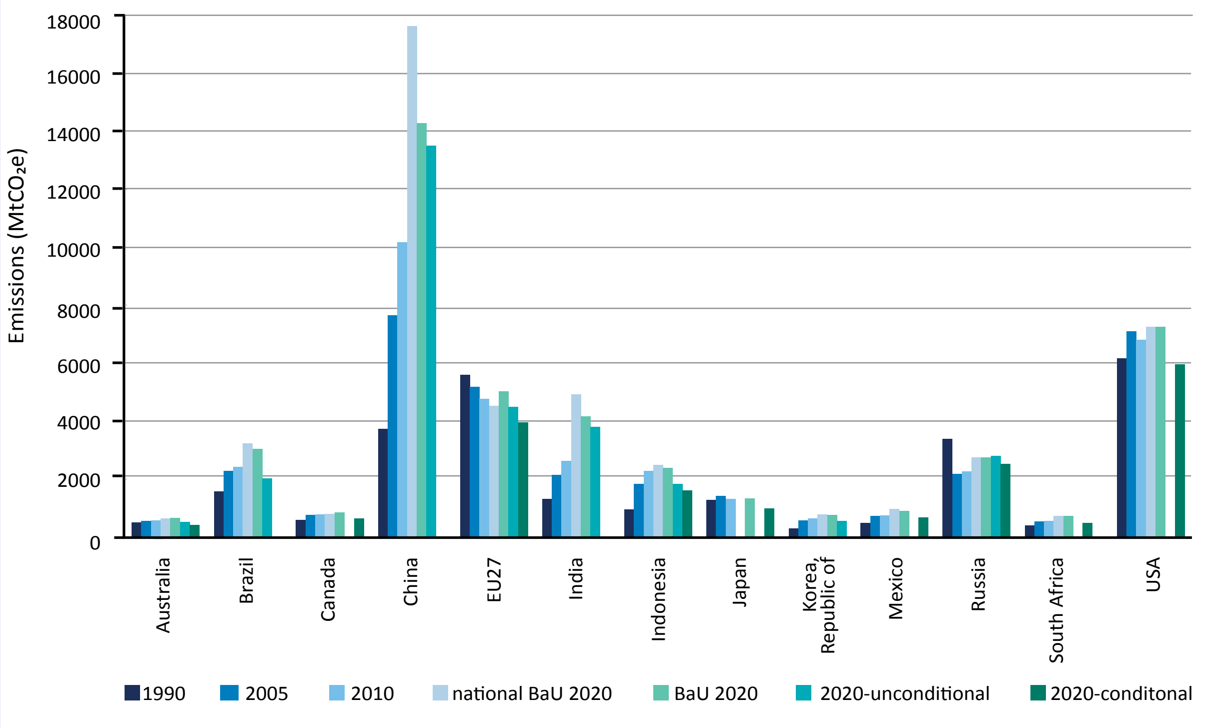

Figure 2.2 Greenhouse gas emissions, including land-use change, for 1990, 2005, 2010 and for 2020 under a national BaU (if available), median of the BaU assumed by modelling groups, unconditional pledge and conditional pledge for UNFCCC parties included in the G20 with a pledge, taking the European Union as a group.
Note: For developed countries, emissions exclude emissions from land-use change.
Note: European Union data include all current European Union member countries except Croatia, which joined the European Union on 1 July, 2013.
Source: EDGAR (JRC/PBL, 2012)[19].

Some pledges are unconditional, whereas others have been made conditional on the ability of a national legislature to enact necessary laws, the action of other countries, or the provision of financial or technical support. We refer to these pledges as, respectively, unconditional and conditional. Some countries have submitted one of each type, whereas others have submitted only a conditional or only an unconditional pledge. This creates a range of possible collective impacts from the pledges, bounded on the low end if only unconditional pledges are implemented, and on the high end if all conditional pledges are implemented. Emission levels in 2020 resulting from implementation of the pledges also depend on the rules used to account for both land use and land-use change credits and debits, and surplus emission units. These concepts are introduced in the following sections, followed by a quantification of the emission reductions resulting from different combinations of pledge cases.

2.4.1 Use of land use, land-use change and forestry credits and debits

Under the Kyoto Protocol, Annex I parties may receive credits or debits from land use, land-use change and forestry (LULUCF) activities dependent on a set of complex accounting rules that contribute to the achievement of their individual emission reduction targets. During the seventeenth Conference of the Parties to the Climate Convention, held in Durban in late 2011, new LULUCF accounting rules for countries participating in the second commitment period (CP2) of the Kyoto Protocol were agreed (UNFCCC, 2012a). The potential contribution of LULUCF accounting under these new rules appears to be relatively modest for Annex I parties that joined the first commitment period of the Kyoto Protocol (Grassi *et al.*, 2012): a difference of up to about 2 percent of 1990 emissions between strict and lenient accounting, equal to about 0.3 $GtCO_2e$ per year. If the USA, which did not join the first commitment period of the Kyoto Protocol, followed these rules, the number would increase to 0.45 $GtCO_2e$ per year[20]. While these estimates

[19] National BaUs were obtained from the following sources. For developed countries, we use the best representation of a with-policies BaU scenario, i.e.: Australia (Department of Climate Change and Energy Efficiency, 2012); Canada (Environment Canada, 2012); European Union (European Environment Agency, 2012); Japan: not available; Russia (Government of the Russian Federation, 2010); USA (EIA, 2012; Bianco *et al.*, 2013). For developing countries without-policies BaU scenarios (den Elzen et al., 2013a), i.e.: Brazil (Brazilian Government, 2010); China (Government of China, 2012), supplemented with the average estimate non-energy CO_2 emission projection from den Elzen et al., 2013a and estimates from Climate Action Tracker; India (Planning Commission, 2011); Indonesia (Ministry of Environment, 2010), Mexico (NCCS, 2013); South Africa (South Africa. Department of Environmental Affairs, 2011); Korea, Republic of (Republic of Korea, 2011). Note that the national BaUs for South Africa and India were reported as a range. For the figures, the mid-point has been used.

[20] For the USA, the estimated potential contribution from LULUCF credits is about 0.15 $GtCO_2e$ per year. This is calculated as follows: for forest management, assuming 2005 as reference year and given the available projections for 2020 (United States Department of State, 2010), the credit is estimated at about 0.07 $GtCO_2e$ per year; an additional credit of about 0.08 $GtCO_2e$ per year is estimated from afforestation/reforestation and deforestation (EPA, 2005).

are generally consistent with the information contained in UNFCCC (2012c), they may underestimate emissions from those countries that may adopt different accounting rules from those of the Kyoto Protocol, for example, Canada, Japan, New Zealand and Russia[21].

2.4.2 Surplus emissions units

Estimates of emission levels in 2020 can also be influenced by the potential use of surplus emission units. These surplus units could arise either when parties' actual emissions are below their emission targets for the first commitment period of the Kyoto Protocol, or when their emissions in 2020 are below their target for that year, when this does not require significant emission reductions. Note that surplus emission units refers to surpluses arising from different types of allowances – assigned amount units, emission reduction units and certified emission reductions – all introduced in the next paragraphs.

The 2012 emissions gap report estimated the maximum emission reduction in 2020 due to surplus credits at 1.8 $GtCO_2e$[22]. However, as a result of the rules for using such surplus allowances agreed to in Doha, these estimates need to be revised (UNFCCC, 2012b; Kollmuss, 2013). The parties agreed that allowances, referred to as 'assigned amount units' (AAUs), not used in the first commitment period can be carried over to the next period. However, recent decisions on surplus emission units significantly limit the use of such surplus allowances and prevent the build-up of new ones. Only parties participating in the second commitment period can sell their surplus assigned amount units. This will exclude Russia, which is the largest holder of surplus assigned amount units, but which will not participate in the second commitment period. Buyer countries can only purchase surplus assigned amount units up to a quantity of 2 percent of their own initial assigned amount for the first commitment period. In addition, Australia, Japan, Liechtenstein, Monaco, Norway and Switzerland have said that they will not purchase units from others, while the European Union has declared that they will not use any surplus emissions units (UNFCCC, 2012b)[23].

Finally, new surplus allowances are prevented by the fact that allowances that exceed the parties' average emission levels in the period 2008–2010 will be cancelled. This rule affects Belarus, Kazakhstan and Ukraine[24].

These decisions reduce the impact of surplus emissions in 2020. Based on Chen *et al.* (2013) and Gütschow (2013), the impact of Kyoto surpluses on 2020 pledges is estimated to be about 0.05 $GtCO_2e$ (range 0.05–0.15 $GtCO_2e$) for the unconditional pledge scenario and 0.55 $GtCO_2e$ (range 0.5–0.6 $GtCO_2e$) for the conditional pledge scenario, down from 1.8 $GtCO_2e$ as previously estimated[25].

The difference between scenarios stems from the European Union's declaration in Doha that its internal legislation will not allow the use of surplus assigned amount units carried over from the first commitment period, for complying with its 20 percent unconditional pledge. For its 30 percent conditional pledge, the European Union has more than enough Kyoto surplus emissions to realize the required emission reductions. The impact of surplus emissions could also be zero if the European Union decides not to use any of its Kyoto surplus emissions for complying with its 30 percent conditional target.

In addition to the assigned amount units, two of the Kyoto Protocol's flexible mechanisms, the Joint Implementation and the Clean Development Mechanism, provide credits that parties can use in the form of emission reduction units (ERUs) in the case of Joint Implementation, and certified emission reductions (CERs) in the case of the Clean Development Mechanism. These credits can be carried over to the second commitment period of the Kyoto Protocol. The 2012 Conference of the Parties to the Climate Convention did not change the rules for these credits: certified emission reductions and emission reduction units can each be carried over up to 2.5 percent of the initial assigned amount of the first commitment period. There are no restrictions on their use. Those units add to a total impact of 0.2 $GtCO_2e$ in 2020.

2.4.3 The potential impact of offsets

Offsets could affect the emissions levels associated with the pledges in two ways. First, double counting of offsets could arise where emission reductions in developing countries achieved through offsets, such as certified emission reductions, are counted towards meeting the pledges of both countries. Second, some of the offsets may actually not achieve the intended, additional emission reductions.

It is clear that emission reductions associated with 'emission reduction units' and 'certified emission reductions' or with the Kyoto Protocol's third flexible mechanism – emissions trading, should not be double counted[26]. Nevertheless, rules for avoiding double counting have not been agreed to. A rough estimate of the impact of double counting is as follows. If all parties' offsets were counted twice – a likely overestimate of double counting – global emissions would be 0.40 $GtCO_2e$ higher in the case of conditional pledges, and 0.55 $GtCO_2e$ higher in the case of unconditional pledges. In the 2012 emissions gap report (UNEP, 2012a) double

[21] For example, in the case of Russia, if the "*appropriate accounting of the potential of the forestry sector*" (UNFCCC, 2012c) is interpreted as not applying the cap on forest management credits agreed in Durban, LULUCF credits in Russia alone may reach 0.3 $GtCO_2e$ per year, instead of the 0.1 $GtCO_2e$ per year assumed in this assessment.

[22] This would apply if all surplus credits were purchased by parties with pledges that do require emission reductions, displacing mitigation action in buying parties.

[23] The European Union stated in Doha that their legislation does not allow the use of carried over surplus units (UNFCCC, 2012b). However, it is unclear if this statement is fully binding. Purchase of units was not excluded by the European Union, but is highly unlikely to happen, as the European Union holds the largest share of surplus units.

[24] In their respective pledges, the governments of Ukraine, Kazakhstan and Belarus proposed target emission levels above that 2008-2010 emissions average. Further details are available in Chen *et al*. (2013) and Kollmuss (2013).

[25] Calculations assume as a starting point the initial assigned amounts of the first commitment period of the Kyoto Protocol. The uncertainty ranges come from the future decisions of Ukraine, Belarus and Kazakhstan. If these countries stay in the second commitment period of the Kyoto Protocol and lower their commitments to their 2008-2010 emission levels, they can make use of surplus emissions.

[26] At least in theory, emission reductions could also be shared, with a certain percentage attributed to the buyer and the seller retaining the remainder.

counting was estimated at 1.5 $GtCO_2e$, which is now believed to be an overly high value[27].

In addition to double counting, there is a risk that more offset credits could be generated than emissions actually reduced. Stated differently: project activities need to be additional to the development expected without the project[28]. Although estimates are fraught with uncertainty, available evidence suggests that a significant amount of emission reductions in Clean Development Mechanism projects are not additional in this sense (Alexeew *et al*., 2010; Michaelowa, 2009; Schneider, 2009). Assuming this share to be 25 percent by 2020, it is estimated that offsets of up to 0.1 $GtCO_2e$ for conditional pledges and 0.15 $GtCO_2e$ for unconditional pledges could be non-additional. This would raise the total estimate of the impact of offsets to about 0.5–0.7 $GtCO_2e$. Assuming a much lower share of 10 percent by 2020, the impact of offsets would be 0.5–0.6 $GtCO_2e$.

2.4.4 Four cases of expected emissions in 2020

The findings from 12 modelling groups have been brought together to estimate expected emission levels in 2020, taking into account emission reduction proposals by parties to the Climate Convention. For more information on the contributing modelling groups, see Table B.1 in Appendix 2.B.

Of the seven modelling groups that participated in the 2012 emissions gap report, most have updated their analyses[29], and five new modelling groups contributed to this year's update[30].

In line with the 2012 report (UNEP, 2012a), the current update is structured around four emission scenarios in 2020, based on whether pledges are conditional or unconditional, and on whether accounting rules are strict or lenient (Figure 2.3). Under strict rules the allowances from LULUCF accounting, offset double counting, and surplus emission credits cannot be counted towards the emission reduction pledges. Under lenient rules this is permitted.

The results for each of the four scenarios are given below. Ranges are expressed as 20th–80th percentiles.

[27] The 1.5 $GtCO_2e$ estimate was taken from Erickson *et al*.(2011). However, given current BaU projections, the agreed limited use of Clean Development Mechanism and other transferable units for the countries not participating in the Kyoto Protocol's CP2, and since the USA and Canada are not planning to use offsets, 0.40 $GtCO_2e$ (in the conditional pledge cases) and 0.55 $GtCO_2e$ (in the unconditional pledge cases) are now believed to be more accurate estimates. For the pledge cases it is assumed that international emission offsets could account for 33 percent of the difference between BAU and pledged emission levels by 2020 for all Annex I countries. (This is an arbitrary, conservative estimate, as many parties have yet to specify any limits to the use of transferable units.) Two exceptions are made, however. First, no offset use for the USA and Canada is assumed, because their respective governments have indicated that they will only make very limited use of offset credits (UNFCCC, 2012c). Second, regarding the European Union's unconditional pledge, the rules in the European Union's energy and climate package are assumed to have been implemented.

[28] A criterion sometimes applied to projects aiming at reducing greenhouse gas emissions. It stipulates that the emission reductions accomplished by the project would not have happened anyway if the project had not taken place.

[29] More specifically, (i) Climate Action Tracker by Ecofys, Climate Analytics and Potsdam Institute for Climate Impact Research, PIK, www.climateactiontracker.org (Climate Action Tracker, 2010); (ii) Climate Interactive (C-ROADS) (Sterman *et al*., 2012); (iii) Fondazione Eni Enrico Mattei (FEEM) (Tavoni *et al*., 2013); (iv) Grantham Research Institute, London School of Economics (updated based on Stern and Taylor, 2010); (v) OECD Environmental Outlook to 2050 (OECD, 2012); (vi) PBL Netherlands Environmental Assessment Agency (den Elzen *et al*., 2013a; Hof *et al*., 2013) and (vii) UNEP Risoe Centre (UNEP, 2012b).

[30] The five new modelling groups are: Energy Research Centre of the Netherlands (ECN), International Institute for Applied Systems Analysis (IIASA), National Institute for Environmental Studies (NIES), Pacific Northwest National Laboratory (PNNL) and Potsdam Institute for Climate Impact Research (PIK). Additional information on the participants in the project (dubbed LIMITS) is given in Appendix 2.B. Kriegler *et al*. (2013) summarises some of the project's findings.

Case 1 – Unconditional pledges, lenient rules
Parties implement their lower-ambition pledges and are subject to lenient accounting rules: the median estimate of annual greenhouse gas emissions in 2020 is 56 $GtCO_2e$, within a range of 54–56 $GtCO_2e$.

Case 2 – Unconditional pledges, strict rules
Parties implement their lower-ambition pledges, but are subject to strict accounting rules: the median estimate of annual greenhouse gas emissions in 2020 is 55 $GtCO_2e$, within a range of 53–55 $GtCO_2e$.

Case 3 – Conditional pledges, lenient rules
Some parties offered to be more ambitious with their pledges, provided some conditions were met. If the more ambitious conditional pledges are implemented, and accounting rules are lenient, the median estimate of annual greenhouse gas emissions in 2020 is 54 $GtCO_2e$, within a range of 52–54 $GtCO_2e$.

Case 4 – Conditional pledges, strict rules
Parties implement higher-ambition pledges and are subject to strict accounting rules: the median estimate of annual greenhouse gas emissions in 2020 is 52 $GtCO_2e$, within a range of 50–52 $GtCO_2e$.

Compared to the 2012 update (UNEP, 2012a), emission levels in 2020 corresponding to the two cases for which strict rules apply are higher by around 1 $GtCO_2e$ under unconditional pledges and comparable with the corresponding estimate in the 2012 update for conditional pledges. The remaining two cases, those in which lenient rules apply, have median emissions that are around 1 $GtCO_2e$ lower compared to the 2012 update. The latter is due to the lower impact of both double counting and surplus assigned amount units due to the Doha decisions and does not reflect an increase in ambition or action, but represent a move towards stricter accounting rules. To illustrate, in last year's emissions gap report, emission levels associated with the strict-rules cases were 3 $GtCO_2e$ lower than those of the lenient-rules cases, whereas this year they are lower by around 1 $GtCO_2e$ (unconditional) and 2 $GtCO_2e$ (conditional).

Including five additional modelling groups has increased the robustness of the analysis. Despite the inclusion of these five new studies, the overall conclusions have not changed.

2.4.5 Pledged reduction effort by Annex I and non-Annex I countries

For Annex I parties, total emissions as a group of countries for the four pledge cases are estimated to be 3–16 percent below 1990 levels in 2020. For non-Annex I parties, total emissions are estimated to be 7–9 percent lower than business-as-usual emissions. This implies that the aggregate Annex I countries' emission goals fall short of reaching the 25–40 percent reduction by 2020, compared with 1990, suggested in the IPCC Fourth Assessment Report (Gupta *et al*., 2007). Similarly, the non-Annex I countries' goals fall, collectively, short in reaching the 15–30 percent deviation from business-as-usual which is also used as a benchmark for emission reductions (den Elzen and Höhne, 2008; 2010).

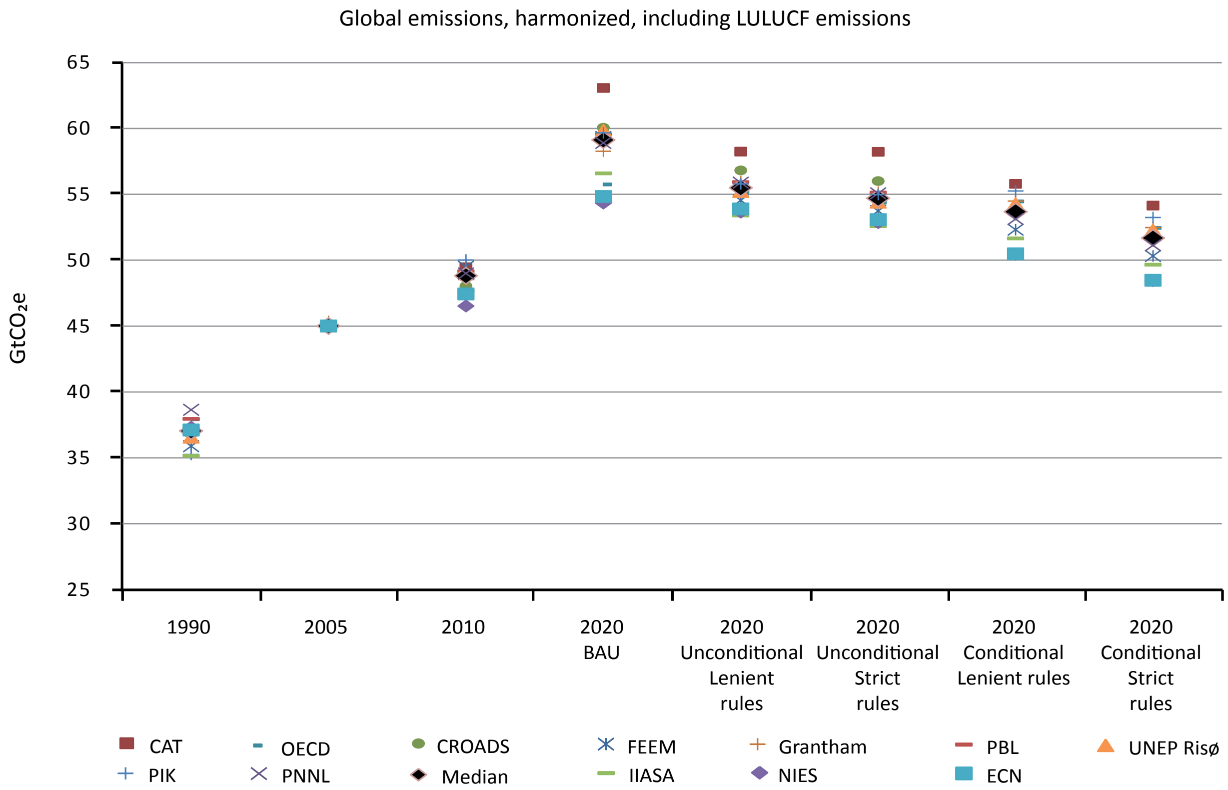

Figure 2.3 Emissions in 2020 under BaU and as a result of pledges under four cases.
Note: To ensure a consistent comparison of the pathways and pledges the data have been harmonized to the same 2005 emissions of 45 $GtCO_2e$, except for Grantham.
Source: See Appendix 2.B.

2.5 National progress: do policies match pledges?

Section 2.4 examined four scenarios for national and global greenhouse gas emissions assuming that parties' pledges would be fully implemented – that is, assuming that, in 2020, parties will emit the amount indicated by their pledges. As 2020 approaches, however, the time is ripe to take stock of the extent to which parties are, in fact, on track to achieve their pledges.

This section considers the likely impact of current domestic policies, describing parties' climate-policy portfolios and examining the extent to which these policies, in combination with other factors, have put parties on track to meeting their pledges. The section focuses on the 13 parties whose economies are amongst the 20 largest in the world and who have formulated a quantitative pledge[31].

It is important to note that the 13 parties' pledges varied in terms of the extent to which they required deviation from various BaU estimates, as discussed in Appendix 2.D. The larger the deviation, the more difficult it is to achieve the pledge and the more important the role of additional policies becomes.

In order to assess whether parties' expected greenhouse gas trajectories are in line with 2020 pledges, projected 2020 emission scenarios that take into account currently adopted policies (current trajectory for 2020) were compared to the 2020 emission levels needed to achieve each pledge through domestic abatement (pledge threshold for 2020)[32].

To establish the current trajectory for 2020, we identified emission scenarios that factor in the effects of currently adopted policies[33]. We based this trajectory on official estimates presented in national communications to the Climate Convention and other government sources, and corroborated these estimates with other available literature (Table 2.1), adjusting where necessary to ensure consistency with official figures, for example, in the treatment of LULUCF. An official trajectory was not available for the Republic of Korea.

To establish the pledge threshold, we sought to identify the maximum level of 2020 emissions that each party would consider to be consistent with meeting its pledge through domestic abatement. Where a pledge is presented as a range, we adopted the higher quantity of resulting emissions as the pledge threshold – for example, if a country states it will reduce its emissions by 5–10 percent, our pledge threshold represents the 5 percent reduction. Note, if 10 percent were used, countries would have lower expected emissions in 2020.

For each of the 13 parties examined, Table 2.1 below presents both official and independent estimates of emission levels in 2020. Five parties – Australia, China, the European Union, India and Russia – appear to be on track to meet their pledges under the policies they have adopted to date, given current assumptions about macroeconomic and technology trends and offsets. Of these, three – China, India

[31] These parties account for 72 percent of global greenhouse gas emissions. They are: Australia, Brazil, Canada, China, the European Union, India, Indonesia, Japan, Mexico, the Russian Federation, South Africa, the Republic of Korea and the USA.

[32] We consider offsets only when a country has explicitly stated its intent to purchase a specific quantity of offsets.

[33] This contrasts with the BaU ranges presented in earlier sections of this report, which include estimates that do not factor in these effects.

and Russia – had pledges that, by some estimates, were less dependent on policy interventions after 2009[34]. Australia and the European Union, on the other hand, needed to strengthen their policy portfolios and, in Australia's case, purchase offsets to meet their unconditional pledges[35].

Four parties – Canada, Japan, Mexico, and the USA – may require further action and/or purchased offsets to meet their pledges, according to government and independent estimates of projected national emissions in 2020. A fifth party – the Republic of Korea – may also require further action but this could not be verified based on government estimates. However, new actions now being taken by all five of these parties may enable them to meet their pledges, although the impact of these actions have not been analyzed here. Examples of new actions include Mexico which has recently adopted comprehensive climate-change legislation, and is in the process of developing its second special programme on climate change (NCCS, 2013)[36].

Table 2.1 Pledges versus current trajectories for G20 countries with a greenhouse gas pledge[37]

Party	Pledge threshold for 2020 ($MtCO_2e$)	Pledge estimate from this study (Figure 2.2)	Current trajectory for 2020 ($MtCO_2e$)		Observation	Notes and references
			Official estimate	Independent estimate(s)		
Australia	537	427–541	637	475–645	Australia intends to meet its unconditional 5 percent pledge in part through domestic abatement and in part by purchasing 100 $MtCO_2e$ in offsets. Australia is experiencing significant policy uncertainty.	Pledge threshold and official trajectory from DCCEE (2012); independent trajectory from Roelfsema *et al*. (2013).
Brazil	2 068	1 973-2 068	N/A	1 500–2 630	Estimates of 2020 emissions vary widely above and below the pledge threshold, approximately 1 900 $MtCO_2e$ (La Rovere *et al*., 2013) and 1500 – 2630 $MtCO_2e$ (Roelfsema *et al*., 2013).	Pledge threshold based on Brazilian Government (2010); independent trajectory from La Rovere (2013) and Roelfsema *et al*. (2013).
Canada	607	614	720	730–780	According to current projections, Canada will require further policy action and/or the purchase of offsets to meet its pledge.	Pledge threshold and official trajectory from Environment Canada (2012); independent trajectory from Roelfsema *et al*. (2013).
China	11 700 (CO_2 only)	13 445-13 561 (all greenhouse gases)	11 700 (CO_2 only)	12 770–14 765 (all greenhouse gases)	Most estimates indicate that China is currently on track to meet its CO_2 intensity pledge, which was similar to some BaU estimates (though not to China's).	Pledge threshold from Roelfsema *et al.* (2013); official trajectory from The People's Republic of China (2012); independent trajectory from Roelfsema *et al*. (2013); figures assume 7 percent GDP growth and include only CO_2 emissions from energy and industry.
European Union (EU27)	4 526	3 935–4 479	4 500	4 500	According to current projections, the European Union is currently on track to meet its 20 percent unconditional pledge through domestic abatement.	Pledge threshold from UNFCCC (2012d); official trajectory from European Environment Agency (2012); independent trajectory from Roelfsema *et al*. (2013); excludes LULUCF.
India	3 537–4 016	3 751-3 834	3 537–4 016	2 655–3 795	Most estimates indicate that India is currently on track to meet its greenhouse gas intensity pledge, which is higher than some BaU estimates.	Pledge threshold and official trajectory from Planning Commission (2011) (figures assume 8 and 9 percent GDP growth, respectively); independent trajectory from Roelfsema *et al*. (2013). Figures exclude agriculture and LULUCF.

[34] Regardless of whether China and India needed new policies to meet their greenhouse gas-intensity pledges, both countries have implemented significant new climate-related policies since 2009.

[35] Australia has announced its intent to meet its pledge half through domestic abatement under its new carbon-pricing mechanism and half through internationally sourced offsets – 100 $MtCO_2e$ each (DCCEE, 2012). Australia's new coalition government, however, has announced its intent to repeal the carbon-pricing mechanism; while there is bipartisan support for Australia's pledge, it is not clear how Australia would deliver on the pledge without the carbon-pricing mechanism (Kember *et al*., 2013).

[36] It is not yet possible to quantify the abatement expected from the new special programme on climate change.

[37] Not considering purchase or sale of offsets. Figures include all gases and sectors, including LULUCF, unless otherwise noted.

Party	Pledge threshold for 2020 ($MtCO_2e$)	Pledge median estimate from this study (Figure 2.2)	Current trajectory for 2020 ($MtCO_2e$)		Observation	Notes and references
			Official estimate	Independent estimate(s)		
Indonesia	2 183	1 603–1 820	N/A	N/A	Indonesia has not published estimates of its projected 2020 emissions taking into account current policies, and independent estimates factor out the sizable share of national emissions from peatlands, due to the significant uncertainty associated with estimating these.	Pledge threshold based on Ministry of Environment (2010).
Japan	946	952	1 148–1 198	N/A	According to official estimates, Japan is on track to achieve a 5–9 percent reduction from 1990 levels, with high uncertainty; the Japanese government intends to revise its 2020 target by late 2013 (GWPH 2013).	Pledge calculated based on Ministry of Environment (2013) using Kyoto Protocol Base Year. Official trajectory based on The Energy and Environment Council (2012).
Mexico	672	672	830	800–845	According to current projections, Mexico will require further action and/or offsets to meet its pledge. New or enhanced policies included in the forthcoming Special Programme on Climate Change may reduce projected 2020 emissions.	Official pledge based on NCCS (2013); official trajectory based on Government of Mexico (2012), adjusted per NCCS (2013); independent trajectory from Roelfsema *et al.* (2013).
Republic of Korea	543	543	N/A	630–675	Information on the Republic of Korea's emission trajectory is limited; independent estimates indicate that further action and/or offsets will be needed to meet the pledge. The Republic of Korea is currently developing new policies, including an emission-trading scheme.	Pledge threshold based on the Republic of Korea (2011); current trajectory from Roelfsema *et al.* (2013); excludes LULUCF.
Russian Federation	2 921	2 515–2 763	2 750	2 085–2 455	Russia is currently on track to meet its pledge, which was above BaU estimates.	Pledge threshold based on Russian Federation (2013); official trajectory from Ministry of Natural Resources and Environment (2010); independent trajectory from Roelfsema *et al.* (2013).
South Africa	583	479	N/A	560–690	South Africa has not published estimates of its projected 2020 emissions, and independent estimates based on currently adopted policies are not available.	Pledge threshold from Department of Environmental Affairs (2011); independent trajectory from Roelfsema *et al.* (2013).
USA	5 144	5 974	6 206	6 041–6 465	According to current projections, the USA will require further action and/or offsets to meet its pledge. New or enhanced policies pursued under the Climate Action Plan announced in June 2013 may reduce projected 2020 emissions.	Pledge threshold based on EPA (2013); official trajectory from United States Department of State (2010); independent trajectory from Bianco *et al.* (2013) (with LULUCF adjusted per US Department of State (2010) and Roelfsema *et al.* (2013)).

Notes:
- Pledge threshold for 2020 refers to 2020 emission levels needed to achieve each pledge through domestic abatement.
- Current trajectory for 2020 provides scenario projections that factor in the effects of currently adopted policies. Where governmental sources are available, these are cited first (official estimates). Independent estimates are quoted next to these, for comparison.

The Republic of Korea is about to implement an emissions-trading scheme and is defining other elements of its Framework Act on Low Carbon[38]. The USA presented a Climate Action Plan in June 2013 (Executive Office of the President, 2013), and analysis has shown that it is possible for the USA to deliver on its pledge if the administration makes full use of available legal instruments (Bianco *et al*. 2013), many of which are referenced in the Climate Action Plan. A 2012 study concluded that Canada's 2020 goal was still achievable if Canada were to implement specific additional policies, though it would become more costly and difficult to achieve the longer further action was delayed (NRTEE 2012). Japan is currently in the process of reviewing both its pledge and its policy portfolio in light of the Fukushima nuclear incident and a recent government transition (GWPH, 2013).

While the three remaining countries, Brazil, Indonesia and South Africa, have all made significant progress on monitoring and reporting in recent years, for a variety of reasons insufficient information is currently available to determine whether they are on track to achieve their pledges. These countries' governments have not published estimates of their 2020 emissions that consider only currently adopted policies, and independent assessments (Roelfsema *et al*., 2013) present a wide range of possible trajectories. Indeed, some of these countries' climate policies are rapidly evolving, making it difficult to develop meaningful estimates of future emissions – South Africa, for example, is considering a carbon tax and a range of additional measures. Emission trajectories for Brazil and Indonesia are subject to considerable uncertainty related to land-use emissions (Roelfsema *et al*., 2013). As policies continue to evolve, the forthcoming Biennial Reports and Biennial Update Reports of 2014 to the Climate Convention can serve as one option for parties to take stock of, and quantify, their progress, and to communicate this internationally.

2.6 Summary

If country pledges are implemented, expected emission levels in 2020 will range from 52 to 56 GtCO$_2$e, depending on how pledges are implemented – for reference, the BaU level is 59 GtCO$_2$e. The factors affecting implementation are whether the pledges are conditional or unconditional, and whether the accounting rules applied are lenient or strict. According to best estimates presented in this chapter, global greenhouse gas emissions are expected to continue to increase. Estimated BaU emissions are 1 GtCO$_2$e higher compared to last year's update. While emission projections in 2020 for the two strict rules cases are comparable with last year's update, the Doha decisions on surpluses, as well as our downward revisions on the impact of double counting, lower the emission levels associated with the lenient rules cases by roughly 1 GtCO$_2$e.

Global 2020 emissions resulting from the implementation of pledges can be lowered by moving from unconditional to conditional pledges, and from lenient accounting rules to strict accounting rules. For example, if conditional pledges were embraced instead of unconditional ones, emission levels in 2020 would be 2–3 GtCO$_2$e lower. If strict rules were adopted rather than lenient ones, emissions levels in 2020 would be 1–2 GtCO$_2$e lower. It is noteworthy that the decisions on surplus assigned amount units in Doha have lowered the emission levels under the lenient rule cases by 1 GtCO$_2$e.

For these figures to hold true, parties must also deliver on their pledges, which in some cases may require additional policies or purchased offsets. Five of the 13 major parties are well positioned to achieve their pledges using policies they have already adopted, enhancing confidence in the pledge scenarios outlined in the previous section. Of the five parties that may not yet be so positioned, all are within striking distance of achieving their pledges in 2020. Three, in particular, have taken significant steps to enhance their policy portfolios, which could lead to the ambitious policies needed to meet their pledges. It should be noted that some parties have defined their pledges at a higher level of emissions than those used to calculate the size of the gap in this report. Moreover, even those parties that have adopted ambitious policies may find it difficult to meet their pledges, owing to political circumstances, implementation shortcomings, and potentially adverse macroeconomic trends. Therefore, it will be important to monitor and, where possible, take steps to mitigate these risk factors.

Finally, serious information gaps preclude a comprehensive assessment of several countries' emission trajectories under current policies. Given the disconnect that can occur between country pledges and the policies that support them, it is imperative to address this information gap in order to fully understand the magnitude of the gap between countries' policy portfolios and the 2^{o} C target.

[38] No official government estimate is available that concludes that the Republic of Korea is not on track to meet its pledge. However, since independent estimates point towards emission levels that are largely inconsistent with those required to meet the pledge, and given that the government of the Republic of Korea is currently developing new, aggressive policies including an emissions trading scheme, it is likely that the country is indeed not yet on track to meet its pledge through current policies. The new policies being developed may reverse this situation.

Chapter 3

The emissions gap and its implications

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3.1 Introduction

Countries have pledged to reduce or limit their greenhouse gas emissions by 2020 and at the same time have agreed to limit the increase in global mean temperature to 1.5° C or 2° C compared to pre-industrial levels. These two important commitments raise some critical questions:

- Does the combined effect of these pledges put the world on a path towards limiting warming to below 1.5° C or 2° C with a high chance of success?
- Is there an emissions gap between where the pledges lead and where pathways indicate emissions should ideally be?
- What are the implications and trade-offs of such a possible emissions gap for the achievability of the 1.5° C and 2° C targets and their associated mitigation challenges?

Earlier emissions gap reports have set out to answer these questions by combining the assessment of where emissions are heading (Chapter 2) with an assessment of emission scenarios that could limit warming to below 1.5° C or 2° C (see Appendix 3.A for background). The assessment is updated here, as it has been annually since 2010 (UNEP, 2010; 2011; 2012).

UNEP's 2012 report mentioned a new class of scenario, termed later-action scenarios, that limit warming to 1.5° C or 2° C. The special aspect of these is that they allow the achievement of climate targets even though global emissions in the near term, up to 2020, are higher than in scenarios based on immediate action. In this 2013 report we take advantage of the many new articles that have been published on later-action scenarios and examine their implications and their assumptions much more closely (Sections 3.4, 3.5 and 3.6).

3.2 Which scenarios are analyzed?

The scientific literature contains many different emission scenarios computed by integrated assessment models that limit global temperature rise to 1.5° C or 2° C above pre-industrial levels (Appendix 3.B). The differences between scenarios arise from the range of assumptions made about inputs such as costs, potential and performance of different mitigation technologies, as well as driving forces of emissions such as economic and population growth. Also important are differences in model design and the design of model experiments. The scenarios highlighted in this chapter stay, respectively, within the 1.5° C or 2° C targets with a certain probability but can differ significantly in their underlying assumptions. We also present a re-analysis of the scenario literature, where the scenarios have been divided into two groups: least-cost and later-action.

Least-cost scenarios depict the trend in global emissions up to 2100 under the assumption that climate targets will be met by the cheapest combination of policies and measures over the time period considered by a particular model. This assumes that, in the model, actions are allowed to begin immediately; that is, in the specified base year of the model's calculations, which is often 2010. This set of scenarios can be seen as a useful benchmark for evaluating implications of less stingent climate policies. As discussed below, the fact that real emissions since 2010 already deviate from these pathways has important implications.

Later-action scenarios also attempt to keep warming to below 1.5° C or 2° C, but assume that actions to reduce emissions are generally weaker and take place later than assumed in least-cost scenarios. Hence, later-action scenarios assume that less action is taken to reduce emissions in the near term as compared to least-cost scenarios (Section 3.5). Although less action is assumed, it might, for example, include complying with current pledges to reduce emissions. The set also includes scenarios that have no policy action at all in some or all regions until 2030. After

2020 or 2030, the later-action scenarios aim for more stringent policies to ensure compatibility with the temperature targets. In other words, the lack of ambition to reduce emissions in the short term is compensated by faster and/or deeper emission reductions later. Once these scenarios do begin emission reductions, they again attempt to minimize costs of mitigation, but some options are no longer available. By definition the later start will lead to higher overall costs.

Each of these scenarios has a particular trajectory of emissions. The reason a particular trajectory keeps within a specified limit of global warming – during the 21st century or in a certain year in the future – is that it stays below a certain maximum value of cumulative emissions of long-lived greenhouse gases such as carbon dioxide and nitrous oxide (Allen *et al.*, 2009; IPCC, 2013; Matthews *et al.*, 2012; Meinshausen *et al.*, 2009; Solomon *et al.*, 2010)[1]. Integrated-assessment models provide insights into how, and at what rate, the global energy system and other greenhouse gas emitting sectors can be transformed so that cumulative emissions do not exceed a particular budget over the long term. Therefore they provide very useful information about what levels of emissions are consistent with temperature targets at different points in the future.

Box 3.1 Gap implications of the Working Group I Contribution to the Fifth Assessment Report of the IPCC

The IPCC launched its fifth, and latest, assessment of climate science in September 2013 (IPCC, 2013). It emphasizes that the scientific community has a higher level of confidence than ever that human activity is significantly impacting the climate system.

A key aspect of the new IPCC Working Group I report is a quantification of the sensitivity of the climate system to increased greenhouse gas emissions and to radiative forcing. This sensitivity is expressed through several different metrics. The two most relevant for this report are the transient climate response (TCR) and the transient climate response to cumulative carbon emissions (TCRE).

The transient climate response is a measure of the temperature rise that occurs at the time of a doubling of carbon dioxide concentrations in the atmosphere. Its current likely range is 1–2.5° C, compared to 1–3° C in the previous IPCC assessment. The climate simulations used in this report are consistent with this new range (Rogelj *et al.*, 2012).

The transient climate response to cumulative carbon emissions is a measure of temperature rise per unit of cumulative carbon emissions, and has not been previously reported in an IPCC assessment. The implication of this concept is that global average temperature can only be kept to a certain value if cumulative carbon dioxide emissions do not exceed a maximum amount, or budget, over time. This is called the "carbon emissions budget". The idea of a budget is that if emissions are high now, then they have to be lower later. In general, the budget total cannot be exceeded. If it were exceeded, carbon would have to be subsequently removed from the atmosphere so that emissions returned to within budget limits. Conversely, if emissions were lower at the beginning, then they can be somewhat higher later. Thus, different emission pathways staying within the same budget will meet the same temperature target. This explains the trade-off between early and late emission reductions. UNEP's emissions gap reports explore these trade-offs by taking into account many important factors that influence emission trends.

3.3 Emissions in line with least-cost 2° C pathways

This section analyses emission levels achieved in least-cost scenarios through comprehensive, immediate action. Implications of later-action scenarios are discussed in Sections 3.5 and 3.6. To analyze these scenarios, we bring them into a common analytical framework and estimate the probability of each scenario exceeding 1.5° C or 2° C of warming. A probabilistic approach is important because of the uncertainties of climate response (see Box 3.1). Probability statements in this chapter only refer to climate-response uncertainties (see Appendix 3.A for more information), not to the plausibility of particular policy outcomes.

Least-cost emission scenarios consistent with a 'likely' chance of staying below 2° C have a median emission level of 44 $GtCO_2e$ per year in 2020, with a central range of 38–47 $GtCO_2e$ per year – dependent on their post-2020 emission trajectories (Figure 3.1 and Table 3.1)[2]. For comparison, emissions in 2005 were 45 $GtCO_2e$ per year. In this and previous emission-gap reports, we define a 'likely' chance as having a greater than 66 percent probability, consistent with the definitions of the IPCC (Mastrandrea *et al.*, 2010). For a less stringent 'medium' chance (50–66 percent), median emission levels in 2020 can be somewhat higher at 46 $GtCO_2e$ per year (range 44–48 $GtCO_2e$ per year). Global emissions in these scenarios peak around 2020 or earlier.

The main results do not differ from those presented in the 2012 report (UNEP, 2012), because most new scenarios also initiate comprehensive action from 2010 onward and near-

[1] Some greenhouse gases such as methane and tropospheric ozone have a much shorter lifetime in the atmosphere than carbon dioxide or nitrous oxide, and are therefore sometimes called short-lived climate pollutants or forcers. As compared to carbon dioxide and nitrous oxide, the *cumulative* emissions of short-lived climate pollutants have a smaller effect on maximum temperature than their *annual* emissions at the time when maximum warming occurs (Smith *et al.*, 2012).

[2] In this chapter we refer to the 20th–80th percentile range as the central range or just as the range, while the minimum-maximum range is referred to as the full spread or just as the spread.

term mitigation potentials have not greatly changed in the past year. Least-cost scenarios are indicative of the emissions path the world would have followed if it had started to implement comprehensive policies at the beginning of this decade, and serve as an important benchmark to evaluate scenarios with delayed or weaker-than-optimal near-term policy actions[3]. The fact that we are currently not on this path already has implications (Section 3.6.2).

Median emissions in 2025 are around 40 $GtCO_2e$ per year (range 35–45 $GtCO_2e$ per year) in our set of scenarios which show a 'likely' chance of staying below the 2° C target. For a 'medium' chance of staying below the target, median 2025 emissions do not exceed 44 $GtCO_2e$ per year (range 42–46 $GtCO_2e$ per year). Continuing through the century, median emissions in line with the 2° C target continue to decline, for example to 35 $GtCO_2e$ per year and 22 $GtCO_2e$ per year in 2030 and 2050, respectively. (For scenarios with a 'likely' chance of meeting the 2° C target see Table 3.1).

The ranges are due to differences in assumptions of the integrated assessment models. Despite wide ranges, the models agree that substantial emission reductions relative to business-as-usual and current emission levels are required by 2050. Higher near-term emissions will have to be offset by steeper and larger reductions later. Moreover, many of the least-cost scenarios assume that emissions become negative in the second half of the century. This raises the question of the feasibility of negative emissions. Negative emissions are achieved in these scenarios through bio-energy and carbon capture and storage (CCS), or through land-use changes, such as afforestation or reforestation. In addition, negative emissions can be achieved, for instance, by direct air capture of carbon dioxide in combination with carbon capture and storage. Technologies such as bio-energy combined with carbon capture and storage are still not proven on the large scale and, moreover, their use can have significant impacts, for instance on biodiversity and drinking-water availability (Coelho *et al.*, 2012). Some models, therefore, try to account for these impacts and explore the consequences of not being able to achieve negative emissions or the consequences of a much smaller bio-energy potential. It was found that scenarios that assumed that negative emissions cannot be achieved required substantially lower emissions in the short term in order not to exceed the carbon budget that complies with the 2° C target[4]. Around mid-century, the scenarios without net negative emissions have similar emission levels as other scenarios, while in the long term, by 2100 they are higher since the other scenarios have negative emissions.

In general, limiting the long-term mitigation potential in scenarios, by, for example, not allowing negative emissions, will require more stringent near-term emissions reductions (Table 3.1) and generally larger mitigation costs. Note that limiting key mitigation technologies in scenarios, including carbon capture and storage and bio-energy, will increase the overall mitigation costs because of the required additional short-term action, and because more expensive technologies will have to be used. Since these scenarios assume cost-effective emission reductions from 2010 onward, they are included in our set of least-cost scenarios.

Table 3.1 Overview of emissions in 2020, 2025, 2030 and 2050 of scenarios with, respectively, a 'likely' (≥ 66 percent) or a 'medium' (50–66 percent) chance of limiting global temperature increase to below 2° C during the 21st century.

	Number of scenarios	Peaking decade*	Total greenhouse gas emissions in 2020		Total greenhouse gas emissions in 2025		Total greenhouse gas emissions in 2030		Total greenhouse gas emissions in 2050	
		year	$GtCO_2e$ per year		$GtCO_2e$ per year		$GtCO_2e$ per year		$GtCO_2e$ per year	
			Median	Range and spread**	Median	Range and spread **	Median	Range and spread **	Median	Range and spread **
'Likely' chance (≥ 66 percent)	112	2010–2020	44	5–(38–47)–50	40	6–(35–45)–49	35	7–(32–42)–47	22	12–(18–25)–32
'Medium' chance (50–66 percent)	66	2010–2020	46	24–(44–49)–53	44	28–(42–46)–54	41	32–(39–44)–55	28	21–(25–32)–44
Subset of scenarios with technology restrictions* **										
'Likely' chance (≥ 66 percent)	56	2010–2020	42	5–(37–37)–50	38	6–(32–44)–49	35	7–(28–40)–47	21	13–(18–24)–31
Subset of scenarios not achieving net negative emissions from fossil fuel and industry by 2100										
'Likely' chance (≥ 66 percent)	42	2010–2020	40	5–(36–44)–50	37	6–(32–41)–47	34	7–(29–39)–47	20	13–(18–22)–27

* Because most models only provide emissions data for 5-year or 10-year intervals, the encompassing period in which the peak in global emissions occurs is given. The peak-year period here reflects the 20th–80th percentile range. With current emissions around 49–50 $GtCO_2e$ per year, a scenario with 2020 emissions below that value would in general imply that global emissions have peaked.
** The range and spread are presented as the minimum value – (20th–80th percentile) – maximum value.
*** Scenarios with technology restrictions explore the implications of a limited availability of mitigation options in the future, either because of societal choices to limit the use of certain technologies, or because technologies do not scale up as completely as currently anticipated.

[3] In this case optimal means following a least-cost pathway.

[4] Negative emissions in this case refer to negative emissions from the fossil fuel and industrial sectors. Land-use emissions are not included here in the calculation of negative emissions. For the subset of scenarios that do not reach net negative emissions in the long term, it was found that their median near-term emissions were about 4 $GtCO_2e$ per year in 2020 lower than the median of all least-cost scenarios that have a likely chance of staying below 2° C.

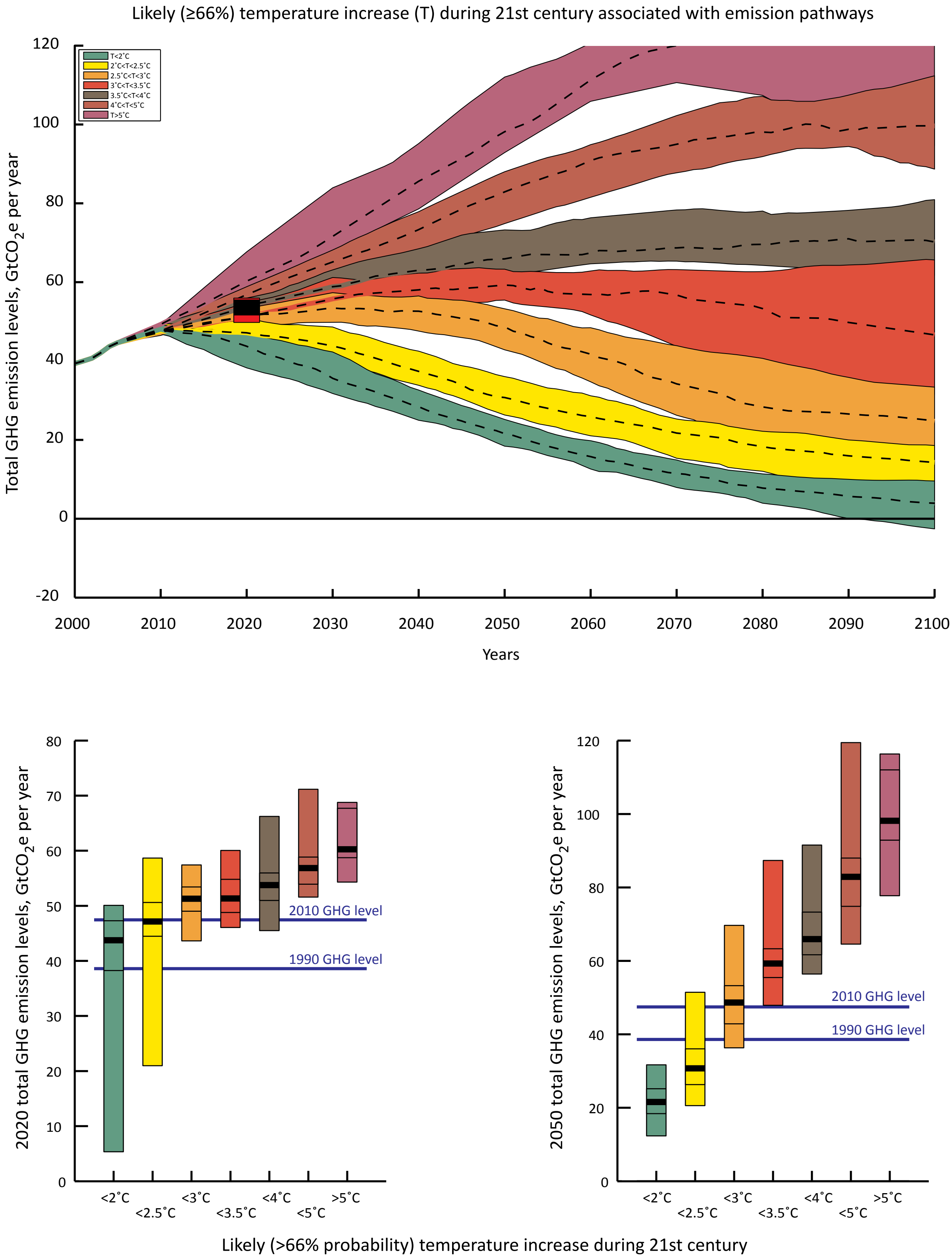

Figure 3.1 Ranges of scenarios limiting global temperature increase with a ‘likely’ (≥ 66 percent) chance of staying below various temperature limits (top panel). Time slices of the ranges are shown in the bottom panel for 2020 and 2050 global total emissions. The small box around 2020 indicates emission levels consistent with current pledges as assessed in Chapter 2.

Table 3.2: Overview of characteristics of 1.5° C pathways available in the scientific literature. The ranges are drawn from the studies' underlying information.

Least-cost pathways					
Temperature target	**Reference**	**Scenario type**	**Total greenhouse gas emissions, $GtCO_2e$ per year**		
			in 2020	**in 2030**	**in 2050**
Limiting warming below 1.5° C with at least 50 percent chance	Rogelj *et al.* (2013b)	Least cost	37–41	27–31	13–17
Limiting warming below 1.5° C with at least 50 percent chance	Luderer *et al.* (2013b)	Least cost	40–44	28–36	5–18
Studies reporting implications of later action for limiting warming below 1.5° C					
Rogelj *et al.* (2013a)	Provides ranges of 2020 emissions from scenarios in line with a 50 percent chance to limit warming to below 1.5° C by 2100 (minimum-maximum spread 36–53 $GtCO_2e$ per year in 2020) and discusses the trade-offs and implications of later action.				
Luderer *et al.* (2013b)	Discusses the economic mitigation challenges – aggregate long-term cost, transitional costs, energy prices – of later action scenarios for a range of temperature targets, including 1.5° C, deriving implications for the lower end of achievable climate targets.				
Rogelj *et al.* (2013b)	Discusses the implications – carbon prices, aggregated mitigation costs, climate risks – of later action scenarios for a range of temperature targets, including 1.5° C, from a risk perspective, taking into account mitigation technology and energy demand variations.				

3.4. Emissions in line with least-cost 1.5° C pathways

The 2010 Cancún Agreements include a provision for a possible 1.5° C limit on global mean temperature rise. The 2012 report found five scenarios in line with 1.5° C, with at least a 'medium' probability, which showed average emissions not exceeding 43 $GtCO_2e$ per year in 2020 (UNEP, 2012). Also, in 2010, UNEP found that stylized emission trajectories that start emission reductions in 2010 and stay within the 1.5° C target have average emissions of up to 44 $GtCO_2e$ per year (range 39–44 $GtCO_2e$ per year) in 2020[5].

No new 1.5° C scenarios are analyzed in this report, as all new scenarios came from model inter-comparisons which focused on the 2° C target. However, some single-model studies have looked at the implications of later action for 1.5° C. Scenarios from these studies were not included in the main scenario set, but are discussed below[6].

Three new studies available in the scientific literature (Luderer *et al.*, 2013b; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b) and one report (Schaeffer *et al.*, 2013b) have looked explicitly at scenarios that limit warming to 1.5° C by 2100. Azar *et al.* (2013) also looked at 1.5° C scenarios, but to 2150 instead of 2100. Least-cost scenarios from Rogelj *et al.* (2013b) have emissions between 37–41 $GtCO_2e$ per year in 2020, 27–31 $GtCO_2e$ per year in 2030, and 13–17 $GtCO_2e$ per year in 2050 (Table 3.2)[7]. Mitigation in these scenarios starts after 2010 and is further tightened to limit warming below 1.5° C by 2100 with at least a 50 percent chance of achieving the target. These scenarios feature a radical commitment to energy efficiency in order to limit greenhouse gas emissions in the future. In addition, they rely heavily on negative-emission technologies such as bio-energy combined with carbon capture and storage (BioCCS). All three studies (Luderer *et al.*, 2013b; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b) show that immediate action is very important if warming is to be limited to below 1.5° C by 2100. However, Rogelj *et al.* (2013a) also present later-action scenarios consistent with 1.5° C. These, which are discussed further in Sections 3.5 and 3.6, are able to limit warming below 1.5° C from emission levels higher than the ones cited above. On the basis of this (limited) information, and compared to the 2° C, the 1.5° C emissions gap in 2020 is between 2 and 5 $GtCO_2e$ per year wider.

3.5 Later-action scenarios in the literature

Since the 2012 update (UNEP, 2012), several new studies of later-action scenarios have become available. These scenarios assume in the near term, up to 2020 or 2030, a lower level of action to reduce emissions than implied in the least-cost scenarios. All other assumptions being the same, the later-action scenarios have higher near-term emissions than least-cost scenarios. These scenarios assume that comprehensive emission reductions would begin at a later point, but are still able to stay within long-term climate targets.

Table 3.3 provides an overview of studies that have produced later-action scenarios. It is important to note that these studies cover a wide range of assumptions regarding the time at which comprehensive mitigation begins, and the nature of the climate-policy regime assumed for the early period until the adoption of comprehensive mitigation actions. Most studies consider scenarios in which comprehensive emission reductions are postponed until 2020 or 2030 (Kriegler *et al.*, 2013b; Luderer *et al.*, 2013a; Luderer *et al.*, 2013b; Riahi *et al.*, 2013; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b). While some scenarios assume climate policies to be absent altogether in the near term, others incorporate the impact of current climate policies or their extensions. Some of these scenarios assume that current country emission pledges for 2020 are implemented. Compared to emissions in least-cost scenarios, emissions in the later-action scenarios are reduced more rapidly after the adoption of comprehensive mitigation actions in order to have at least a 'medium' chance of meeting the 2° C target.

[5] Stylized emission scenarios are ones that are not computed with a detailed integrated assessment model, but by assuming an evolution of emission reduction rates throughout the century.

[6] The reason for only including model inter-comparisons in the main scenario set is to achieve a somewhat balanced representation of the various modelling frameworks that are available in the scientific literature. Including particular single-scenario studies, which combined have produced more than 1 000 scenarios, would bias the results presented here towards the results of one or two models. Therefore, these studies are discussed separately.

[7] Luderer *et al.* (2013b) found a range of 40–44 $GtCO_2e$ per year in 2020, 28–36 $GtCO_2e$ per year in 2030 and 5-18 $GtCO_2e$ per year in 2050.

Box 3.2 Key Properties of 1.5° C and 2° C Scenarios

Scenarios consistent with 1.5° C and 2° C targets have several similar characteristics. First, their emission-reduction rates throughout the 21st century are high – and both improvements in energy efficiency and the introduction of zero- and low-carbon emission technologies are often at rates faster than experienced historically over an extended period of time (van der Zwaan *et al.*, 2013). Second, the scenarios typically reach their peak emission levels before or around 2020 in order to avoid an extensive overshoot of emission budgets, concentrations and, possibly, temperatures in the 21st century (Kriegler *et al.*, 2013c). Third, the scenarios often have net negative emissions in the second half of the century. Finally, these scenarios almost universally feature an accelerated shift towards electrification (Krey *et al.*, 2013).

The 2012 report (UNEP, 2012) highlighted the potential role of both negative emissions and energy-efficiency measures. Negative emissions refers to the potential of actively removing more carbon dioxide from the atmosphere than is emitted at a given period. Here we highlight new literature on the topics of both negative emissions and energy efficiency in scenarios that meet the 1.5° C and 2° C targets.

Negative emissions

About one third of the scenarios analyzed in this chapter with either a 'likely' or a 'medium' chance of meeting the 2° C target – and most of the small number of 1.5° C scenarios – have negative total emissions of all Kyoto gases, not only carbon dioxide, before 2100. Moreover, about 40 percent of the scenarios that have a likely chance of complying with the 2° C target have negative energy and industry-related carbon dioxide emissions by 2100. In these scenarios, bio-energy with carbon capture and storage is usually applied in the second-half of the century, assuming this option is economically attractive within a least-cost path over time. Such a path implies that the discounted costs of an additional unit of reduction is stable over time, and thus allows for much more expensive technologies to expand in the second half of the century. Also considered economically attractive is the ability to avoid very rapid, and thus costly, emission reductions in the short term (Azar *et al.*, 2010; Edmonds *et al.*, 2013; van Vuuren *et al.*, 2013). It should be noted that the application of bio-energy with carbon capture and storage is even more necessary in later-action scenarios, as well as in 1.5° C scenarios, because they need steeper and deeper cuts after 2020/2030 (Section 3.5).

Negative emissions can be achieved in several ways, including afforestation/reforestation, carbon dioxide storage in combination with direct air capture, and bio-energy in combination with carbon capture and storage (Tavoni and Socolow, 2013). The last option is often applied in model-based studies because of its attractive costs and overall potential. Still, the validity of assuming large-scale bio-energy with carbon capture and storage deployment crucially hinges on two key factors (UNEP, 2012; van Vuuren *et al.*, 2013):

- the technical and social feasibility of large-scale carbon capture and storage, for example, the development of a carbon capture and storage infrastructure; and
- the technical and social feasibility of sustainable large-scale bio-energy production, for example, the development of second-generation bio-energy conversion technologies, such as technologies for producing fuels from woody biomass.

Even if both technologies are technically feasible and socially acceptable, the deployment of bio-energy with carbon capture and storage may have severe sustainability implications, for instance in terms of food-price developments and pressure on water resources. Many factors that may limit the availability of bio-energy are not fully represented in integrated-assessment models (Creutzig *et al*., 2012), and current integrated-assessment model estimates of the total mitigation potential vary greatly, sometimes by a factor of three (Tavoni and Socolow, 2013). Importantly, integrated assessment models also show that stringent climate targets can be achieved without bio-energy with carbon capture and storage (Riahi *et al*., 2012). As noted previously, if scenarios do not rely on this in the future, significantly lower emissions are required in the near term. Conversely, high emissions in the near term lock in the need for negative emissions later (Section 3.6).

Energy efficiency

Energy-efficiency improvements also play a key role in the early phases of mitigation, since they provide relatively rapid returns on investment and require technologies less advanced than low-carbon options (IEA, 2012; Kainuma *et al.,* 2012; van Vuuren *et al.*, 2007). However, as costs of low-carbon technologies gradually decline, and the most cost-effective energy-efficiency improvements are exhausted, further efficiency improvements gradually play a smaller role (Krey *et al.*, 2013). By contrast, although 1.5° C scenarios require the same type of technology options as 2° C scenarios, these might only be sufficient when they are combined with strong and sustained efficiency improvements (Luderer *et al.*, 2013b; Rogelj *et al.,* 2013a; Rogelj *et al.*, 2013b). In general, across all temperature targets and technology options, energy efficiency improvements appear crucial in significantly reducing overall costs. Strong and sustained efficiency improvements can also be a hedge against the risk of other mitigation technology failures, which would preclude achieving stringent temperature targets (Luderer *et al.*, 2013b; Riahi *et al.*, 2013; Rogelj *et al.*, 2013a).

Table 3.3: Overview of later-action scenarios in the literature

Study	Delay until	Near-term climate policies
Model comparison studies		
AMPERE WP2 (Bertram *et al.*, 2013; Eom *et al.*, 2013; Riahi *et al.*, 2013) (9 participating models)	2030	Two higher-than-optimal interim emission targets for 2030.
AMPERE WP3 (Kriegler *et al.*, 2013a) (11 participating models)	2030	Staged accession to international climate agreement.
LIMITS (Kriegler *et al.*, 2013b) (8 participating models)	2020, 2030	Weak and stringent interpretation of Copenhagen (UNFCCC COP15) pledges.
RoSE (Luderer *et al.*, 2013a) (3 participating models)	2020, 2030	Unconditional and lenient Copenhagen (UNFCCC COP15) pledges, and moderate reductions beyond 2020.
EMF-22 (Clarke *et al.*, 2009) (10 participating models)	2050	Staged accession to international climate agreement.
RECIPE (Jakob *et al.*, 2012; Luderer *et al.*, 2012) (3 participating models)	2020	No climate policies or fragmented climate policies with different coalitions as first movers.
Single-model studies		
van Vliet *et al.* (2012)	2020	Copenhagen (UNFCCC COP15) pledges.
OECD (2012)	2020	Copenhagen (UNFCCC COP15) pledges.
Rogelj *et al.* (2013a)	2020	Various higher-than-optimal interim emissions targets for 2020.
Rogelj *et al.* (2013b)	2020, 2030	No climate policies, except for efficiency measures.
Luderer *et al.* (2013b)	2020, 2030	Unconditional and lenient pledges, and moderate reductions beyond 2020.

3.6 The emissions gap: trade-offs and implications of today's policy choices

3.6.1 The emissions gap

We now update the estimate of the emissions gap from previous reports. To do so we draw on the assessment of emission reduction pledges in Chapter 2, and the computed range of emissions from the analysis of least-cost scenarios in Section 3.3. As in previous reports, we define the emissions gap in 2020 as the difference between global emissions from least-cost scenarios that are consistent with the 2° C target and the expected global emissions implied by the pledges. Table 3.4 shows that, depending on the interpretation and implementation of the pledges, this gap ranges from 8–12 $GtCO_2e$ per year in 2020 for having a 'likely' chance of staying below 2° C, and from 6–10 $GtCO_2e$ per year for having a 'medium' chance. As indicated earlier, a large number of least-cost scenarios assume implementation of climate policy from 2010 onwards.

Certain later-action scenarios imply that in some cases current pledges could be compatible with the 2° C target, if a radical shift to stronger emission reductions is assured later – risks and trade-offs are discussed in Section 3.6.3. However, if these emission reductions do not materialize, then the 2020 emissions under the four pledge cases in Chapter 2 (52–56 $GtCO_2e$ per year), will be on a trajectory with a 'likely' chance of limiting warming to 3–4° C, not 2° C (Figure 3.1) [8].

[8] Both least-cost and later-action scenarios require strong absolute emission reductions throughout the entire century. However, the stringency of emission reductions in least-cost scenarios – for example, in terms of the increase of discounted marginal abatement costs – is spread equally over time, starting from the base year.

3.6.2 Implications of the gap for achieving least-cost 2020 emission levels

Our assessment shows that there is a gap in 2020 between the emission levels implied by the pledges and the emissions under a least-cost scenario consistent with limiting warming to below 2° C. It is important to note, however, that the least-cost scenarios assume that comprehensive emission reductions begin immediately after the base year, typically 2010[9]. We are now in 2013, and actual emission levels are above most least-cost scenarios, indicating that we have missed an opportunity to lower emissions in the cheapest way possible from the starting year 2010. As time progresses, more and more of the near-term emission reduction opportunities assumed in the least-cost scenarios might be lost, making it increasingly difficult to reach the initial least-cost 2020 emission levels. Some studies indicate it is still possible to close the gap by 2020 (Blok *et al.*, 2012). However, as time passes, this comes with increasingly higher costs than indicated by the least-cost scenarios. The more real-world emissions deviate in the coming years from least-cost pathways, the greater the extra reduction efforts required for closing the gap in 2020 [10].

3.6.3 Implications and trade-offs of not closing the gap

If the gap between global emissions from least-cost scenarios and global emissions implied by the pledges is not closed by 2020, then a later-action scenario has, effectively, been assumed for limiting global temperature increase to 1.5° C or 2° C. As noted previously, later-action scenarios are designed to investigate a delay of globally comprehensive reductions of emissions with comparatively lower near-term reductions. A number of recent studies

[9] Consistent with the first mentioning of a 2° C temperature limit under the Climate Convention (UNFCCC, 2010).

[10] Denotes efforts both in terms of costs and actual reductions.

(Kriegler *et al.*, 2013b; Luderer *et al.*, 2013a; Luderer *et al.*, 2013b; Riahi *et al.*, 2013; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b; van Vliet *et al.*, 2012) show that such a choice implies important trade-offs.

On the one hand, later-action scenarios show short-term flexibility – they reduce the mitigation burden and associated costs in the near term, and move emission reduction requirements further into the future. This would give more time to build a global framework of ambitious policies, and for national policy makers to implement commensurate policies and measures. On the other hand, this short-term flexibility comes at the expense of stronger long-term requirements, reduced choices and higher risks of climate policy failure over the long term. Moreover, to meet the 1.5° C target, there is much less flexibility to delay emission reductions in the coming years and mitigation requirements remain very stringent (Luderer *et al.*, 2013b; Rogelj *et al.*, 2013a). As discussed in Box 3.2, any climate change mitigation scenario aiming at limiting warming to no more than 2° C or 1.5° C comes with major societal, economic and technological challenges. Recent studies with explicit focus on interim targets (Kriegler *et al.*, 2013b; Luderer *et al.*, 2013a; Luderer *et al.*, 2013b; Riahi *et al.*, 2013; Rogelj *et al.*, 2013a) indicate that delays or less stringent near-term policies will exacerbate many of these challenges. The key impacts of later-action scenarios, and, by extension, of not closing the emissions gap, are:

Stronger medium-term emission reduction requirements. Higher near-term emissions imply more rapid emission reductions later on to stay within the carbon budget consistent with, for example, the 2° C target.

Lock-in to carbon-intensive and energy-intensive infrastructure. Unless credible, comprehensive and ambitious climate policies are put into place, the world will continue to expand its carbon- and energy-intensive infrastructure, and will not sufficiently incentivize the development and scale-up of climate-friendly technologies. Later-action scenarios delay the installment of such policies.

Reduced societal choices. The more modest the near-term emission reductions, the higher society's dependence on specific technologies, thus foreclosing options and societal choices for the future. In particular, more scenarios depend on negative emissions to achieve the 2° C target.

Higher overall costs and economic challenges. Lower near-term costs in later-action scenarios imply a lower burden on current economic growth but larger overall mitigation costs. They also imply much higher economic challenges during the transition towards a comprehensive climate-policy regime, including substantial impacts on global economic growth and energy prices in the long term.

Higher climate risks. The risk that the world fails in its effort to limit global warming to 2° C or 1.5° C increases strongly with further delays of global action.

Stronger medium-term emission reduction requirements

As discussed in Sections 3.2 and 3.3, limiting global warming to 1.5° C or 2° C implies a tight limit on cumulative greenhouse gas emissions. As a consequence, scenarios with higher emissions in the near term require stronger medium-term mitigation to reach the same global average temperature over the long term. Inevitably, once comprehensive climate policies are finally introduced, emission reduction rates need to be greater than those in scenarios with strong near-term reductions. The AMPERE study found that modest emission reductions until 2030 imply that about 70 percent of the 2010–2100 cumulative carbon-dioxide emissions budget for a medium chance of limiting warming below 2° C target will have been consumed by 2030 (Bertram *et al.*, 2013; Riahi *et al.*, 2013).

Least-cost scenarios that achieve the 2° C target take stringent action immediately to reduce emissions. Their rate of emission reductions over the medium term, 2030-2050, is around 2–4.5 percent per year[11]. Historically, such reductions have been achieved by individual countries (Peters *et al.*, 2013), but not globally.

By contrast, later-action scenarios delay stringent measures to reduce emissions, and consequently the annual rate of medium-term reductions needs to be much higher, around 6–8.5 percent in the case that emission reductions are modest until 2030 (Riahi *et al.*, 2013), to meet the same target. Rogelj *et al*. (2013a) found similar results. Hence limiting the amount of mitigation over the next few years would require twice as fast a reduction in global emissions after 2030. It is important to note that these scenarios do not account for political and societal inertia, which could make such fast and radical emission reductions even more difficult to achieve if the change in policy comes unexpectedly (Riahi *et al.*, 2013). A strong and reliable early policy signal is required in order to reduce emissions now, or have a chance of achieving higher ambition levels in the following decades.

Table 3.4 Assessment of the emissions gap between global emissions implied by the pledges and global emissions from least-cost scenarios consistent with limiting warming below 2° C. The gap range is based on the 20th–80th percentile ranges of both the pledge and the scenario assessments. Values in parentheses are from last year's report (UNEP, 2012).

		BAU	Case 1	Case 2	Case 3	Case 4
What is the expected gap for a 'likely' chance of staying below 2° C?	Median	**15** (14)	**12** (13)	**11** (10)	**10** (11)	**8** (8)
	Range	**9–19**	**7–15**	**6–14**	**5-13**	**3-11**
		(10–19)	(9–16)	(7–14)	(7–15)	(4–11)
What is the expected gap for a 'medium' chance of staying below 2° C?	Median	**13** (12)	**10** (11)	**9** (8)	**8** (9)	**6** (6)
	Range	**8–16**	**6–12**	**5–11**	**4–10**	**2–8**
		(9–16)	(8–13)	(6–11)	(6–12)	(3–8)

[11] Exponential reduction rates were used here.

Lock-in to carbon-intensive and energy-intensive infrastructure

Apart from having higher global emissions in the near term, later-action scenarios also have fewer options for reducing emissions later. This is because of carbon lock-in, that is, the continued construction of high-emission fossil-fuel infrastructure unconstrained by climate policies (Bertram *et al.*, 2013; Luderer *et al.*, 2013a; Rogelj *et al.*, 2013a). As an example, some later-action scenarios in the AMPERE study have a 50 percent larger capacity of coal-fired power plants compared to current levels by 2030 (Bertram *et al.*, 2013). The lack of near-term climate policies in these scenarios is also found to hinder the scaling up of low-emission, green-energy technologies (Eom *et al.*, 2013).

The same lock-in effect applies to lost opportunities for energy efficiency. The Global Energy Assessment (Riahi *et al.*, 2012) shows the critical importance of energy-efficiency measures for limiting warming to below 2° C during the 21st century, and similar findings are valid for returning warming to below 1.5° C (Luderer *et al.*, 2013b; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b). Later-action scenarios tend to further lock-in power plants, buildings and other infrastructure with low levels of energy efficiency. This makes the transition to a high-energy-efficiency future more difficult, and creates a greater demand for alternative emission reduction measures.

These lock-in effects can be reduced through an early policy signal as discussed above. For example, if power companies know for sure that stringent reductions will be required over the coming years, they might favour more in low-emissions infrastructure investments.

Reduced societal choices

As stated earlier, later-action scenarios need to compensate for their higher near-term emissions with faster and deeper reductions later. Many later-action scenarios assume that a full portfolio of mitigation options is available, including technologies that are not yet proven on the large scale such as bio-energy combined with carbon capture and storage. When key future mitigation technologies do not become available, costs increase (Kriegler *et al.*, 2013c). This increase was found to be bigger in later-action scenarios than in least-cost scenarios (Luderer *et al.*, 2013b; Riahi *et al.*, 2013; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b; van Vliet *et al.*, 2012). If the range of future technological options is constrained, then the later-action scenarios were found to have higher mitigation costs and have a more difficult time complying with temperature targets than the least-cost scenarios. Furthermore, the more emission reductions are delayed, the greater the dependence on future technologies (Luderer *et al.*, 2013b; Riahi *et al.*, 2013; Rogelj *et al.*, 2013a)[12]. In other words, beginning emission reductions early, as is done in the least-cost scenarios, means that policymakers have a greater chance of meeting these temperature targets.

[12] As an example of technological dependency, it was found that only two out of nine models in the AMPERE study could reach a long-term 450 ppm carbon-dioxide concentration target, and thereby comply with the 2° C target, without scaling up carbon capture and storage (Riahi *et al.*, 2013). A similar dependency is found for other mitigation technologies (Riahi *et al.*, 2013; Rogelj *et al.*, 2013b; Rogelj *et al.*, 2013a).

It is not only the availability of specific technologies, that is, an important factor in later-action scenarios, but also the pace at which they can be scaled up. For example, emissions under later-action scenarios have to be reduced very quickly and this requires very rapid decarbonization of the energy system, which in turn puts great pressure on society to rapidly deploy low-carbon technologies[13].

Higher overall costs and economic challenges

Later-action scenarios show that a delay in beginning global comprehensive mitigation action increases the overall costs to reach a climate target (Clarke *et al.*, 2009; Jakob *et al.*, 2012; Kriegler *et al.*, 2013b; Luderer *et al.*, 2013a; Luderer *et al.*, 2013b; OECD, 2012; Riahi *et al.*, 2013; Rogelj *et al.*, 2013b; Rogelj *et al.*, 2013a). The larger the delay, the higher costs. Furthermore later-action scenarios clearly shift the burden of mitigation costs to later generations (Luderer *et al.*, 2013b; OECD, 2012; Rogelj *et al.*, 2013a)[14].

The cost penalty of later action depends on when comprehensive mitigation actions finally begin, the magnitude of emission reductions up to that point, and the future availability of technologies[15].

Later-action scenarios may also have higher economic costs during the transition from modest early actions to comprehensive mitigation actions (Kriegler *et al.*, 2013b; Luderer *et al.*, 2013a; Luderer *et al.*, 2013b). For scenarios meeting the 2° C target, transitional economic costs increase strongly with further delay. For example, beginning comprehensive reductions after 2030, rather than after 2015, causes a three times greater effect of mitigation policies on economic growth in the decade after reductions begin (Luderer *et al.*, 2013b), as in this case very rapid reductions are required beyond 2030 that can only be achieved through adopting high-cost mitigation measures.

Higher climate risks

Although later-action scenarios can reach the same temperature targets as their least-cost counterparts, later-action scenarios pose greater risks of climate impacts for four reasons.

First, delaying action causes more greenhouse gases to build up in the atmosphere, thereby increasing the risk that the carbon emissions budget is exceeded for particular temperature targets. The risk comes from the fact that the steep reductions required later may not materialize.

[13] Eom *et al.* (2013) find that the expansion of both nuclear power and solar photovoltaic (PV) installations in the 2030–2050 period increases by a factor of three when stringent emission reductions are delayed until 2030, as compared to when they are introduced immediately.

[14] For example, Rogelj *et al.* (2013a) found that mitigation costs between 2020 and 2050 could be up to 20 percent higher in scenarios that meet the 2° C target if global emissions in 2020 are 56 $GtCO_2e$ per year instead of 44 $GtCO_2e$ per year. Global carbon reduction prices after 2020 are increased by about a factor of two or more. This translates into an increase of discounted costs between 2020 and 2050 of more than US $7 trillion. Meanwhile, the cost of reducing emissions in the near-term, 2010–2020, was estimated to be about one third of this amount. When estimating cumulative mitigation costs over longer time frames, the medium to long-term economic effects appear to be relatively small because of discounting.

[15] Note, however, that the costs of mitigation in least-cost scenarios can also vary widely depending on the set of mitigation technologies assumed to be available in the future.

[16] For the case of staged accession to a global climate agreement aiming at stabilizing atmospheric greenhouse gas concentrations at 450 ppm carbon-dioxide equivalent, Kriegler *et al.* (2013a) found that the risk of overshooting the 2° C limit might increase from around 30 to around 50 percent even if reluctant nations join later, since late-joiners might not be willing to compensate for their initially higher emissions.

This may happen because key technologies such as carbon capture and storage cannot be scaled up as expected. Equally likely is that future policy makers may be unwilling to take on the higher costs of mitigation[16]. Failure to steeply reduce emissions would cause a higher level of cumulative emissions than initially projected, and this would lead to higher eventual warming and a lower likelihood, or in some cases the impossibility, of staying below temperature targets (Meinshausen *et al.*, 2009). As one example, Luderer *et al*. (2013b) found that delaying comprehensive mitigation actions beyond 2030 increases the achievable lower level of global temperature during the 21st century by about 0.4° C as compared to a scenario with comprehensive reductions starting in 2020, in effect pushing the 2° C target out of reach.

Second, the risk of overshooting climate targets, both concentration and temperature, is higher (den Elzen *et al.*, 2010; Rogelj *et al.,* 2013a; Schaeffer *et al*, 2013a; van Vliet *et al.*, 2012). Later-action scenarios have higher near term emissions than least-cost scenarios and this tends to increase the temporary overshoot of climate targets (Clarke *et al.*, 2009; den Elzen *et al.*, 2010; Kriegler *et al.*, 2013a; Luderer *et al.*, 2013a; Rogelj *et al.*, 2013a; Schaeffer *et al.*, 2013a; van Vliet *et al.*, 2012). Overshooting these targets, or extending the overshoot period, implies a greater risk of large-scale and possibly irreversible changes in the climate system (Lenton *et al.*, 2008). The extent of the risk is very uncertain.

Third, the rate of temperature increase in the near to medium term is higher (den Elzen *et al.*, 2010; Schaeffer *et al.*, 2013a; van Vliet *et al.*, 2012) and this can imply an earlier onset of particular climate impacts and require more rapid adaptation. For example, based on results from 11 integrated-assessment models, Schaeffer *et al.* (2013a) found that later-action scenarios meeting the 2° C target have on average a 50 percent higher rate of decadal temperature increase in the 2040s than least-cost scenarios.

Fourth, when action is delayed, options to achieve stringent levels of climate protection are increasingly lost. All other factors being the same, each year of delay results in the steady loss of options to meet temperature targets with high probability (Luderer *et al.*, 2013b; Rogelj *et al.*, 2013b). Assuming that emission reductions begin in 2010, Rogelj *et al.* (2013b) found that some scenarios have more than a 50 percent chance of limiting warming below 1.5° C. However, if comprehensive mitigation action is delayed until 2020, the probability sinks to 40–50 percent. If delayed until 2030, the probability sinks to 10–20 percent. Also, spending large sums on mitigation, by assuming a carbon price of about US $1 000 per tonne of carbon dioxide, cannot make up for these lost options.

3.6.4 Policy implications of the 2020 emissions gap and later-action scenarios

In Section 3.6.1 and 3.6.2, we have indicated that a large emissions gap continues to exist between least-cost scenarios and the current emission pledges for 2020. The least-cost scenarios assessed in this report assume that climate policies are introduced from 2010 onwards. However, emission reductions in reality have not kept up with the least-cost paths. As a result, it is becoming increasingly difficult to achieve the emission levels in 2020 specified by least cost scenarios. This situation has inspired the research community to look into scenarios that explore the impact of later action. While such scenarios can lessen the necessity for short-term emission reductions they come with many additional costs and challenges. To avoid these costs, it is important to increase near term policy efforts aiming at reducing emissions by 2020, even if they do not reach the level of the least-cost scenarios. Without such efforts, the carbon-emission budgets consistent with keeping temperatures below 1.5° C or 2° C are exhausted rapidly, and mitigation challenges in the future are increased.

Chapter 4

Bridging the gap I: Policies for reducing emissions from agriculture

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4.1 Introduction

Bridging the emissions gap requires a substantial increase in ambition and action, as the previous chapters of this report have illustrated. In 2012, the UNEP Emissions Gap Report (UNEP, 2012) reviewed a number of policies in three sectors – building, transport and forestry – that are proving successful in substantially reducing emissions. In this report we review best-practice policies in agriculture, an often-overlooked emissions-producing sector. The sum of the policies from these different sectors, if replicated and scaled up, shows great potential for narrowing the emissions gap. Moreover, in many cases, these policies can help fulfil important national development objectives beyond climate goals as they can, depending on the policy, boost agricultural productivity, save costs of heating homes, promote eco-tourism, reduce traffic congestion, abate air pollution and associated adverse health effects, or a combination of these.

Here we focus on agriculture because it is among the sectors most affected by climate change, while, at the same time, contributing a significant fraction of the world's greenhouse gas emissions (IPCC, 2007a). Tubiello *et al.* (2013) recently estimated that in 2010 direct emissions from agriculture contributed to 10–12 percent of global greenhouse gas emissions, releasing 5.4–5.8 $GtCO_2e$ into the atmosphere. UNEP (2012) gave a best estimate of 11 percent.

According to Bellarby *et al.* (2008) 38 percent of the emissions can be attributed to nitrous oxide from soils, 32 percent to methane from enteric fermentation in ruminant livestock, 12 percent to biomass burning, 11 percent to rice production and 7 percent to manure management. Direct agricultural emissions, as opposed to indirect ones discussed below, account for 60 percent of global nitrous oxide emissions and 50 percent of global methane emissions (Smith *et al.*, 2008).

Globally, 80 percent of deforestation and forest degradation is believed to be related to agriculture (Kissinger *et al.*, 2012). A more realistic evaluation of emissions related to agriculture should therefore include the emissions released by the conversion of forests and grasslands into agricultural land and the degradation of peat lands. These emissions can be described as indirect emissions from agriculture and, according to Vermeulen *et al.* (2012), amounted to 2.2–6.6 $GtCO_2e$ in 2008. If agricultural pre- and post-production emissions are also added, the global food system accounts for about 19–29 percent of global greenhouse gas emissions (Vermeulen *et al.*, 2012)[1].

Between 1990 and 2005, direct agricultural emissions rose by around 0.6 $GtCO_2e$ per year (IPCC, 2007b), reflecting trends in major drivers such as population growth and rising affluence. These trends are expected to continue although their trajectories largely depend on our choices in natural resource management, food systems and consumer behaviour. Scenarios of continued population growth and consumption suggest that, by 2055, global agricultural methane and nitrous oxide emissions might increase by 57 percent and 71 percent, respectively (Popp *et al.*, 2010).

Although current trends predict strong growth of agricultural greenhouse gas emissions, there is significant potential to reduce them in the coming decades, particularly if mitigation options are mainstreamed into agricultural policies and incentives. At marginal costs of less than US $50–100 per tonne of carbon-dioxide equivalent, the direct emission reduction potential of agriculture lies in the range of 1.1–4.3 $GtCO_2e$ per year in 2020 (Chapter 6). About 89 percent of this potential could be realized through improved management practices such as conservation tillage, combined organic/inorganic fertilizer application, adding biochar to the soil, improved water management and reducing flooding and fertilizer use in rice paddies (Smith *et al.*, 2008). Emissions could be further reduced by abating emissions in the broader food sector, for example, by reducing food waste and meat consumption.

[1] Emissions originate from the global food system during pre-production (fertilizer manufacture, energy use in animal-feed and pesticide production); during production (direct and indirect emissions from producing crops and livestock); and during post-production (primary and secondary food processing, food storage, packaging and transport, food refrigeration, retail of food products, catering and domestic food management, and the disposal of food waste).

The most promising and cheapest mitigation options in agriculture are those that lead to an increase in productivity and income, while the demand for inputs, land or labour rise at a lower rate. It is, however, necessary to minimize environmental externalities to avoid undermining the long-term provisioning capacity of our agro-ecosystems (Garnett *et al*., 2013; Neufeldt *et al*., 2013). It should also be noted that climate mitigation in agriculture involves more than reducing emissions. It can also mean increasing the uptake of carbon dioxide from the atmosphere by biomass or soil organic matter. Furthermore it can also involve avoiding or displacing emissions, either by substituting fossil fuels with biofuels, or forestalling the conversion of natural vegetation into agricultural lands (Smith *et al*., 2008).

Bringing about change in agricultural management practices, however, for climate or other reasons is not easy. More often than not there are important market- or tenure-related barriers that need to be overcome. Experience also suggests that overcoming these barriers individually is often unsuccessful. It is better that they are addressed in an integrated way, with interventions simultaneously supporting farmers, the governance and market conditions in which they operate, and the science and resources upon which technological change depends. Experience has also shown that the policies successful in overcoming barriers are often the ones that are attuned to local conditions.

In the remainder of this chapter we present examples of concrete agricultural policies that have managed to overcome barriers and have been successful in mitigating climate change while raising income and enhancing food security.

4.2 Conversion of tillage to no-tillage practices

Drivers and benefits of policy change

Conventional plough-based farming developed largely as a means for farmers to control weeds. However, it leaves soils vulnerable to water and wind erosion, increases agricultural runoff, degrades soil productivity and releases greenhouse gases by disturbing soils and burning fossil fuels for farm machinery. No-till practices – sowing seeds directly under the mulch layer from the previous crop – reverse this process by minimizing mechanical soil disturbance, providing permanent soil cover by organic materials and diversifying crop species grown in sequence and/or association (FAO, 2013a).

The financial benefits of no-till practices can be considerable, but depend on the location. Farmers save between 30–40 percent of time, labour and fossil fuel inputs using no-till practices, compared to conventional tillage (FAO, 2001; Lorenzatti, 2006). In Argentina it was found that one litre of fuel was needed to produce 50 kg of grain under conventional tillage, but it could produce 123 kg under no-till practices (Lorenzatti, 2006).

Climate adaptation benefits can also be significant. While Kazakhstan's 2012 drought and high temperatures halved wheat yields overall, wheat grown under no-till practices were more resilient, producing yields three times higher than conventionally cultivated crops (FAO, 2012).

Although no-till practices have only a small effect on reducing methane or nitrous-oxide emissions (Smith *et al*., 2008), a number of studies show the significant potential of no-till cultivation to sequester carbon. The expansion of Brazil's no-tillage system under its National Plan for Low Carbon Agriculture (ABC Plan), for example, may build up an additional 500 kg per hectare and year of soil organic carbon, offsetting a total of 16–20 $MtCO_2e$ by 2020, equivalent to 1.6–2.0 $MtCO_2e$ per year. Kenya anticipates an increase in carbon uptake of 1.1 $MtCO_2e$ by 2030, equivalent to 0.04 $MtCO_2e$ per year, from no-till farming activities under its Climate Change Action Plan (Stiebert *et al*., 2012). In China, no-till farming may sequester a total of 2.27 $MtCO_2e$ of soil carbon by 2015, equivalent to 0.5 $MtCO_2e$ per year (Cheng *et al*., 2013a). These are all estimates of the potential to mitigate greenhouse gas emissions; estimates of what has already been achieved are given in the next section.

Policies that work

Governments have traditionally encouraged no-till practices as a measure to curtail soil erosion, and have only recently begun to promote it as a way to mitigate greenhouse gas emissions. However, farmers face difficult challenges during the transition to no-till practices related to high investment costs for machinery, increased dependence on such herbicides as glyphosate, changes in production inputs, and differences in crop and cover-crop management[2]. Thus, support is required for farmers during the transition.

In 2011 Brazil established its ABC Plan, the first national policy promoting no-till cultivation, which includes state-level activities, based upon local and sub-national government plans[3]. It sets implementation goals, anticipating that adoption of no-till practices increase from 31 million hectares to 39 million hectares under the plan. Farmers have access to ABC Plan credit and finance as well as training and extension services if management practices are compliant with the approach.

The adoption of no-till practices in Brazil was brought about by many factors: new knowledge on no-till systems stemming from research by the Brazilian Agricultural Research Corporation; support from farmer associations such as the Brazilian Federation of Direct Planting and Irrigation; backing from agricultural machinery companies who recognize the potential benefits from promoting the technology and expanding their markets; and recognition by farmers that no-till practices bring increased land productivity and reduced production costs (Casão Junior *et al*., 2012).

Between 1982 and 1997 overall cropland erosion dropped by more than a third in the USA, where policy interventions to promote no-till practices on highly erodible land contributed up to 62 percent of the overall reductions (Claassen, 2012)[4]. Classifying soils as highly erodible made it easier to target

[2] To combat weeds, farmers may resort to an over-use of glyphosate or may rely on genetically modified crops, notably corn or soy. Alternatives are available, but support for farmers is required if those alternatives are to be introduced.

[3] Brazil's ABC Plan also includes: species diversification through rotation of crops, succession or combination of crops in a variety of production systems; permanent soil cover, either as mulch or perennial species; organic matter of sufficient quality and according to the soil's biological demand; and further conservation agriculture practices, depending on the location.

[4] From 3.1 billion tonnes of soil in 1982 to 1.9 billion tonnes in 1997.

specific areas for conversion to no-till cultivation, enabled by financial support from the United States Department of Agriculture. To get this support, farmers on highly erodible lands, approximately 25 percent of all USA cropland, had to devise and have approved a soil conservation plan. As a result, in 2009, 35 percent of USA cropland, mostly producing soy, was under no- or reduced-tillage, although often not permanently, which reduces its effectiveness to sequester carbon.

No-till agriculture increased in Australia from 9 percent of cropland in 1990 to 74 percent in 2010 (Llewellyn and D'Emden, 2010), particularly in grain producing areas. Awareness of soil erosion problems, region-specific information and learning opportunities for farmers, and declines in the price of glyphosphate, all contributed to the adoption of no-till practices (D'Emden, *et al*., 2006; Llewellyn and D'Emden, 2010). Australia's Landcare Programme, a community-based approach to land management, which is now made up of 6 000 farmer groups across the country, has played a key role in information dissemination and technical support (Department of Agriculture, 2013). The programme provides a refundable tax offset, financed by carbon-tax revenues, of 15 percent of the purchase price of an eligible no-till seeder to participating farmers. More recently, Australia has recognised the greenhouse gas reduction potential of no-till practices by including them in its Carbon Farming Futures programme – part of Australia's Clean Energy Future Plan, and central to the cropland management component of Australia's national greenhouse gas-reduction target.

Chinese interventions to increase the use of no-till practices have aimed to reduce soil erosion, treat crop residue, and eliminate their post-harvest burning.[5] Up to now, reducing greenhouse gas emissions has not been a factor. As in much of Asia, smaller farm sizes restricted adoption of no-till practices. In addition, crop residues were commonly used for alternative purposes, such as feed for livestock (Lindwall and Sontag, 2010). China hopes to expand no-till practices to 13.3 million hectares by 2015 (Ministry of Agriculture, 2009), especially by providing subsidies to farmers (Zhao, *et al*., 2012).

No-till practices have spread across diverse soil types and agricultural production systems around the world over the last 30 years. The MERCOSUR countries of Argentina, Brazil, Paraguay and Uruguay have the highest rates of no-till cultivation, covering 70 percent of total cultivated area, two-thirds of which are under permanent no-till schemes, resulting in significantly increased soil carbon storage (Derpsch *et al*., 2010). Table 4.1 shows the cumulative mitigation benefits of up to 240 $MtCO_2e$ of avoided emissions in selected countries based on annual greenhouse gas mitigation rates in different climatic zones as provided in Smith *et al.* (2008) and best-available information on the coverage of no-till cultivated areas[6].

Table 4.1 Greenhouse gas mitigation through no-till cultivation, selected countries.

Country	Climate zone	Base year	Area under no-tillage in 2007/8	Best estimate cumulative avoided greenhouse gas emissions by replacing till- with no-till cultivation (between indicated base year and 2007/8)
Unit			*(million hectares)*	*($MtCO_2e$)*
Notes	*(a)*	*(b)*	*(c)*	*(d)*
Australia *(e)*	warm-dry	1976	17	95.2
Argentina	warm-moist	1993	19.7	109.4
Bolivia	warm-moist	1996	0.7	3.1
Brazil	warm-moist	1992	25.5	145.7
Canada	cool-moist	1985	13.5	82.3
China[(f)]	cool-dry	2000	2	1.6
Kazakhstan	cool-dry	2006	1.2	0.2
New Zealand	cool-moist	1993	0.16	0.7
Uruguay	warm-moist	1999	0.66	2.0
USA	cool-moist	1974	26.5	241.3

Notes:
(a) Considering the lack of information on where no-till cultivation is being practiced, we assume one climate zone throughout the country, considering, where possible, the regional distribution of no-till agriculture.
(b) The base year is the estimated year in which the area of no-till cultivation began significantly expanding from a small baseline value in the country. The base year was estimated by linearly extending adoption rates from Derpsch *et al.* (2010), unless otherwise stated.
(c) From Derpsch *et al.* (2010), unless otherwise stated.
(d) Mitigation here refers mostly to avoided carbon dioxide emissions, with a small amount of avoided nitrous oxide emissions. Mitigation estimates on a per hectare basis are from Smith *et al.* (2008). These were multiplied by the area covered by no-till cultivation to obtain a value for total avoided emissions in Mt per year in the country for a particular year. To obtain the cumulative emissions in column 5, the annual emissions were summed for each year from 2007/8 back to the base year (in column 3). To compute the area covered by no-till cultivation in each year, it was assumed that the area covered decreased linearly from 2007/8 back to the base year (in column 3). In countries with long histories of no-till agriculture this probably led to an underestimate of the mitigation that was achieved. However, if the use of no-till cultivation began very slowly, then it is also possible that cumulative avoided emissions were overestimated.
(e) The 2007/8 estimate is derived from Derpsch *et al.* (2010) whereas the base year was established from Llewellyn and D'Emden (2010).
(f) The area stated for China is derived from Liu and Qingdong (2007) and Ministry of Agriculture (2009).

[5] Refers to materials left in the field after harvest, such as straw, which can act as mulch if retained until the next crop.
[6] These best estimates have a wide uncertainty range caused by the variation in conditions under which measurements were made, among other factors.

4.3 Improved nutrient and water management in rice systems

Drivers and benefits of policy change

Rice cultivation contributes more than 25 percent of global anthropogenic methane emissions but there are good options for reducing these emissions. Here we focus on three innovative and promising cropping practices that not only reduce methane emissions but also greatly improve the management of water and nutrients in rice cultivation – alternate wetting and drying (AWD), the system of rice intensification, and urea deep placement (UDP).

Alternate wetting and drying is a water management practice for irrigated rice fields through which farmers can achieve 5–30 percent water savings, lower labour costs, no significant yield penalty and profit increases of up to 8 percent (IRRI, 2013). Where it has been used on farms in Bangladesh, yields have risen by more than 10 percent, raising income by US $67–97 per hectare (IRRI, 2013). In Rwanda and Senegal, rice yield increased from 2–3 tonnes per hectare to 6–8 tonnes per hectare due to the similar system of rice intensification (Baldé, 2013; Cissé, 2013).

Another option for reducing emissions, urea deep placement, consists of inserting urea granules into the rice root zone after transplanting. It is reported to reduce fertilizer use by 35 percent while increasing crop yields by about 20 percent (IFDC, 2012). In Nigeria, for example, farmers were able to harvest 2.69 tonnes more rice per hectare using this technology than when broadcasting urea (IFDC, 2012)[7].

Although the emission reduction potentials of these nutrient and water conserving techniques are in principle very high, actual reduction figures are sparse. Adoption of alternate wetting and drying has been shown to reduce the emissions of methane by 40 percent per year on China's rice paddies, compared to continuously flooded rice production (Li *et al*., 2005). With urea deep placement, large fertilizer users such as China and India could achieve nitrogen fertilizer savings of up to 6.43 Mt and 2.89 Mt per year, respectively (Sutton *et al*., 2013). At the same time, nitrous oxide emissions would be reduced because of lower leaching and denitrification. In China, for instance, a mitigation potential of 0.08 to 0.36 tCO_2e per tonne of grain yield is possible by reducing nitrogen chemical fertilizer rates along with intermittent flooding in paddy rice cropping systems (Cheng *et al.,* 2013b).

Policies that work

There are many examples of success in adopting alternate wetting and drying, the system of rice intensification and urea deep placement across the world. Governments have helped in many cases by providing the necessary incentives and support.

In Bangladesh, government support and policies, as well as targeted public-private partnerships and research, have led to high adoption rates of both alternate wetting and drying and urea deep placement. As an example of government support, alternate wetting and drying was introduced into the draft of the first National Irrigation Policy of Bangladesh. A key incentive turned out to be the government's support for appropriate irrigation pipes or the adaptation of existing pipes (Kürschner *et al*., 2010). The International Rice Research Institute and the Bangladesh Rice Research Institute played key roles in mainstreaming the technique by raising awareness of its benefits and providing technical guidance. The use of TV, radio and newspapers also played an important role in the awareness raising process (Kürschner *et al*., 2010) – to date more than 100 000 farmers have adopted alternate wetting and drying practices (IRRI, 2012).

As a promoter of the fertilizer deep placement technology, the International Fertilizer Development Center took a leadership role in introducing urea deep placement to Bangladesh in the mid-1980s. Among other actions, the Centre organized demonstrations of urea deep placement techniques. By 2012 more than 2.5 million Bangladeshi farmers were using the technology, and it was expected to be adopted by an additional 1 million farmers across the country (IFDC, 2013).

Alternate wetting and drying and the system of rice intensification (a technique similar to alternate wetting and drying) have also been introduced very successfully to other parts of Asia. According to Uphoff (2012) more than 1 million Vietnamese farmers had adopted the system of rice intensification by 2011; in the Philippines, more than 100 000 farmers had begun using alternate wetting and drying by 2012, and it is expected that 600 000 farmers will have adopted this technology by 2015 (Rejesus *et al*., 2013; IRRI, 2013).

In Africa, the government of Madagascar supported the diffusion of the system of rice intensification by providing access to microcredit services, particularly in areas with weak coverage by microfinance institutions. The government facilitated the acquisition of farm equipment by liaising with microcredit institutions and by offering incentives to the private sector in production areas (Ministry of Agriculture, 2008). These credits also promoted knowledge and information sharing and thereby helped scale up the technology.

As women play a prominent role in rice production in Madagascar, the government also relied extensively on women's networks to promote the system of rice intensification. Priority was given to providing women with training in how the system is practiced. Some rural communities relaxed current restrictions on women's access to land and agricultural equipment, suggesting that women, through government support, have significantly contributed to the increase in usage of the system[8]. The technique is also being used on a small scale, but with increasing interest, in several other African countries, including Benin, Cameroon and Senegal (Agridape, 2013)[9].

As a general lesson, emissions of greenhouse gases from rice cultivation can be substantially reduced through efficient management of fertilizer and water. Here we have

[7] Broadcasting refers to a uniform distribution of fertilizer on the soil surface. It differs from deep placement in the sense that it requires more fertilizer and also increases leaching and run-off of nitrogen, especially during the rainy season.

[8] In many African locations women do not have land ownership rights.

[9] The governments of Rwanda and Senegal have helped introduce the system of rice intensification by providing credits to rice cooperatives and through knowledge and information sharing (Cissé, 2013).

Figure 4.1 Mature *Faidherbia albida* between maize in Tanzania. One of the characteristics of the species is its reverse phenology: the tree sheds its leaves in the rainy season and goes dormant, reducing competition for light and water while providing valuable nitrogen-rich litter that is also good fodder. (Copyright: ICRAF).

talked about three innovative and promising approaches – alternate wetting and drying, urea deep placement and the system of rice intensification. Several steps could be taken to quickly scale up of these useful practices. First, they could be included in national agricultural policies. Second, direct financial support could be provided to farmers. Third, it would be very helpful to coordinate the support coming from the private sector and from organizations involved in research and agricultural extension training. Finally, direct support to women involved in rice cultivation would be very effective in scaling up these practices.

4.4 Agroforestry

Drivers and benefits of policy change

Agroforestry refers to a land management approach involving the simultaneous cultivation of farm crops and trees. In addition to sequestering carbon in the tree biomass, agroforestry generally improves microclimate and water balance, reduces erosion and raises soil fertility, among other ecosystem services. It leads, therefore, to higher crop and livestock productivity and, hence, income (Garrity *et al.*, 2006; Schoeneberger *et al*., 2012). For instance, Haglund *et al*. (2011) reported 18–24 percent higher household incomes following the introduction in Niger of a variant of agroforestry called 'farmer managed natural regeneration'. Garrity *et al*. (2010) summarized experiences with maize grown in association with a tree called *Faidherbia albida* in several African countries, reporting yield increases of 6–200 percent, depending on the age of the trees (Figure 4.1). In temperate mechanized agroforestry systems, Dupraz and Talbot (2012) have shown land equivalent ratios reaching 1.2–1.6, suggesting that planting trees and crops together is more efficient than when the two are planted separately[10].

Through diversification of income from fuel, fodder, fruit, timber, and the reduction of labour for firewood collection and the generally strong resilience of trees to climate variability, agroforestry has also shown to provide greater food security under climate shocks than conventional farming (Thorlakson and Neufeldt, 2012).

The mitigation potential of agroforestry systems is theoretically very high, but strongly dependent on the agro-ecosystem, the species being planted, and on the specific type of agroforestry practice. One estimate is that it could potentially mitigate 2.2 $GtCO_2e$ per year (Verchot *et al*., 2007). This large figure stems from the fact that agroforestry has the possibility of being applied to 630 million hectares worldwide (Verchot *et al*., 2007).

The amount of carbon sequestered in agroforestry systems typically ranges from 1.06 tCO_2 per hectare per year to 55.77 tCO_2 per hectare per year for biomass carbon (Nair *et al*., 2009) and from 0.17 tCO_2e per hectare per year to 1.89 tCO_2e per hectare per year for soil carbon (Smith *et al*., 2008). Recently Aertsens *et al*. (2013) estimated that agroforestry could provide 90 percent of the potential of agriculture in Europe to take up additional carbon dioxide from the atmosphere[11].

Policies that work

Despite agroforestry's high potential for increasing welfare and providing environmental services, there may be significant opportunity costs associated with establishing such systems and long time-lags before they generate returns (FAO, 2013b). Particularly in smallholder farming, the barriers include lack of access to farm inputs, capital, markets and training; uncertain land tenure situations; weak institutions and governance structures; and poor seed and seedling provisioning systems (Thorlakson and Neufeldt, 2012). Policies are needed to overcome these barriers.

[10] A land equivalent ratio of 1 suggests that planting crops and trees together requires just as much land as planting them separately. A ratio greater than 1 indicates that it requires less land to produce the same amount of crops and trees.

[11] The total technical potential in the EU-27 is estimated to be 1 566 $MtCO_2e$ per year, corresponding to 37 percent of all carbon dioxide equivalent emissions in the EU in 2007. The introduction of agroforestry is the measure with the highest potential – 90 percent of the total potential of the measures studied (Aertsens *et al*., 2013).

Niger is one example of a country where these barriers have been overcome. Here, a combination of declining traditional governance structures in the 1920s and 1930s and severe droughts and famines in the 1970s and 1980s resulted in the overuse of common lands, which led in turn to a shrinking of natural tree cover by about 90 percent (Sendzemir *et al*., 2011). Reforestation began in earnest in the 1980s when the practice of 'farmer managed natural regeneration', introduced by several non-governmental organizations, was adopted on a large scale because of a change in government policies regarding the use and felling of parkland tree species (Reij *et al*., 2009). While farmers had previously ripped out germinating trees because they had no claim to ownership over the trees' products and services, they now let them grow selectively. Within two decades this combination of non-governmental and governmental support led to a re-greening of about 5 million hectares of nearly barren bush savanna (Reij *et al*., 2009).

Another example is Kenya, where the government has adopted policies to promote farm forestry[12]. Key actions include the relaxation of restrictions on harvesting and marketing of tree products, tax incentives for growing trees on farms, and the creation of contract farming schemes to enhance trading of tree products between landholders and companies[13]. Wangari Mathai's Green Belt Movement has also been instrumental in raising awareness about the importance of trees and for mobilizing thousands of women to plant millions of trees. In western and central Kenya this mix of regulation and incentives has resulted in a 215 000 hectares expansion of agroforestry over the last 30 years (Norton-Griffiths, 2013). Other national policies have promoted tree planting on Kenyan farms (Ajayi and Place, 2012) by supporting the training of extension service staff, establishing tree nurseries countrywide and prohibiting the harvesting of trees from public forests[14].

In northern India, beginning in the late 1970s, poplar trees have been rapidly added to irrigated wheat and barley farms and now cover about 280 000 hectares – or 10 percent of irrigated agricultural lands in this region. Poplars provide timber and other benefits to farmers and barely compete with crops for light and water. Meanwhile, the Forest Conservation Amendment Act of 1988 prohibited cutting timber from state forests, and this increased the price of wood and created an economic incentive to plant trees on farms (Ajayi and Place, 2012). Agroforestry was further encouraged through credits for tree planting from the National Bank for Agriculture and Rural Development and through support provided by the timber industry in the form of higher quality planting material, such as seeds, fruit or aggregate fruit; training in agroforestry; and guaranteed timber prices.

In Europe and North America, agroforestry is mainly promoted for the ecosystem services it provides (Dupraz and Liagre, 2008; Current *et al*., 2009; Jacobson, 2012; Schoeneberger *et al*., 2012). Yet, despite its long-term economic benefits, agroforestry has not achieved its potential in Europe because of high investment costs and the perceived complexity of introducing annual and perennial plantings into high-input, mechanized agriculture (Papanastasis and Mantzanas, 2012). To encourage the expansion of agroforestry, the European Agroforestry Federation has recently called for reforms of the European Common Agricultural Policy, including greater financial support to farmers and more flexible eligibility rules (EURAF, 2013).

4.5 Lessons learned

To mitigate greenhouse gas emissions effectively while achieving development goals in the agriculture sector, the following factors should be considered:

- **Agricultural mitigation options require a coordinated mix of policy support, private and public sector investment, strengthened research, and capacity building of key stakeholders.** Specific actions are needed to demonstrate the benefits of new technologies to farmers, to coordinate needed investments and to disseminate information about benefits and how to overcome barriers. These actions can be supported by public-private partnerships and by research centres, governments, agricultural extension services, the private sector and non-governmental organizations.
- **Multiple benefits require multiple goals.** At the early policy-development stage it makes sense to articulate a number of environmental, social and other goals rather than one objective alone. This makes it easier to identify synergies between different goals rather than having to resolve trade-offs between them. Multiple goals can lead to multiple benefits of climate change mitigation, improved agricultural productivity and enhanced food security.
- **Financial incentives are needed.** A major barrier to the adoption of emission reduction measures has been the lack of financial incentives for farmers to adopt new technologies and practices. Financial incentives, including tax offsets, subsidies, and credits, are needed to help farmers in both developing and developed countries defray high up-front investment costs. Incentives are also needed because no-till and agroforestry practices can have a several year time-lag before their climate and other benefits are realized. Subsidies and microcredit may be particularly important for poor rice farmers who usually lack access to capital and credit.
- **In order to be successful in mitigating emissions, new technologies must be context-specific to the region or country where they are introduced.** For example, for no-till practices to be successful they must take into account local farm size, crop and soil types, carbon/nitrogen ratio over the crop rotation. Context specific research at landscape scale, as well as learning from past mistakes, is important for making each mitigation option work. In addition, land tenure issues have to be resolved before the needed investments and changes in new agricultural practices can be made.

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[12] Through the Economic Recovery Strategy (Ministry of Planning and National Development, 2003), the Forest Act (Ministry of Water and Irrigation, 2005) and the Draft Forest Policy (Ministry of Enviroment and Natural Resources, 2007).

[13] Contract farming is agricultural production carried out according to an agreement between a buyer and farmers, which establishes conditions for the production and marketing of a farm product or products (FAO, Rome, 2008).

[14] The Forest Policy (Goverment of Kenya, 1968) and the Rural Afforestation and Extension Services Division, set up in 1971.

Chapter 5

Bridging the gap II: International cooperative initiatives

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5.1 Introduction

There are many initiatives underway outside of the Climate Convention aimed at reducing emissions of greenhouse gases by promoting actions that are less greenhouse gas intensive. We refer to these initiatives collectively as international cooperative initiatives[1]. These initiatives complement and support pledges and other actions under UNFCCC in a number of different ways: some focus on assisting countries to meet a variety of goals and have climate change mitigation as an ancillary benefit, while for others the central objective is reducing emissions of greenhouse gases for climate purposes.

This chapter pays particular attention to those initiatives that can support meeting and exceeding current pledges and help narrow the emissions gap. Specifically, this would include international cooperative initiatives that provide emission reductions that are likely to be additional to those stemming from national emission reduction pledges and actions.

The chapter first provides an overview of the different initiatives, including a categorization by type. Appendix 5.A complements this information by giving a sample of the many international cooperative initiatives currently active. It then identifies where large potential exists to close the gap and finishes with a set of possible criteria for designing initiatives that could be most effective in closing the emissions gap.

5.2 Current international cooperative initiatives

A categorization of existing initiatives reveals that the topics covered, actors involved and participation levels vary greatly across them. The reader is referred to Appendix 5.A for an overview of initiatives (note that the overview is illustrative and not comprehensive).

[1] In this chapter we assume that international cooperative initiatives are initiatives with participants from at least three countries. These could be governmental entities from the national, sub-national or local level and/or non-state actors, including businesses and NGOs.

Initiatives underway can be put into three categories:

1. **Global dialogues.** These initiatives provide a forum for national governments to exchange information and understand national priorities. Some are primarily at the head-of-government level, such as the G8 and the G20; others at the ministerial level, such as the Major Economies Forum. Some include industry, academia, and/or civil society. These groups may issue statements of intent or voluntary commitments and otherwise contribute to consensus building.
2. **Formal multilateral processes.** A number of international organizations and formal international negotiation processes are addressing issues that are relevant to the reduction of greenhouse gas emissions. These include international treaties such as the Montreal Protocol on Substances that Deplete the Ozone Layer or sector specific organizations such as the International Civil Aviation Organization or the International Maritime Organization. These international cooperative initiatives can produce binding international agreements to reduce emissions.
3. **Implementation initiatives**. There are many initiatives that focus on enabling countries to meet their pledges through sharing good practices and technical knowledge. Some concentrate on **technical dialogues**, including for instance the Mitigation and MRV Partnership, or the Clean Energy Ministerial. The more technical the discussion, the more non-governmental actors are often involved. Other initiatives go beyond dialogue to support **sector-specific initiatives** through the collective implementation and, in many cases, funding of programmes or projects. This may include the facilitation of clean energy projects, for example, through the Renewable Energy and Energy Efficiency Partnership, the development of sector-specific action plans such as those developed under the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants, or the implementation of programmes

to reduce emissions from deforestation and forest degradation such as the REDD+ Partnership. Some of these sector-specific implementation groups are independent of national governments.

To assess the extent to which international cooperative initiatives can help bridge the emissions gap, it is necessary to differentiate between the type of contribution each initiative makes – direct or indirect. Global dialogues and many of the implementation initiatives focus on building consensus and sharing best practices, making an important – but indirect – contribution to narrowing the gap. Other initiatives lead to direct greenhouse gas reductions. To the extent that they cover sectors and countries currently outside of the pledges, or support countries to reduce emissions beyond these pledges, they make a direct contribution to narrowing the gap. The remainder of this chapter focuses on initiatives that may lead to direct reductions, particularly in those areas that represent high mitigation potential.

5.3 Promising areas for international cooperative initiatives to close the gap

Three studies (Blok *et al.*, 2012; IEA, 2013; UNFCCC, 2013) have identified promising mitigation measures and areas to narrow the gap (Table 5.1). Criteria used to identify these promising areas across the studies include:

– a minimum level of already-started activity;
– an organization that can take the lead in scaling up activities;
– a positive or neutral impact on the economy;
– a minimum level of mitigation potential, of size or critical mass of participants.

The above three studies highlighted four priority mitigation measures in particular:

– energy efficiency;
– fossil fuel subsidy reform;
– methane and other short-lived climate pollutants; and
– renewable energy.

Table 5.1 Promising areas for international cooperative initiatives and three estimates of associated reduction potential

Mitigation measures and areas		Reduction Potential			Initiatives
		Wedging the gap (Blok *et al.*, 2012) $GtCO_2e$ per year in 2020	**UNFCCC technical paper (UNFCCC, 2013)** $GtCO_2e$ per year in 2020	**IEA energy/ climate map (IEA, 2013)** $GtCO_2e$ per year in 2020	**Approximate number**
Energy efficiency	Buildings' heating and cooling	0.6	2	0.5	25
	Ban of incandescent lamps	0.5		0.5	
	Electric appliances	0.6			
	Industrial motor systems			0.4	
	Car- and truck-emission reduction	0.7		0.2	
Renewable energy	Boost solar photovoltaic energy	1.4	1–2.5		17
	Boost wind energy	1.2			
	Access energy through low- emission options	0.4			
Limiting inefficient coal use in electricity generation				0.7	None
Methane and other short-lived climate pollutants	Reducing methane emissions from fossil-fuel production	*	1.1	0.6	7
	Other methane and other short-lived climate pollutants				
	Efficient cook stoves	*			
Fluorinated greenhouse gases		0.3	0.5		3
Fossil-fuel subsidy reform		0.9	1.5–2	0.4	1
International transport		0.2	0.3–0.5		4
Agriculture		0.8	1.3–4.2		1
Reduce deforestation		1.8	1.1–4.3		15
Waste			0.8		1
Reduce emissions from companies	Top-1 000 company emission reduction	0.7			4
	Supply chain emission reduction	0.2			1
	Green financial institutions	0.4			1
	Voluntary offset companies	2.0			None
Voluntary offsets by consumers		1.6			None
Major cities initiative		0.7			3
Sub-national governments		0.6			2
Total		9.7**	Not added because of ranges	3.3 ***	

*not estimated, **accounting for overlaps, *** total does not add up because of roundings
Notes: The reduction potential is not strictly comparable. The UNFCCC technical paper (UNFCCC, 2013) presents mitigation potentials for entire sectors. Blok *et al.* (2012) estimate the potential of an initiative assuming that it can realize only a fraction of the theoretical potential. IEA (2013) reports model estimates. The numbers of initiatives are approximations based on the annex, which includes only a selection of initiatives.

Fluorinated greenhouse gases and international transport are also frequently listed as priority areas. In addition, the International Energy Agency (IEA) highlights the large short-term potential of limiting inefficient coal use in electricity generation, an area that is currently not covered by any international cooperative initiatives. On the other hand, other areas are covered by more than one initiative, for example, reducing emissions from deforestation.

To date there have been very few quantitative assessments of the impact of cooperative initiatives. Some studies analyze the past and possible future impact of individual initiatives, notably studies on the Sustainable Energy for All Initiative (Rogelj *et al.* 2013), the WWF Climate Savers Programme (Ecofys, 2012), the Covenant of Mayors (Cerutti *et al.*, 2013), and the phase out of hydrofluorocarbons (Hare *et al.*, 2013; Molina *et al.*, 2009; UNEP, 2011; Velders *et al.,* 2009; Velders *et al.*, 2012; Xu *et al.,* 2013; Zaelke *et al.,* 2012). No study was found on the aggregate past impacts of cooperative initiatives.

Only a few initiatives are clearly outside the scope of national pledges, namely those on international aviation and shipping, and those on short-lived climate pollutants, or initiatives on non-carbon dioxide gases for those countries whose pledges only apply to carbon dioxide emissions. All other initiatives potentially overlap with national pledges and, because of this, it is not yet possible to assess the volume of reductions expected from these initiatives alone.

The overview of initiatives in Appendix 5.A illustrates the diversity found in both approach and membership, as well as the overlap found in some priority mitigation measures. An element of coordination or integration among overlapping initiatives would likely strengthen their collective effectiveness.

Finally, participation in the initiatives, especially for developing countries, is constrained by various factors. One is the limited amount of time and capacity available for participation. Another is limited expertise in the subject areas of the initiatives. These factors raise concerns about the credibility and legitimacy of some initiatives. This would argue for fewer, but more effective and ambitious initiatives. Some have proposed that a coalition of initiatives could be helpful (Blok *et al.,* 2012).

5.4 How to make international cooperative initiatives effective in closing the gap?

Few studies have been conducted on the effectiveness of initiatives (Bausch and Mehling, 2011; Weischer *et al.,* 2012; Young, 2011). Nevertheless, based on the small amount of experience gained up to now, we speculate that five aspects are particularly important: focus and goals; participation; funding and institutions; incentives and benefits; and transparency and accountability.

Focus and goals

It has been argued that some international cooperative initiatives might be "*specialized venues [that] could each address a small piece of the puzzle that the UNFCCC could not tackle as a whole*" (Moncel and van Asselt, 2012). As an example, the Consumer Goods Forum, a global industry network of over 400 retailers, agreed to begin phasing out hydrofluorocarbon refrigerants by 2015, and work to achieve zero net deforestation by 2020. Following this model, international cooperative initiatives could be effective by having a sharp focus on a limited number of ambitious goals.

Participation

Some authors argue that limiting the number of participants is an important factor for effectiveness. Smaller groups are able to act faster (Biermann *et al.,* 2009) and can be expected to be 'narrow-but-deep', reaching substantial policy goals that would not have been reached in a 'broad-but-shallow' regime that has more participants but less ambition due to the compulsions of placating all signatories (Aldy *et al.,* 2003). On the other hand, the contribution to closing the gap will be larger if all major current and future emitters participate, which might argue for a slightly larger group (Bausch and Mehling, 2011).

In the field of renewable energy, we find all models. The recently launched German initiative for a renewables club brings together a small group of ministers from 10 countries considered to be leaders. Meanwhile, the Clean Energy Ministerial encompasses a larger group of 23 countries accounting for 80 percent of global greenhouse gas emissions, and the International Renewable Energy Agency has almost universal participation, with 114 member states, plus 46 in accession. No assessment has been made on the effectiveness of these different models, but it is likely that the right group size depends on an initiative's mandate.

Participation of stakeholders, beyond the government representatives that traditionally conduct climate negotiations, is another factor that might enhance effectiveness. International cooperative initiatives might help bring in constituencies that have so far not been active in climate change issues, but could make essential contributions to solving the problem (Moncel and van Asselt, 2012). This can include government agencies that deal with related issues such as energy or security, as well as business and civil society. Two examples of multi-stakeholder partnerships bringing together governments, industry representatives, non-governmental organizations and researchers are the Renewable Energy Partnership for the 21st century (REN21) and the Climate and Clean Air Coalition to reduce Short-lived Climate Pollutants.

Another important aspect of participation is whether high-level participation, for example from ministers or heads of government, might lead to a stronger political buy-in and thus make an international cooperative initiative more effective in closing the gap. To facilitate implementation of their programmes, it might be useful for such initiatives to include not only high-level dialogues, but also mechanisms for working-level cooperation. For example, the Clean Energy Ministerial and the Climate and Clean Air Coalition both incorporate meetings of ministers with meetings of working groups consisting of experts who work on implementation.

Funding and institutions

The design of international cooperative initiatives has to strike a difficult balance between providing the necessary institutional framework for meaningful cooperation yet avoiding too bureaucratic an operation. An appropriate set-up might include a secretariat, clear procedures and sufficient resources (Bausch and Mehling, 2011). Conversely, avoiding bureaucracy means fewer formalities, allowing for more flexibility and pragmatic action. For example, the G8 and G20 presidencies rotate from year to year and have no permanent secretariat, which makes systematic implementation and follow-up difficult, whereas the International Energy Agency's Implementing Agreements have a secretariat, a dedicated budget and the capacity to implement their own projects.

Incentives and benefits

If international cooperative initiatives are to catalyse significant additional emission reductions, they need to offer compelling reasons for potential participants to join. These incentives would predominantly be economic benefits that need to be significant, equitably distributed among participants and, at least to a certain extent, exclusive to the participants (Weischer *et al.,* 2012). One example of benefits is the technical and policy support provided by the Collaborative Labelling and Appliance Standards Program to governments working on energy efficiency standards and labels. Other examples are the two separate, complementary funding mechanisms provided by the Forest Carbon Partnership Facility.

Transparency and accountability

In order to determine whether an international cooperative initiative is making a contribution to closing the emissions gap, its activities and their emissions impact need to be transparent. Enhancing transparency and accountability might also make initiatives more effective, as it represents an incentive to follow through on commitments and provide participants with confidence that others are acting as well (Bausch and Mehling, 2011). This might, for instance, include regular reporting or peer-review procedures. A good example is the Covenant of Mayors initiative, which developed detailed monitoring requirements for its actions, regular reporting by participants, and the independent verification of results.

5.5 Links with the United Nations Framework Convention on Climate Change

At present, there are no formal links between UNFCCC and the various international cooperative initiatives. Nevertheless, within the Convention's *Ad Hoc* Working Group on the Durban Platform there is an on-going discussion about what role initiatives could play in helping to close the 2020 emissions gap. Whether and how to account within the convention for the emission reductions achieved by international cooperative initiatives is a key part of the discussion. Parties could, in principle, do this through existing reporting practices and rules, or through a purpose-made methodology to account specifically for reductions attributable to international cooperative initiatives. Irrespective of the form it takes, such a reporting mechanism could provide an informal platform for recognizing efforts and, in this way, encourage performance.

5.6 Conclusions

International cooperative initiatives have the potential not only to support existing pledges, but to go beyond them to narrow the gap. To achieve this, however, they need to focus on the large opportunity areas and be designed and implemented in an effective way.

A large number of international cooperative initiatives currently exists, and they are very diverse in scope and approach. Some make an indirect contribution to closing the emission gap by promoting dialogue and sharing experience and best practice. Others have the potential to make direct contributions, as their mandate focuses on catalysing additional mitigation – by involving additional actors or covering additional sectors or by providing incentives for action beyond current pledges.

A review of the limited literature available suggests four broad priority areas:

1. **Energy efficiency** with significant potential, up to 2 $GtCO_2e$ by 2020. It is already covered by a substantial number of initiatives. Focus and coherency is needed.
2. **Fossil-fuel subsidy reform** with varying estimates of the reduction potential: 0.4–2 $GtCO_2e$ by 2020. The number of initiatives and clear commitments in this area is limited.
3. **Methane and other short-lived climate pollutants** as a mix of several sources. Reducing methane emissions from fossil-fuel production has received particular attention in the literature. This area is covered by several specific initiatives and one that is overarching.
4. **Renewable energy** with particularly large potential: 1–3 $GtCO_2e$ by 2020. Several initiatives have been started in this area. Focus and coherency is needed.

While further research is needed to arrive at more comparable figures on emission reduction potential, additional sectors in which the potential may be high include fluorinated greenhouse gases, international transport, limiting inefficient coal use in electricity generation, agriculture and forestry. It would be useful to have guidelines for clear and quantifiable commitments, and transparent monitoring and reporting to allow for a more precise quantification of the contribution of international cooperative initiatives to closing the gap.

Any instigator of a new initiative should assess the landscape before beginning something new. In issue areas with a high number of existing initiatives, a consolidation of efforts could be considered.

International cooperative initiatives need to be effective in delivering actual emission reductions. The following provisions can enhance the effectiveness of international cooperative initiatives:

- a clearly defined vision and mandate;
- the right mix of participants appropriate for that mandate, going beyond traditional climate negotiators;
- stronger participation from developing country actors;
- sufficient funding and an institutional structure that supports implementation and follow-up, but maintains flexibility;
- incentives for participants;
- transparency and accountability mechanisms.

These are preliminary findings. Additional research is clearly needed to systematically identify empirical lessons from the existing initiatives and gain a clearer understanding on what makes initiatives effective.

Chapter 6

Bridging the gap III: Overview of options

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6.1 Introduction

The analysis in Chapters 2 and 3 of this report concluded that the emissions gap in 2020 is likely to be 8–12 $GtCO_2e$ and showed an increase in projected business-as-usual emissions in 2020 compared to the 2012 report. Starting from the estimated total emission reduction potential, and based on the findings of the previous chapters, this chapter provides an overview of options to reduce the emissions gap.

The chapter starts by asking whether the gap can be bridged. To answer this question, the best available estimates of the total emission reduction potential and possible changes in these estimates are discussed. Following this, a summary of options to narrow, and potentially bridge, the emissions gap in 2020 is presented.

6.2 Emission reduction potentials in 2020 and 2030: can the gap be bridged?

The options to narrow the emissions gap discussed in the previous chapters of this report – emission reduction pledges, Chapter 2; national climate and development policies, Chapters 2 and 4; and international cooperative initiatives, Chapter 5 – all have connections with one another and all will help bridge the emissions gap in 2020.

UNEP's Bridging the Emissions Gap Report (2011a) estimated the total emission reduction potential in 2020 to be in the range of 17 ± 3 $GtCO_2e$ [1,2]. Table 6.1 provides an overview of emission reduction potentials by sector from the earlier report together with estimates for 2030 from the IPCC (2007).

The mid-range of 17 $GtCO_2e$ is slightly greater than the estimated difference between business-as-usual emissions in 2020 and the 2020 emissions level consistent with a likely chance of staying within the 2° C target of 15 $GtCO_2e$. This indicates that there is still a chance to close the gap by 2020, but it also means that even relatively small changes in the total emission reduction potential could have important implications on the ability of society to bridge the gap. Total emission reduction potentials change over time, reflecting among other things technological development and the speed and comprehensiveness with which policies and options are adopted and implemented.

UNEP's Emissions Gap Report 2012 emphasized that, although the emission reduction potential in 2020 remains high, time is running out with respect to realizing this potential (Chapter 3). First, there can be a considerable time lag between the adoption of emission reducing policies and options, their implementation and the reaping of the associated emission reductions. Second, many investments in, for example, transportation systems, energy production, buildings and factories are long-lived. Failure to invest today in best available technologies and options not only represents a lost opportunity to reduce emissions, it also curtails our ability to reduce them in the near future as high energy use and emission patterns are locked-in for several decades. Postponing action implies that part of the potential in 2020 may be lost and that steeper and more costly action will be required to achieve the remaining potential (Chapter 3).

Table 6.1 Estimates of sectoral greenhouse gas emission reduction potentials, 2020 and 2030

Sector	Emission reduction potential in 2020 ($GtCO_2e$ per year)	Emission reduction potential in 2030 ($GtCO_2e$ per year)
Power sector	2.2–3.9	2.4–4.7
Manufacturing industry	1.5–4.6	2.5–5.5
Transportation	1.7–2.5	1.6–2.5
Buildings	1.4–2.9	5.4–6.7
Forestry	1.3–4.2	1.3–4.2
Agriculture	1.1–4.3	2.3–6.4
Waste	Around 0.8	0.4–1.0
Total (central estimate)	**17 ± 3**	**23 ± 3**
Total (full range)	**10–23**	**16–31**

Source: Emission reduction potential in 2020 is taken from UNEP, (2011a; 2012). The 2030 potential is taken from IPCC (2007).

[1] Adopting a sectoral bottom-up approach, with marginal costs in the range of 50–100 US $/$tCO_2e$.

[2] Assuming that the uncertainties are independent between sectors, which may hold under many cases, an error propagation rule to calculate the range of the sum of the sectors is applied – that is, the square root of the sum of squares of the range for each sector. This gives a reduced range of ± 3 $GtCO_2e$ compared to the full range of ± 7 $GtCO_2e$.

Furthermore, it is unclear to what extent national pledges and international cooperative initiatives cover the sectoral emission reduction potentials. As countries rarely specify a split of their pledge by sector, it is difficult to make a complete assessment of the degree of overlap. Ideally, such overlaps should be taken into account when assessing options for narrowing the emissions gap through additional action.

Comprehensive and regular updates of emission reduction potentials are a prerequisite for in-depth assessments of the feasibility of bridging the emissions gap. Unfortunately, the number of new studies published since the 2012 update (UNEP, 2012) is limited and prevents a thorough re-evaluation of the emission reduction potentials in Table 6.1. The new studies do, nonetheless, provide an assessment of the possible take-up of emission reduction options for particular scenarios and specific assumptions regarding policy regimes and carbon prices. They give an indication of current trends for the sectoral emission reduction potentials reported in Table 6.1. Recent developments in the power and transportation sectors point towards possible increases in the emission reduction potentials for 2020 – modest – and 2030 – potentially substantial. More specifically, for the power sector, rapid growth of renewable energy (Breyer, 2011; REN21, 2013) might be able to more than compensate for the limited development reported for nuclear energy and carbon capture and storage reported by the International Energy Agency (IEA, 2013). Some authors highlight that, if the current rate of growth of wind and solar photovoltaic power continues after 2020, decarbonization rates for electricity could be higher than expected in even the most ambitious scenarios, increasing the 2030 emission reduction potential by several $GtCO_2e$ (Blok and Van Breevoort, 2011). In the transportation sector, a rapid decline of carbon-dioxide emissions per vehicle kilometre for passenger cars is observed (IEA, 2013). Less is known about other parts of the transportation sector. A study for 2030 shows that implementation of appropriate policies for vehicle efficiency, modal shift and activity reduction could lead to a reduction in greenhouse gas emissions of 5.8 $GtCO_2e$ in 2030, compared to a business-as-usual scenario (Façanha *et al*., 2012). This is more than double the potential in 2030 given in Table 6.1, although developments in other parts of the transport sector would need to be factored in.

Progress in the manufacturing industry and building sectors is limited and raises concerns about the feasibility of achieving its mid-range potential by 2020. For the manufacturing industry current uptake of energy-efficient technology is moderate according to the International Energy Agency (IEA, 2013). However, large developing countries such as China and India now have substantial industrial energy efficiency programmes in place, although the actual impact of these is difficult to quantify at this stage. Given the limited level of implementation globally, the remaining potential in 2020 is likely to be closer to the lower end of the range rather than the higher. Since a large part of the potential is retrofit and add-on technology, the estimate of the 2030 potential is probably still valid. The building sector shows limited progress, according to Ürge-Vorsatz *et al*. (2012) and the International Energy Agency (IEA, 2013), who claim that a large untapped potential exists. This raises concern about the feasibility of reaching the 2020 potentials and also makes it difficult to make a statement about the change in potential for 2030.

Similarly for agriculture and forestry, the limited level of actual implementation of policies may limit the feasibility to achieve the higher ends of the range of emission reduction potentials for 2020.

To conclude, the findings of recent studies are generally consistent with the range of 2020 emission reduction potentials summarised in Table 6.1. However, they do give reason for concern about the feasibility of achieving the potentials by 2020. They also illustrate the need for comprehensive updates of the potentials for each sector for 2020 and 2030, and for tracking progress towards them.

Most of all, this section, along with the previous chapters of this report, illustrates that emission reduction potentials will only be realised if strong, long-term and sector-specific policies and policy portfolios are in place at the international and national level (Box 6.1).

6.3 Options to narrow and potentially bridge the emissions gap in 2020

A number of options to narrow the 2020 emissions gap can be identified based on the information of the previous chapters of this report. These range from applying more stringent accounting practices for pledges to increasing the scope of pledges to going beyond them. Figure 6.1 summarizes these options and illustrates how, if implemented together, they have the potential to bridge the emissions gap in 2020. Each of these options and their potential contribution to narrowing the emissions gap are summarised below.

As described in Chapter 2, the gap can be narrowed by 1-2 $GtCO_2e$ by applying more stringent accounting practices for emission reduction pledges, i.e. by moving from lenient to strict rules. This includes:

- Minimizing the use of lenient land-use credits .
- Minimizing the use of surplus emission units
- Avoid double counting of offsets

The gap can be further narrowed by 2-3 $GtCO_2e$ if all countries were to move from their unconditional to their more ambitious conditional pledges. This would require the fulfilment of the conditions on those pledges and the swift implementation of policies to deliver the additional reductions. These conditions include expected action of other countries as well as the provision of adequate financing, technology transfer and capacity building. Alternatively it would imply that conditions for some countries be relaxed or removed.

These two approaches, applying more stringent accounting practices plus implementing the more ambitious pledges, leads to a reduction of the emissions gap of 4 $GtCO_2e$.

The gap can be further narrowed by other actions aimed at increasing the scope of current pledges:

- Coverage of all emissions in national pledges (up to 0.5 $GtCO_2e$): some country pledges cover only a part of a country's total emissions. For example some countries have pledges to reduce carbon dioxide emissions and have not specified actions for the other greenhouse gases. This would apply to roughly 3 $GtCO_2e$ of current emissions. Assuming these are reduced by 15 percent

[3] Some countries are set to move in this direction (see Section 2.5)

Box 6.1 Best-practice policies for reducing greenhouse gas emissions and achieving development goals from the 2012 and 2013 UNEP emissions gap reports

The 2012 and 2013 UNEP emission gap reports identify policies for four sectors that have proven successful in reducing greenhouse gas emissions in many different countries, while contributing to national development goals (Chapter 4; UNEP, 2012). Such sector-specific policies have the potential to make a significant contribution to bridging the gap, if scaled up in both ambition and geographical reach.

Agriculture

- Promotion of no-tillage practices: no-till refers to direct seeding under the mulch layer of the previous season's crop, reducing greenhouse gas emissions from soil disturbances and fossil-fuel use by farm machinery.
- Improved nutrient and water management in rice production: includes innovative cropping practices such as alternate wetting and drying and urea deep placement that reduce methane and nitrous oxide emissions.
- Agroforestry: consists of different agricultural management practices that all deliberately include woody perennials on farms and the landscape, and which promote a greater uptake of carbon dioxide from the atmosphere by biomass and soils.

Buildings

These policies lower energy use and therefore reduce carbon-dioxide and other emissions:

- Building codes: regulatory instruments that set standards for specific technologies or energy performance levels and that can be applied to both new buildings and retrofits of existing buildings.
- Appliance standards: regulations that prescribe the energy performance of manufactured products, sometimes prohibiting the sale of products that are below a minimum level of efficiency.
- Appliance labels: energy-efficiency labels that are fixed to manufactured products to describe the products' energy performance. Endorsement labels are seals of approval that are awarded if energy-saving criteria are met. Comparative labels allow consumers to compare performance among similar products.

Forests

These policies slow down deforestation and thereby reduce carbon dioxide and other emissions:

- Protected areas: designating some forested areas as protected areas.
- Command-and-control measures: enacting and enforcing environmental regulations and putting adequate monitoring systems in place to ensure compliance.
- Economic instruments: using economic tools such as taxes, subsidies, and payments for ecosystem services for encouraging forest conservation.

Transport

These policies reduce energy use and therefore reduce carbon dioxide and other emissions:

- Transit-oriented development: the practice of mixing residential, commercial and recreational land uses to promote high-density neighbourhoods around public transit stations.
- Bus Rapid Transit (BRT): key elements of bus rapid transit include frequent, high-capacity service; higher operating speeds than conventional buses; separated lanes; distinct stations with level boarding; and fare prepayment and unique branding.
- Vehicle performance standards: establish minimum requirements based on fuel consumption or greenhouse gas emissions per unit of distance travelled by certain vehicle classes.

These policies do not represent a comprehensive list. Moreover, some best-practice policies will be more appropriate and successful in reducing emissions in some countries than in others. Their success also depends on how stringently they are implemented.

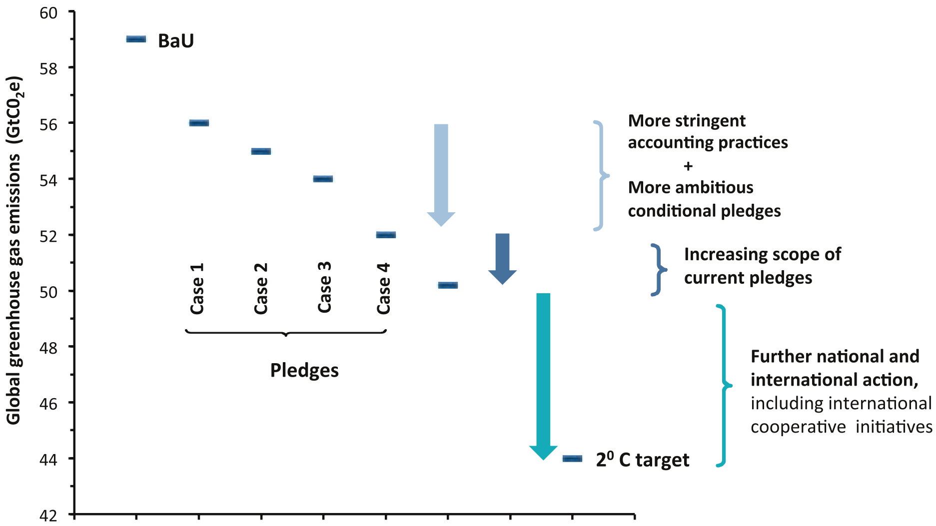

Figure 6.1 Overview of options to narrow the emissions gap in 2020.

by 2020, the order of magnitude of pledges made by other countries, the resulting reduction would be 0.5 $GtCO_2e$.

– New pledges by countries that have not yet pledged (up to 1 $GtCO_2e$): some countries have not yet put forward pledges. Aggregated emission levels from those countries amounted to roughly 7 $GtCO_2e$ in 2010. If they were to reduce emissions by 15 percent by 2020, which is the order of magnitude of pledges made by other countries, the resulting reduction in emissions would be 1 $GtCO_2e$.
– Additional reductions from sectors not covered by national pledges (0.3 $GtCO_2e$): Some sectors, notably international transport, are not covered by national pledges. The mitigation potential in these sectors is 0.3 $GtCO_2e$ (UNEP, 2011a).

These three actions to increase the scope of current pledges would further reduce the gap by up to 1.8 $GtCO_2e$.

Adding together the more stringent accounting practices, the more ambitious pledges, and the increased scope of current pledges, reduces the gap by around 6 $GtCO_2e$, or about a half.

The remaining gap can be bridged through further national and international action, including international cooperative initiatives. These initiatives may partly overlap with national pledges, but can also be additional to these pledges. If they are additional and implemented rapidly, they have the potential to substantially reduce the gap by 2020 (Blok *et al*., 2012).

Reductions of short-lived climate pollutants would have to occur in addition to reductions of emissions of long-lived greenhouse gases, and would not be a replacement. Some ozone precursors and black carbon are not covered by national pledges, but are already assumed to be reduced in the calculations of the gap. Missing out on these reductions would increase the gap by a rough equivalent of 1–2 $GtCO_2e$ (Hare *et al*., 2012; UNEP, 2011b).

6.4 Conclusions

This chapter illustrates that it is difficult to estimate the impact of various options for reducing emissions and narrowing the gap. For this reason it would be beneficial to set up an objective accounting system for tracking progress towards closing the gap. Also, comprehensive updates of emission reduction potentials in different sectors would provide invaluable information for decision making as we move closer to 2020.

Importantly, this chapter shows that applying more stringent accounting practices, implementing more ambitious pledges, and increasing the scope of current pledges, will bring the world halfway to bridging the gap. The remaining gap can be bridged through further national and international action, including international cooperative initiatives. As shown in the beginning of this chapter this is technically possible.

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ISBN: 978-92-807-3353-2
Job Number: DEW/1742/NA

COMMENTER:

Department of Energy (DOE)

General comments

The Supplementary Technical Information (STI) document notes on page 5 that leak detection and repair protocols are not being specified at this time due to potential overlap with ongoing regulatory actions, indicating that a proposal for this commitment option will be phased in at a later date. Reviewer notes that this is a significant gap in the BMPs and wonder if there is some way for DOE to assist with the initial development of these protocols, including the details of any associated flexibility mechanisms (as alluded to on page 5).

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According to an analysis by ICF International for the Environmental Defense Fund[1], replacing gas-driven Kimray pumps with electric pumps at natural gas production facilities had large positive returns to operators and could result in approximately 5 Bcf in methane emissions abatement annually. However, it appears that Kimray pump replacement is not included as a source category to be addressed in the STI document. Reviewer recommends that EPA consider adding Kimray pump replacement as an area where companies could make a commitment to best management practices.

Specific comments

Page 5: The timeframe proposed for the Methane Challenge Program would allow companies pursuing the One Future abatement pathway to achieve their emissions abatement targets by 2025. However, analysis conducted by DOE's Office of Energy Policy and Systems Analysis suggests that meeting the President's objective of reducing methane emissions from the oil and gas sector to 40 to 45% below 2012 levels by 2025 will require meeting the One Future objective by at latest 2020 and further reducing natural gas leakage from natural gas supply chain below 1% of production after that time. This analysis is assumes continued growth in the natural gas production projected by the Energy Information Administration[2] and using emissions rates from EPA's Greenhouse Gas Inventory[3]. Reviewer recommends that EPA explicitly encourage operators to meet One Future and BMP commitments quickly, ideally no later than 2020.

Page 22, in response to question 2: An analysis by ICF International conducted for EDF[4] suggests that replacing intermittent-bleed pneumatic controllers with low-bleed pneumatic controllers could result in

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[1] ICF International prepared for the Environmental Defense Fund. "Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries." March 2014. https://www.edf.org/sites/default/files/methane_cost_curve_report.pdf

[2] Energy Information Administration. "Annual Energy Outlook 2015: Energy production, imports, and exports." April 14, 2015. http://www.eia.gov/forecasts/aeo/section_energyprod.cfm

[3] U.S. Environmental Protection Agency. "U.S. Greenhouse Gas Inventory Report: 1990-2013." April 15, 2015. http://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html

[4] ICF International prepared for the Environmental Defense Fund. "Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries." March 2014. https://www.edf.org/sites/default/files/methane_cost_curve_report.pdf

more than 10 Bcf of avoided methane emissions annually at a cost to operators of less than $2 per Mcf of avoided emissions (assuming cost recovery for captured natural gas at $4 per Mcf). Reviewer recommends that EPA consider including replacement of intermittent-bleed devices with low-bleed devices as an area in which operators could make a BMP commitment. The intermittent-to-low bleed BMP could be structured analogously to that for transitioning from high-to-low bleed pneumatic devices.

COMMENTER:

Department of Energy – National Energy Technology Laboratory (DOE-NETL)

Review Comments (NETL) for Natural Gas STAR Methane Challenge Program: Supplementary Technical Information (For Stakeholder Feedback)

General Comment:

We are hearing from some in industry that the proposed 95% emissions reduction thresholds for performance on a number of measures is overly ambitious, somewhat arbitrary and not readily verified with commercial technologies. For example, when leak detection and repair methods are used as an abatement strategy, the level of achieved abatement is not necessarily known, because most commercially available leak detection technologies are not measuring emissions flux rates before or after repairs are conducted. Therefore, reviewer suggests that EPA consider alternative thresholds (or, in some cases, no thresholds) for performance, in cases where there is no viable means for directly measuring performance before and after repairs.

Page 6 – Natural Gas Continuous Bleed Pneumatic Controller Exceptions

The Methane Challenge tracks mitigation of continuous high-bleed pneumatic controllers with bleed rates greater than 6 scf/hour with the exception of those that are required based on functional needs, including but not limited to response time, safety and positive actuation. The exception requirements appear to be very loosely defined. It may make sense to collect greater detail on these devices which are exempt from mitigation than simply reporting the number of them. Maybe an additional data element should be collected under the heading of "Reason for Exception" for each controller greater than 6 scf/hour which will not be included as part of the challenge.

Page 8 - Liquids Unloading Mitigation Options

The second bullet under Mitigation Option

- Track and report emissions for all wells conducting liquids unloading including the duration of the event, emissions associated with venting during liquids unloading, and the types of controls.

This appears to be misplaced in the document. Perhaps this bullet belongs under the Reporting section rather than the Mitigation Option section as the tracking and reporting of emissions is not a mitigation method.

Page 9- Centrifugal Compressors-venting

Re-order the mitigation options as follows:

1) Use centrifugal compressors with dry seals.
2) Route wet seal degassing to a capture system for beneficial use to achieve at least a 95% reduction in methane emissions, or
3) Route wet seal degassing to flare or control device to achieve at least a 95% reduction in methane emissions, or

Page 16 – Mains – Cast Iron and Steel % Annual Replacement/Repair Table

The approach used to determine the minimum % Replacement/Repair for the BMP option is based on a 5 tier system with annual rates of mitigation ranging from 6.5% for Tier 1 to 1.5% for Tier 5. This approach appears to be rather random and allows for strange inequities. For instance, a company with 1,000 miles of cast iron and unprotected steel mains would be required to replace/repair at the rate of 50 miles per year while a company with 1,500 miles of pipe inventory would only have to replace at the rate of 45 miles per year and a company with 1,501 miles of inventory would only have to replace at the rate of 30 miles per year. A better approach might be to provide a table of Miles of Pipe vs. Replacement Miles/year with replacement miles/year always monotonically increasing.

Page 17 – Unprotected Steel and Cast Iron Services – requested feedback on structure of BMP commitment option

Suggest providing a table relating the number of services in company inventory which require mitigation vs. number of services to be mitigated per year. The number of mitigations/year should increase monotonically as the number of services in inventory which require mitigation number increases. Perhaps select a future date for 100% mitigation of unprotected steel and cast iron services and derive the numbers in the table so that this goal is achieved. The algorithm could be set up such that the fraction of services mitigated per year decreases as the number of services increases as was done in the tier approach for Mains.

Page 19 – Excavation Damages – Mitigation Options

The first two mitigation options for this source,

- Shorten average time to shut-in for all damages
- Reduce the number of damages per thousand locate calls

Are not really mitigation options, but are the desired effect of properly applied mitigation options which are presented in the third and fourth bullets. Not sure of purpose for using data collected to set company-specific goals for reducing methane emissions due to excavation damages. Excavation damage is primarily caused by factors outside of the control of the operating company. Reporting the voluntary actions taken over the course of the year and publication of the effects of these actions in terms of reducing total excavation accident emissions should be adequate for gauging the effectiveness of the company’s voluntary efforts to reduce this emission source.

Page 23, Item #18

Perhaps there should be a mechanism by which historical actions conducted before joining the Methane Challenge could be recognized. Allow for companies to go back at least two years. In order to achieve recognition the companies will have to provide the same data they will provide for future recognition. Collection of this data could provide useful information for achieving the overall goals of the Methane Challenge program.

From: Timothy J. Skone, P.E., NETL

Subject: Review of EPA Draft “Natural Gas STAR Methane Challenge Program: Supplementary Technical Information” document dated 10/19/15

General Comments:

1. The document is well written and conveys a difficult topic well. The glossary of terms, Appendix C, is an extremely valuable component to the document and elements regarding applicability may be better served repeated in the beginning of the main document.
2. The scope of the Methane Challenge Program is broader in applicability than Natural Gas systems. It applies to Natural Gas system, oil production wells, and enhanced oil recovery wells. The applicability of the program should be clarified in the beginning of the document. The fact that it is part of, within, the Natural Gas STAR Program leads one to think it is only applicable to natural gas industry partners. Has there been any interaction/feedback from the conventional oil and enhanced oil recovery industry?
3. Reporting requirements for each element should include gas production data, or throughput, for each group of sources to measure increased efficiency of hydrocarbon (natural gas, oil, natural gas liquids, condensate) extraction operations, processing, and delivery. Regional/company/facility variability in annual production rates will confound data interpretation for cross-year metrics analysis. The reporting requirements as outlined quantify annual emissions well but do not provide the ability to assess the effectiveness of methane reduction technologies or best management practices on a unit of product throughput basis. Exclusion of production or throughput data will significant limit your ability to measure efficiency improvements and discuss Program successes in a manner that would help potentially new Partner participants from recognizing the benefits that existing Partners have achieved with respect to methane reduction by technology or best management practice option.
4. Reporting of methane reduction (mt Ch4) for each category should by reported by type of BMP/mitigation option employed. Currently, the reporting requirements allows the Partner to sum all mitigation options employed into a single reduction value for the site or facility. This significant reduces the Program’s ability to understand which options are successful and acceptable to industry and to then communicate Program successes to new or potential Partners.
5. The combination of gas throughput (specified as the entry or exit of the category/equipment) with the additional detail of methane reduction per mitigation option employed will enable one (EPA) to validate if the reported emissions are reasonable. Without this information it will be very difficult to identify reporting/data entry errors, benchmark performance of methane mitigation options, and effectively communicate Program successes to the public and future/potential Program participants.

<u>Page Level Comments:</u>

Page 6, Natural Gas Continuous Bleed Pneumatic Controllers, Mitigation Options

The intent of the last bullet would be improved if the qualifier "natural gas" was removed from the sentence to prevent confusion with the second option. Recommend the sentence read "Remove pneumatics controllers from service with no replacement."

Page 7, Fixed Roof, Atmospheric Pressure Hydrocarbon Liquid Storage Tanks, Reporting

Row 4, Data Elements Collected…, it would be helpful if the Partner's also reported the efficiency of the Ch4 recovery of existing systems and a method to quantify improvement to the 95% commitment target.

Page 8, Liquids Unloading, Mitigation Options

Second bullet is not a mitigation option, it is reporting only. Recommend moving to the reporting section.

Page 9, Centrifugal Compressors-venting, Source Description

Recommend removing the qualifier "a process" from the first sentence. It is unclear if this qualifier is intended to limit the reporting to a specific "process" type of natural gas. The intention is all natural gas for this section.

Page 10, Liquids Unloading, Reporting

Row 3, Data Elements Collected…, second entry – recommend adding the word "vented" to "Annual CH4 emissions vented to the atmosphere from wet seal…"

Row 3, Data Elements Collected…., third and fourth entries – recommend splitting these into the separate categories of flares, combustion units, and capture systems for beneficial use. Tracking these separately will help the Program prioritize future research needs and communicate which options are being adopted by the Partners to achieve the methane reductions.

Page 11, Liquids Unloading, Reporting

Last row, Data Elements Collected…, last entry – recommend splitting by type (routed to VRU, beneficial use, flare, control device, converted to dry seal) to target/recommend effective strategies being employed by the Partner's in the Methane Challenge Program. This information will prove valuable in communicating what works and what is being adopted.

Page 11, Reciprocating Compressors – Rod Packing Vent, Source Description

Recommend removing the qualifier "a process" from the first sentence. It is unclear if this qualifier is intended to limit the reporting to a specific "process" type of natural gas. The intention is all natural gas for this section.

Page 12, Reciprocating Compressors – Rod Packing Vent, Reporting

Row 3, Data Elements Collected…., Fourth and fifth entries, recommending sub-dividing this reporting element between beneficial use and flare/control device. This information will be valuable for communicating successfully adopted Program strategies to incentivize new Program participants.

Page 13, Reciprocating Compressors – Rod Packing Vent, Reporting

Last row, Data Elements Collected, last entry – recommend reporting by type (VRU, beneficial use, flare, control device, replaced rod packing) to quantify what BMP choice is being adopted and what option is creating the majoring of reduction benefit. At a minimum, if the Partner could report the percentage methane reduction resulting from each type, one could calculate the mass reduction.

Gas throughput is also necessary to determine the net efficiency form this category. Not all compressors operate at 100% of nameplate capacity. Most operations have spare compressor capability to maintain operations during equipment maintenance or failure. The compressor count as depicted will not accurately characterize the methane reduction from this category without understanding gas throughput and level of operating capacity for each.

Page 14, Transmission Pipeline Blowdowns between Compressor Stations, Reporting

Last row, Data Elements Collected…., all entries – quantification of methane reduction for this category is at the highest level of resolution and therefore will be very difficult to validate and/or understand if the reported emission reductions are reasonable/valid. The magnitude of methane emission varies significantly for each blow down based on differences in operator practices for gas evacuation to a safe working level. Recommend adding elements to report the mass of methane reduction by mitigation option/type. This next level of detail is necessary to understand what works best and is acceptable to participants. The information collected needs to be put into context with annual changes in mass of gas throughput and distance transported to develop metrics for methane reduction. Knowing only the number of blowdowns and net methane reduction from potential will significantly challenge your ability to compare differences in methane reduction between reporting years and to determine if forward progress is being made after the first year. It would also be helpful to define/explain if the “total potential emissions (mt CH_4)” is recalculated each year or is based on the first full year of participation in the program for a Partner. A mechanism to understand differences in new transmission assets brought into services versus decommissioned or sold will be important to interpret the results to validate progress in methane reduction has occurred.

Page 15, Distribution Pipeline Blowdowns, Reporting

Reporting requirements are structured for the 1st year of Partner participation. Add detail to explain how w they change for 2, 3, …n years after participation.

See comment above for Transmission Pipeline Blowdowns between Compressor Stations above for applicability to this category.

If the Potential Emissions include BMPs implemented the previous year it would create an ever reducing goal that would drive continual methane reduction. An alternate reporting method to demonstrate the historical benefits could be constructed to show full methane reduction over a Partner’s participation in the Program.

Page 15, M&R Stations/City Gates

If, gas throughput was reported it would help refine the estimates of CH4 loss at M&R Stations/City Gates to expand upon the evidence reported by Lamb et al. This evidence could be used to incentivize Partners who have not upgraded to do so. May be a small but easy opportunity to get Partners early success from Program participation.

Page 17, Mains – Cast Iron and Unprotected Steel, Reporting

A beak-out of emissions reductions by type would help explain "how" reductions were achieved. Need to report the annual gas throughput with the distance and emission reductions to benchmark performance across the sector and between reporting years.

Page 18, Unprotected Steel and Cast Iron Services

A beak-out of emissions reductions by type would help explain "how" reductions were achieved. Need to report the annual gas throughput, length of pipe in miles (same as Cast Iron and Unprotected Steel, Reporting) and emission reductions to benchmark performance across the sector and between reporting years.

Page 25, Appendix C, Natural Gas Processing and Natural Gas Transmission Compression & Underground Natural Gas Storage

Both sections include in the definition of applicability the following phrase "…, that emits or may emit any greenhouse gas." This unique qualifier in these definitions for applicability make 100% of all operations report. This definition should reflect methane emissions as the Program does not address emissions from any other greenhouse gases. Secondly, the term "may" is very problematic for Partners to apply consistently. Recommend specifying a threshold for mt CH4 per year or deleting the qualifier from the sentence.

COMMENTER:

Dominion Resource Services, Inc. (Dominion)

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November 13, 2015

Ms. Carey Bylin
EPA Methane Challenge Program
via email: methanechallenge@tetratech.com

Dear Ms. Bylin:

Dominion Resources Services, Inc. (Dominion) is pleased to submit these comments on EPA's Natural Gas STAR Methane Challenge Program: Proposed Framework document published on July 23, 2015. The comments include our review of EPA's "Natural Gas STAR Methane Challenge Program: Supplementary Technical Information" dated October 19, 2015.

Introduction

Dominion is one of the nation's largest producers and transporters of energy, with a portfolio of nearly 24,600 megawatts (MW) of generation capacity, 10,900 miles of natural gas transmission, gathering and storage pipelines, and 21,900 miles of gas distribution pipelines, exclusive of service lines. Dominion operates one of the nation's largest underground natural gas storage systems with a storage capacity of 947 billion cubic feet of natural gas. Dominion's transmission, gathering, and storage pipelines operate in eight states (Georgia, Maryland, New York, Ohio, Pennsylvania, South Carolina, Virginia, and West Virginia) through its subsidiary companies – Dominion Transmission Inc. (DTI) and Dominion Carolina Gas Transmission, Inc. (DCG). Dominion's distribution pipelines operate in Ohio and West Virginia through its subsidiary companies – Dominion East Ohio (DEO) and Dominion Hope (DH), respectively. DTI also operates natural gas processing facilities in West Virginia and a liquefied natural gas (LNG) import and storage facility at Cove Point, Maryland. The Cove Point facility has received regulatory approvals and is undergoing construction activities to enable the facility to export natural gas.

Dominion has participated in EPA's voluntary Natural Gas STAR program for a number of years to reduce emissions of greenhouse gases (GHG). DTI has participated in Natural Gas STAR since 2011 and has been reporting on emission reduction measures. DCG has been part of Natural Gas STAR since 1996 (under different ownership). Both subsidiaries have achieved significant methane emission reductions through implementation of cost effective and pragmatic measures. DEO joined the program in 2014 and DH joined the program in 2015.

We recognize EPA's efforts to achieve emission reductions through voluntary programs such as the Natural Gas STAR program. We commend EPA's efforts to reach out to all stakeholders to devise an accountable and transparent program to achieve voluntary methane reductions through the Methane Challenge program and believe this program has the potential to be a significant element of the White

House's efforts to achieve 40-45% reduction in methane emissions from 2012 levels by 2025. We appreciate the availability of more options in the proposed program than the originally discussed Gold STAR program.

Recognizing the diversity of natural gas companies along the natural gas supply chain, it is appropriate that EPA offers multiple options for participating in the Methane Challenge program. The proposed framework document outlines a structure for each of the options, however, we offer for your consideration some key challenges and recommendations. The three (3) key challenges are:

1. **Providing flexibility in the BMP option for companies to demonstrate ongoing reductions by allowing use of additional BMPs, and the ability to implement BMPs where it makes the most sense across an entire company.** The list of BMPs available under the program is limited and companies such as Dominion who have been participating in the existing STAR program have implemented many of these measures. For example, DTI has already implemented a DI&M program for compressor vents and station blowdown vents, resulting in approximately 120,000 mcf in natural gas saved since 2012. In addition, DTI has been reducing pressure on pipelines prior to certain maintenance activities, where cost effective, safe, and when schedules allow, since 2012, resulting in over 450,000 mcf of natural gas saved. Implementing one or more BMPs throughout company facilities may not be the most cost effective or operationally feasible implementation plan for reducing emissions or showing continuous improvement. We ask EPA to allow the use of alternative BMPs which might achieve comparable or greater reductions in methane emissions. For example, DTI has implemented compressor engine blowdown recovery at five of its compressor stations, resulting in about 230,000 mcf in gas savings since 2012. Engine blowdown recovery is not a proposed BMP under the Methane Challenge Program. We offer specific comments regarding additional BMPs for EPA's consideration in the final program below.

2. **Providing participants with the opportunity to take credit for significant emission reductions achieved through voluntary programs implemented in the past.** Companies such as Dominion's subsidiaries in the T&S segment (DTI and DCG) have achieved early and significant reductions in methane emissions which should be acknowledged in the Methane Challenge program. We recommend a mechanism for reporting these early reductions. Since joining the NG STAR program in 2011, DTI has reduced over 900,000 thousand cubic feet (mcf) of natural gas through BMPs such as directed inspection and maintenance (DI&M), engine blowdown recovery, reducing pipeline pressure before maintenance activities, hot tap installations, installing turbines instead of reciprocating compressors, and replacing high-bleed pneumatic devices. Dominion offers specific suggestions below.

3. **Providing information sufficient enough to evaluate participation for both options – the Best Management Practices Option (BMP Option) and ONE Future Option.** The supplemental document provides additional information to evaluate the BMP Option, but the targets to be achieved by individual companies under the ONE Future option are unknown at this time. With

the information provided to date, Dominion is unable to evaluate what would be required in order to participate in the ONE Future Option.

We have evaluated the proposed program and offer the following comments and recommendations, which we believe would provide a more efficient framework that achieves meaningful, accountable and continuous reductions in methane emissions.

Key Issues and Recommendations

1. **Flexibility for BMP Commitments**
   The proposed framework provides for companies such as Dominion, who operate in different segments, to make BMP commitments across a company in one or more segments. Appendix 3 of the framework document also solicits comments on the proposed reporting entity for each segment. As proposed, the program requires companies to report the BMPs for each segment at the division or the business unit level as defined by FERC or a public utility commission. We find limiting the reporting entity to this level in a corporate structure could have unintended consequences and restrict participation. The BMP measures which could be implemented for each segment are guided by business and other regulatory drivers. Methane emission reductions which could be achieved year-on-year for a given business segment might vary.

   First, companies should have the flexibility to select BMPs for maximum reduction opportunity. For example, one of our distribution companies has a bare steel pipe replacement program, and a pump down and hot tapping practice on its high pressure lines, both of which do not meet the targets established by the Methane Challenge program individually. However, the bare steel replacement program combined with the recovery of pipeline blow down emissions achieves significant emission reductions. Such companies should be encouraged to participate in the Methane Challenge program by providing the flexibility to select and implement BMPs and report associated emission reductions without specifying a percent penetration.

   Secondly, EPA should provide the flexibility to participate at the parent company level for a company with multiple business units or to consolidate reporting across similar business units such as local distribution companies. For example, a parent company may own and operate two distribution companies, one of which can achieve the bare steel pipe replacement target in the Methane Challenge and the other cannot meet the target. Averaging the two companies' replacement rates would allow the parent company to achieve the rates proposed under the Methane Challenge. Companies will look at achieving greater overall reductions in methane emissions at the optimum reporting level, which clearly aligns with EPA's objective with this program.

   We understand that the ONE Future Option is intended as the "flexible" option under the proposed Methane Challenge framework, wherein a company has the flexibility to implement BMP measures as it sees fit as long as the emission rate targets are achieved on schedule. However, a company must join the ONE Future coalition in order to participate in that option.

Dominion recommends that EPA allow similar flexibility under its BMP Option. In that way, EPA will incentivize more participation and maximize methane reductions, while transparently tracking methane emissions across participating companies.

2. Early Reduction Credits

The proposed program emphasizes ambitious commitments and continuous improvements in emission reductions. The list of BMPs identified in Appendix 2 of the framework document is intended to achieve significant methane emission reductions from the respective segments. However, for companies such as DTI and DCG, who are currently participating in the Natural Gas STAR program, many of the BMPs identified in Appendix 2 have already been implemented and associated emission reductions have been (or are being) achieved. Past reductions are already incorporated into the company's methane emissions baseline, making additional reductions and continuous improvements more difficult to demonstrate within the proposed Methane Challenge framework. We are pleased that EPA recognizes the challenges faced by companies who have achieved emission reductions and is soliciting comments on program features that could encourage their participation in the Methane Challenge. We offer the following recommendations to encourage early and greater reductions from companies.

a. As a part of the data reported to EPA which will be made public, companies should have the opportunity to report emissions and associated reductions from periods prior to the first implementation of a specific BMP. For example, if a company replaced all its high bleed pneumatic devices starting in 2010, the annual emissions and emission reductions achieved since that time should be tracked and reported. Credit should be given for methane emission reductions since inception of the BMP and not just since the beginning of the Methane Challenge program. This is especially important when further implementation of a BMP would only address a small subset of sources and where the emission reduction potential would be reduced. This will ensure that emissions reductions are transparently accounted for and due credit is given for measures implemented prior to the start of the program and after the program was initiated. Past credit could be reported utilizing the same data elements proposed in the supplemental document. For example, under the pneumatic device reporting table, the last four reporting elements can be repeated as follows:
    a. Number of high-bleed controllers converted to low-bleed <u>prior to the Methane Challenge</u>
    b. Number of high-bleed controllers converted to zero emitting or removed from service <u>prior to the Methane Challenge</u>
    c. Number of low bleed controllers converted to zero emitting or removed from service <u>prior to the Methane Challenge</u>
    d. Emission reductions from voluntary action (mt CH_4) <u>prior to the Methane Challenge</u>

b. Dominion recommends that more BMP options be added to, or allowed into, the program. Companies should be given the option of implementing BMPs that are not currently listed as options in the Methane Challenge program. This is especially important for instances when companies have implemented a BMP which resulted in large methane emissions reductions but where it has been determined that additional implementation would not achieve additional cost-effective reductions. In such a case, a company should have the opportunity of proposing alternative BMP measures (even if not listed in the BMPs in Appendix 2) which achieves comparable or greater emission reductions. This will not only recognize early reductions achieved, but also ensure continuous progress towards future methane reductions. Several examples include engine blowdown recovery, focused DI&M on a subset of emission sources (those most likely to leak at the highest rates) at a subset of facilities, and capped emergency shutdowns. See below for further details on these recommended BMPs.

3. **Options for Participating**

The proposal provides three options for companies to participate in the program (ONE Future option, BMP commitments, and Emission Reduction option). EPA is soliciting feedback on the Emission Reduction option. We offer specific comments on each of the three options and suggest recommendations for EPA's consideration.

a. ***ONE Future Option***

Dominion finds the ONE Future option attractive for its flexibility in achieving methane reductions; however, details about the program's methodology and target rates are not available to non-coalition members. The proposed program requires companies to join in the OneFuture coalition, which advocates for a leak rate of one percent or less from the natural gas value chain. The coalition will establish target leak rates by segment to be achieved by 2025. We understand the use of an average rate of emissions intensity approach for reducing methane emissions; however, unless a company is a member of the coalition, insufficient details are available on this option to make a commitment to participate. Specifically, we have the following concerns:

- The use of this option requires companies to participate in the ONE Future coalition, requiring a financial investment, and which may restrict the flexibility for achieving targeted leak rates. Companies should be able to use the emissions intensity approach without the requirement to participate in the coalition. Companies would still need to demonstrate that compliance with specific emission intensity targets is achieved but would not be dependent on the OneFuture coalition to achieve its targets.
- As recognized by EPA in the proposal, companies which are already at or near the intensity target would be disincentivized to do anything more which is counter to the objectives of the program. To address this, the program should be modified to allow companies to define their baseline intensity levels and to establish future targets based on their baseline levels. This company-specific tailored approach would achieve more meaningful emission reductions than the current proposed program.

b. ***Emission Reduction Option***

The emission reduction option requires companies to achieve mass emission (tons) reductions from a baseline period by a specified future period. This approach would be problematic for a company projecting future demand increases and associated increases in emissions due to that growth. Dominion recommends that companies have the flexibility to define the baseline period and the sources to be covered under this option. We also recommend that only existing sources be covered by this program, as new sources would likely be addressed through future regulations (such as proposed NSPS OOOOa). Companies should also have the flexibility to define the reporting entity at the division/business unit level or the company level, whichever works best to achieve meaningful and continuous emission reductions.

c. ***BMP Option***

As discussed earlier, only a limited list of BMPs is provided. Although EPA has determined that this limited list will achieve significant emission reductions from the natural gas sector, some companies have already implemented many of the BMPs listed in the proposal and significant emission reductions are not likely to occur from further implementation of these BMPs. The inability to show further methane reductions (continuous improvement) through these established BMPs may deter some companies from participating in the program. Requiring a 100% percent implementation of technology-based BMPs would also be a disincentive. Dominion recommends that companies have the opportunity to implement BMPs at facilities for which the measure makes economic and operational sense. Factors such as safety and design can impact whether a BMP would be effective at a particular facility. For example, some stations may not be designed to re-use captured blowdown gas for fuel due to piping configuration and/or unsafe line pressures. We also recommend that additional BMPs be added to the program. Several examples, as mentioned above, include engine blowdown recovery, focused DI&M on a subset of emission sources (those most likely to leak at the highest rates) at a subset of facilities, and capped emergency shutdowns (ESDs). Companies should also have the opportunity to substitute BMPs originally proposed in the implementation plan with other BMPs which achieve comparable or greater emission reductions. Companies should also have the ability to change proposed BMPs as more information becomes available on the various sources contributing to emissions and as improvements in control measures to reduce methane emissions develop. We offer comments on additional BMPs which should be considered as a part of this program below.

4. List of BMPs

As discussed above, the list of BMPs in the proposed program are limited and do not offer the flexibility which might be beneficial for a voluntary program to achieve the desired results. We are proposing some revisions to the list of BMPs identified in the proposal which we believe will enable greater and more meaningful participation from companies.

In the proposal, EPA indicated that companies could choose one or more BMPs to achieve mitigation commitments. We appreciate the optionality provided in the proposal that not all

BMPs need to be implemented for a natural gas segment. This would be particularly important for sources located in the gathering segment of the industry, where three of the five BMPs listed in the "Onshore Production and Gathering and Boosting" sector are only applicable to the Production segment.

The proposal requires that 100% (or a specified percentage) of the facilities implement a specific BMP selected by the company. However, as stated above, there may be some site-specific constraints which might prevent BMPs from being implemented at all stations. For example, routing gas from rod packing vents to re-use is only viable at stations where there is other equipment running available to use the recovered gas. Companies should have the flexibility of not having to implement the BMP at all facilities and/or to choose an alternative BMP which achieves meaningful emission reductions.

We offer the following specific recommendations on BMPs included in the proposal:

Rod Packing on Reciprocating Compressors

The proposal includes a BMP for reducing emissions from rod packing associated with reciprocating compressors where replacing of the rod packing every 26,000 hours of operation or 36 months is required, unless the gas is otherwise re-routed to a flare of capture system. We suggest adding an option to inspect the rod packing (either via automatic monitoring system or manually) and monitor for leaks on a periodic basis. Replacement of the packing would be required only if determined to be necessary due to excessive leakage. This approach would also require quantification of emission reductions by measuring the leaks before and after replacing the rod packing. It would ensure that emissions are transparently tracked and reported and emission reductions are achieved in a pragmatic manner.

BMPs for Distribution

The proposal includes a BMP for reducing emissions during high-pressure pipe blowdowns by maximizing gas recovery and/or emission reductions through gas capture, flaring, hot tapping and/or squeezing. In certain circumstances, safety and/or other operational constraints could prohibit the implementation of this measure. As stated above, these practices can yield significant reductions, but a specific percent penetration should not be required.

We support the tiered approach provided in the Methane Challenge framework document and the addition of the Tier 5 (> 3,000 miles of pipelines) for replacement of unprotected steel and cast iron mains. We believe that the pipeline replacement program presents a planned and programmatic approach towards making the distribution system safer and achieving significant methane emission reductions. The pipeline replacement targets in some jurisdictions allow for a faster replacement schedule than that provided in the Methane Challenge program. EPA should encourage companies to achieve faster replacement of bare steel and unprotected mains than that required by the program. In addition, companies should be recognized for reductions achieved beyond that required by the program.

We support the use of programs to prevent damages during excavation; however, these measures have already been implemented at companies such as Dominion. We recommend that, if this BMP is included, early reduction credits be made available for implementing such programs prior to the proposed program becoming final. Regarding the reporting elements presented in the supplemental document table for this BMP, the first eleven data elements involve information specific to each damage event, which is unnecessary and excessively burdensome. In addition, because many of the damage excavations involve third parties, it is not appropriate to provide details of those events to EPA as publicly available information. The remaining elements listed in the table should be sufficient to track performance and emission reductions, and could include past activities and reductions. Dominion suggests that EPA include the following into the program for tracking excavation damages:

- Total number of excavation damages per thousand locate calls prior to the Methane Challenge (use data from the year before program implementation)
- YEAR OF PROGRAM IMPLEMENTATION prior to the Methane Challenge (added field)
- Total estimate of natural gas released for *all calendar years* prior to the Methane Challenge (beginning with the year of program implementation to first MC reporting year)
- Total number of excavation damage incidents where the operator was given prior notification of excavation activity prior to the Methane Challenge (beginning with the year of program implementation to first MC reporting year)
- Total number of excavators by type that caused excavation damage incidents prior to the Methane Challenge (beginning with the year of program implementation to first MC reporting year)

Additional BMPs

We recommend that EPA expand the number of available BMPs, which have a greater potential for reducing emissions from this segment. We also recommend that any segment can select any BMP, if applicable. For example, the Methane Challenge BMPs for the Gathering and Boosting segment are quite limited (three of the five listed are for the Production segment only). Since the Gathering and Boosting segment has compressor stations, we recommend that any BMP dealing with compressor stations be available to any segment.

We offer the following specific recommendations on BMPs that should be included in the proposal:

Engine Blowdown Recovery

Dominion recommends adding engine blowdown recovery to the list of BMPs. Capturing and rerouting blowdown gases from compressor engines is an emissions reduction technique that can lead to significant gas loss savings. DTI has implemented this technique at five of its compressor stations and has reduced almost 230,000 mcf of natural gas loss since 2012. Several more stations are being considered for similar modifications. Unfortunately, due to engine and piping configuration, as well as needing an adequate system to capture and reuse the gas, not all stations can be modified to implement this BMP company-wide. Offering the flexibility to implement BMPs in the way that makes the most sense will encourage companies to continue making significant emissions reductions.

Focused Directed Inspection and Maintenance (DI&M)

Dominion supports as a BMP the inclusion of company-specific DI&M programs that focus inspection and repair programs on high-risk emission sources. The DI&M program element document provided to EPA by the Interstate Natural Gas Association of America (INGAA) in 2015 can serve as the basis for development of company-specific DI&M plans. These plans can be considered by EPA under the MOU process for inclusion in a company's Methane Challenge program. To date, DTI has reduced gas loss from its DI&M program by almost 120,000 mcf.

Capped ESD Tests

Dominion recommends including capped ESD tests as a BMP under the Methane Challenge Program. At DTI, a full blow down test is only required (by Standard Operating Procedure) once every five years, which DTI staggers in order to minimize annual emissions. During the other four years, stations do their annual safety test using Yale (or other) enclosures to prevent gas loss. Since 2012, DTI has saved almost 60,000 mcf of gas using this technique. Capped ESD testing does not occur at every station every year; however, utilizing it when possible can lead to significant gas loss savings.

5. **Other Miscellaneous Issues**

   a. **Separation of Voluntary and Regulatory Reporting**
   The proposed program requires reporting of supplemental data, including emissions and activity data for sources, which might not be covered by the mandatory GHG reporting program. We understand the potential interest for this additional reporting; however, we encourage EPA to keep the voluntary and mandatory reporting requirements separate.

   b. **Transition from Natural Gas STAR and Methane Challenge Programs**
   For companies which are already participating in EPA's Natural Gas STAR program, several of the BMPs in the Methane Challenge program have already been implemented for many years. In addition, companies have been reporting Partner Reported Opportunities (PROs) which in some cases result in significant emission reductions. In the proposal, EPA indicates that a mechanism to avoid duplication and participation in each program will be developed. We recommend the following to ensure a smoother transition and avoid duplication between the Natural gas STAR and Methane Challenge programs:

i. If BMP flexibility is allowed in the Methane Challenge program, companies can transfer all their current activities under the NG Star program to Methane Challenge and take credit for all their mitigation measures. Otherwise, companies that want to continue implementing BMPs not listed in the Methane Challenge will need to report under two separate voluntary programs.
ii. We recommend a transition period of 2 years, when companies can (if they wish) report to both programs and then eventually move to the Methane Challenge program.

In the interim period, companies would continue to report under the PROs and any other BMPs not reported under the Methane Challenge to the Natural Gas STAR program. The Natural Gas STAR program will also provide companies the opportunity to "pilot" new BMPs before recommending for future inclusion in the Methane Challenge.

Supplemental Technical Document Feedback

The supplemental technical document issued by EPA on October 19, 2015, provides additional clarification on the direction and intent of the program, as well as specific technical information to enable companies to consider participation. Below we address some of EPA's specific requests for feedback on aspects of the program relevant to Dominion.

Quantification Method

On page 4 of the document, EPA requests feedback on including other quantification methods outside of Subpart W for certain emission sources. Dominion supports the proposed quantification approach proposed by EPA. For historic information and/or for emission sources that can be grouped together, it makes sense to simplify activity counts and emission reductions at a less granular level than what is required under Subpart W. Specific recommendations are provided within BMP and reporting discussions to follow.

Pneumatic Device Replacements

As explained above, a simple way to enable reporting of past reductions from a BMP is to have the company report the calendar year in which the company began implementing the BMP (prior to Methane Challenge), and combine activity data and emission reductions for each data element from that year through the calendar year in which the company began the Methane Challenge. The company would report total devices replaced early and total emission reductions achieved early. The information would be available in a public, transparent manner to give credit for early achievements.

Intermittent pneumatic devices are not a significant source of emissions, and are typically needed for safety purposes and thus are not likely to be replaced, especially in remote areas.

Transmission Pipeline Blowdowns

Dominion appreciates EPA's recognition that 100% implementation of this BMP is infeasible. However, a commitment to a smaller percent reduction (EPA proposes a 50% reduction from total potential blowdown emissions each year) is still a concern for the following reasons: (1) If a maintenance event is not planned, or a leak is discovered that needs immediate attention, there is not always adequate time to bring in additional equipment or resources; (2) . Some blow downs are minimal in nature and do not warrant the time and expense of mitigation measures; (3) Pump downs and other mitigation measures lead to longer outages, generation of other pollutants during the pump-down operations, and additional manpower and equipment, which could impact contractual obligations to local commissions, rate payers and customers. Dominion acknowledges that methane reductions from these techniques can be substantial, but no percentage reduction should be specified. Tracking and reporting the emissions reductions from this BMP in a public, transparent manner will document achievement under Methane Challenge.

Distribution Pipeline Blowdowns

The same issues described above impact control of blow down gas from distribution mains. Further comments specific to distribution mains, to address questions asked by EPA to stakeholders, include the following:

- Most maintenance events at Dominion involve a blow down to atmospheric pressure; therefore Dominion believes it is reasonable to base the calculation method on that assumption.
- Dominion supports the additional tier categories proposed.
- Dominion supports the proposal to use the plastic pipe emission factor for miles of pipes remediated with plastic liners or inserts.

Unprotected Steel and Cast Iron Services

EPA has requested feedback on how to structure the BMP commitment option for this source. Although Dominion is not aware of any cast iron services within its distribution areas, bare steel services make up a large percent of our inventory. Dominion does not specifically target service replacements unless leaks are detected, damage has occurred, or the service is located along a mainline segment that has been targeted for replacement. However, during pipeline replacement, unprotected steel services are often replaced while excavation is underway. Over the past three years, DEO has replaced an average of 3-4% of its total population of bare steel services per year, which mirrors its bare steel pipeline replacement percentage rate. EPA may consider using the same Tier table and annual replacement/repair rates based on cast iron and unprotected steel main inventory.

Excavation Damages

Dominion's distribution companies have active damage prevention programs in place and would consider participating in this BMP under Methane Challenge. However, the proposed reporting requirements are excessively burdensome. As described in the BMP section above, reporting individual activity data for close to a thousand incidents per year would not be feasible. If the data element list were limited to only aggregated information presented at the bottom of the table, then companies may consider participating for this BMP. Limiting the scope of reporting to only those damages involving pipe operating at 15 psi or greater would reduce the burden by approximately 80%, but would not represent the full scope of achieved reductions under a company's damage prevention program.

Sunset Dates

The current Natural Gas STAR program allows participants to accrue emission reductions after implementation of a specific mitigation measure for a specific length of time. Dominion supports this concept under the Methane Challenge program and suggests a period of five years to coincide with the length of the BMP Option commitment.

Summary

In summary, Dominion is interested in participating in this voluntary program as a charter member and supports EPA in its efforts to achieve reductions in methane emissions from the natural gas industry. We encourage EPA to consider the recommendations proposed in this letter, which will ensure greater participation of our subsidiaries.

If you have any questions regarding these comments, please do not hesitate to contact me at (804) 273-3467, Anand Yegnan at (804) 273-3893 (anand.yegnan@dom.com) or Alice Prior at (804) 273-4127 (alice.prior@dom.com).

Sincerely

Pamela F. Faggert

COMMENTER:

Downstream Initiative (DSI)

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November 13, 2015

Ms. Carey Bylin
Natural Gas STAR Program
U.S. EPA
1201 Constitution Ave NW
Washington DC 20004

RE: Feedback on EPA's Natural Gas STAR Methane Challenge Program Proposal

Dear Ms. Bylin,

On behalf of the Downstream Natural Gas Initiative (DSI), we appreciate the opportunity to provide feedback on the Natural Gas STAR Methane Challenge Program Proposal and Supplementary Technical Information document. This letter provides feedback on the proposed BMP Option, including source descriptions, mitigation options, and proposed GHGRP and voluntary reporting data elements. Current Downstream Initiative members include Consolidated Edison Company of New York, Inc., National Grid, Pacific Gas & Electric, Public Service Electric & Gas, Southern California Gas Company, and Xcel Energy. Our feedback below provides our comments and recommendations and we look forward to continued engagement on this topic.

Overview

DSI members support the goal identified by EPA for the Methane Challenge Program - to recognize leading companies that make commitments to increased action to reduce methane emissions from their operations. DSI members are committed to taking a leadership role to substantially reduce methane emissions to contribute to the Obama Administration's 2025 methane reduction goals.

Public recognition through the Methane Challenge Program will help support the efforts of local distribution companies (LDCs) to communicate the value of operational excellence and methane emission reductions to regulators, consumer advocates, customers, and environmental organizations.

EPA should also consider ways to provide public recognition for states and public utility commissions (PUCs) that provide the necessary regulatory structures that enable increased action to reduce methane emissions from LDC operations. The Obama Administration, including EPA, DOE, and other federal agencies, should support Methane Challenge Program partners at the state level through engagement with state regulators and other stakeholders to voice support for investments in best management practices (BMP) and methane emission reductions.

Voluntary and Regulatory Actions

Methane Challenge Program partner commitments that are above and beyond current infrastructure modernization and replacement plans are dependent on obtaining additional approval from state regulators. The challenge for LDCs is to obtain cost recovery for "voluntary activities", which may be incorrectly interpreted by some stakeholders as being paid for using shareholder dollars without recovery. A LDC is not fulfilling its duty and obligation to its shareholders if it makes investments that do not earn a rate of return. Therefore, in order for LDCs to make additional investments to accelerate the pace of methane emission reductions, supporting state regulatory structures and cost recovery mechanisms are critical.

In addition, some LDCs may be required to reduce methane emissions from their operations, through the adoption of BMPs, as a component of state climate change goals and programs. For example the California Legislature passed SB 1371 in 2014, which seeks to reduce methane emissions from leaks in the gas transmission, distribution and storage utilities in California. In January 2015, the California PUC launched Rulemaking (R.) 15-01-008 in response to SB 1371 to establish and require the use of BMPs for leak surveys, patrols, leak survey technology, leak prevention, and leak reduction. It is likely that the Methane Challenge Program proposed BMPs will overlap with the BMPs identified by the California PUC. As such, EPA should work with LDC Methane Challenge Program partners to address how LDCs may receive recognition for these actions under the program.

BMP Commitment Option

DSI members support EPA's BMP commitment option. One of the main benefits of this option is the flexibility it provides potential program partners to choose which sources they will address. DSI companies are committed to working with EPA to continue to develop the technical requirements for the BMP commitment option for the natural gas distribution segment. In addition, DSI members encourage EPA to consider adding BMP sources and measures over time as outlined below.

DSI members support EPA's approach to maintain consistency between the technical details and reporting elements associated with the BMPs between the BMP and ONE Future Emissions Intensity Commitment Options. As you are aware, one of the founding members of DSI, National Grid, is also a member of ONE Future.

DSI members support the approach outlined by EPA to become a Methane Challenge Program partner –entering into a memorandum of understanding (MOU) with EPA documenting commitments and reporting. We also support the development of an Implementation Plan to detail anticipated rate of progress, key milestones, and context for partner implementation plans within six months of joining the Methane Challenge Program.

Furthermore, DSI members support the proposed level at which LDCs would make commitments under the Methane Challenge Program BMP Option - a LDC as regulated by a single state public utility commission. This proposed level is consistent with the Subpart W facility definition and how companies manage their infrastructure assets.

The 5-year BMP implementation time line proposed by EPA is appropriate in most cases. This timeframe will allow companies time to gather and analyze data, evaluate and develop mitigation approaches, engage stakeholders and secure approval from PUCs for rate recovery and implement the BMP.

DSI members support EPA's commitment to transparency for the Methane Challenge Program. It is important that partners report on their voluntary mitigation actions that contribute to their commitments through a public platform managed by EPA. In addition, for companies that go further than the BMP minimum requirements, they should receive additional public recognition from EPA.

DSI supports leveraging Subpart W reporting as much as possible to minimize administrative burdens and costs. DSI also agrees with the need for supplemental data reporting in order to capture Methane Challenge Partner activities that reduce methane emissions but that will not be reflected in Subpart W methane emission trends. The e-GGRT system would be an appropriate mechanism to collect voluntary supplemental data.

In order to provide stakeholders with an accurate and transparent view of Methane Challenge Partner's efforts to reduce methane emissions, the supplemental data should be summarized and presented with the same public visibility as the Subpart W reporting. In addition, within Subpart W emission summaries released by EPA every September, DSI recommends that EPA clearly identify Methane Challenge Partners to acknowledge their participation and communicate that the Partner reports supplemental data to EPA.

M&R Stations City Gates
DSI members agree with EPA's proposed approach on M&R stations. The recently published Washington State University (WSU) study concluded that emissions from M&R stations are low. According to WSU leak surveys at 229 M&R stations, no leaks were detected in 30 percent of the sites. This can largely be attributed to equipment replacements/facility rebuilds, improved leak surveys, and modern station designs.

In fact, survey results from five LDCs for 90 sites showed approximately 60 percent of these facilities had undergone some level of equipment change since 1992. Equipment changes were in three key areas: 1.) conversion of pneumatics from high bleed to low or no bleed using instrument air; 2) change from relief valves for over pressure protection to the use of closed systems that have two regulators in series (a monitor regulator and an operating regulator); and 3) a move from orifice metering to rotary, turbine and ultrasonic metering. Partners that have upgraded M&R stations and reduced methane emissions should be recognized by EPA through the Methane Challenge Program as outlined below.

In addition, since 2011 data year reporting under Subpart W of the GHGRP, LDCs have conducted leak detection surveys at above ground stations on an individual component basis. Since T&D station surveys for some LDCs are a large undertaking, EPA allowed LDCs to spread out the leak detection surveys over a 5-year period. LDCs are required to survey an equal number of stations across the five year period, without monitoring the same station twice. Minimal leaks are found and are usually thread-related. Typically when leaks are found during these surveys, they are repaired.

While the majority of M&R stations have been upgraded and modern station design is lower emitting, there may be M&R stations that remain to be upgraded especially at smaller LDCs that are not currently subject to Subpart W reporting. Therefore, EPA should include M&R stations as a BMP source in the Methane Challenge Program. The approach EPA could use for this BMP option may consist of: conversion of pneumatics from high bleed to low or no bleed and annual leak surveys and emissions reporting similar to Subpart W.

Mains – Cast Iron, Unprotected Steel
DSI members support the approach EPA has proposed with this BMP option: replace cast iron mains with plastic or cathodically protected steel and replace or cathodically protect unprotected steel mains, or rehabilitate cast iron and unprotected steel pipes with plastic pipe inserts, also referred to as slip-lining or u-liners, or cured-in-place liners. This approach provides LDCs with flexibility to implement the strategies most appropriate for their given infrastructure make up, cost effectiveness and other factors.

DSI members support the proposed adjustments to the minimum annual replacement/rehabilitation rates contained in the American Gas Association's comments. These revised minimum replacement/rehabilitation rates are reasonable given the barriers LDCs face implementing these programs including; cost and ratepayer impacts, uncertainty of cost recovery, adequacy of skilled labor, community disruptions and public objections.

Furthermore, DSI members agree that EPA should use the LDC partner's main inventory as of January 1 of the year the LDC joins the Methane Challenge Program to determine the applicable Tier for the first 5-year implementation period. EPA should also clarify the program requirements when a LDC reduces its cast iron and unprotected steel main inventory resulting in a change to the applicable Tier and subsequent increase in the minimum replacement/rehabilitation rate. In these cases, the LDC partner should be allowed to commit to the new Tier for the next 5-year implementation period.

LDCs that achieve a higher replacement rate than the minimum should receive additional recognition from EPA. LDCs that currently replace mains at a faster rate than the minimum proposed by EPA should also receive EPA recognition and could commit to maintaining that rate or increasing it in the future.

DSI members support the inclusion of lining and inserts in this BMP. Pipeline lining can be a cost effective strategy on a project specific basis where access to the main is difficult including railroad, highway, bridge and river crossings. Studies have shown that lining is just as effective as replacement from a safety perspective and longevity perspective. Cornell University has studied the longevity of lining cast iron pipe and has found over a 100 year lifetime.

DSI members encourage EPA to include internal and external joint sealing for cast iron mains larger than 20 inches in diameter that logistically cannot be replaced. While we understand that EPA prefers lining because this option not only reinforces the joint but also the entire pipe, pipes of this size have thick walls and do not break other than due to excavation damages. These larger mains are buried deep underground (sometimes at depth greater than 20-30 feet), under major highways, cities, and other areas which present considerable financial and logistical barriers to replacement.

In most cases, joint sealing is the only viable and cost effective option to repair leaks which occur primarily at the joints. In addition, lining of pipes of this diameter and larger are cost prohibitive, require the main to be taken out of service for multiple days resulting in customer impacts and additional costs and complexity. Internal (CISBOT) and external cast iron joint sealing has been proven by several DSI members as a cost effective approach. CISBOT allows the repair to be completed without taking the main out of service, reducing customer impacts and overall costs. Cost savings associated with CISBOT are on the order of 50 percent compared with conventional point repair. Tests by Cornell University (for the New York Gas Group) and British Gas prove a 50 years minimum life expectancy for cast iron joint encapsulation, the most common external sealing method used.

DSI also suggests that EPA and other federal agencies work with Methane Challenge Partners on the appropriate emission factor for sealing (internal and external) and joint encapsulation for cast iron mains.

DSI members support the reporting elements for this BMP as outlined by EPA in the Supplemental Technical Information document. LDCs that utilize lining and insert strategies will now be able to create a public record of the total miles of cast iron or unprotected steel distribution mains that have plastic liners or inserts. DSI members support the use of the plastic emission factor for lining and inserts. While emission factor research has not been conducted in this area, this proposed approach seems reasonable. Historically, LDCs that implement lining or plastic insert strategies to address leak prone pipe have not been publicly recognized for these efforts. While main and service replacement is the preferred approach, lining and inserts are used in circumstances where replacement is cost prohibitive or too disruptive to the public. By using the plastic main and services emission factors, LDCs will now be able to account for the leak reduction benefit of these strategies.

Services– Cast Iron, Unprotected Steel
DSI members support the approach EPA has proposed with this BMP option: replace unprotected steel and cast iron services with copper, plastic, or protected steel, or rehabilitate cast iron and unprotected steel services with plastic pipe inserts. Similar to mains, DSI members support the inclusion of lining for this BMP.

DSI members recommend EPA structure this BMP as follows: at a minimum LDCs commit to replace or rehabilitate the associated unprotected steel and cast iron services when the main is replaced or rehabilitated. In addition, LDCs with dedicated programs to replace/rehabilitate unprotected steel and cast iron services should be recognized by EPA under this BMP.

DSI members also support the reporting elements for this BMP as outlined by EPA in the Supplemental Technical Information document.

High Pressure Pipe Blowdown
DSI members support the mitigation approaches EPA has proposed with this BMP option: route gas to a compressor or capture system for beneficial use; route gas to a flare; route gas to a low-pressure system; reduce system pressure prior to maintenance; installing temporary connections between high and low pressure systems; utilize hot tapping to avoid the need to blow down gas.

These mitigation options provide LDCs with the ability to implement a suite of strategies that are most appropriate and cost effective per project to reduce methane emissions associated with blowdowns or "operational natural gas releases". Operators conduct operational releases for a variety of reasons including: maintenance activities, main replacement, emergencies and safety driven regulatory requirements – Maximum Allowable Operating Pressure (MAOP). In fact, DSI members anticipate an increase in the need to conduct operational releases in the near to medium term based on regulatory requirements. LDC systems are unique as are the maintenance and main replacement and rehabilitation activities which drive operational releases. Mitigating operational releases is good practice for a number of reasons including, safety, nuisance/odor issues, and methane emissions avoidance.

DSI members support EPA's focus on blowdowns of pipelines operating above 60 psi. However, the language in the Supplementary Technical Information document states "pipelines operating at 60 psi or more". We recommend that EPA clarify this language and focus on operational releases above 60 psi. From a cost effectiveness perspective, operational releases from high pressure mains are the most appropriate to focus on mitigating in the near term. We also agree with EPA that this BMP should not be applicable to emergency situations.

DSI members agree with the approach proposed by EPA to reduce methane emissions by 50 percent from total potential emissions each year within a 5 year period. For most LDCs, this will be a significant undertaking. LDCs will have to integrate new data collection and standard operating procedures into the maintenance and pipeline replacement process. LDC engineering departments will need to identify candidate projects, identify the preferred mitigation options considering local circumstances and costs, and coordinate with other projects in order to have the necessary equipment and skilled labor. In addition, these changes are likely to require utility commission approval for cost recovery, especially for the purchase of mobile compressors if used as one of the mitigation strategies. LDCs who demonstrate success with this BMP should be encouraged to develop stretch goals in the future.

EPA should permit LDCs the flexibility to identify a pathway to BMP implementation over a 5 year implementation horizon. First, LDCs do not routinely track operational releases below certain required thresholds. Second, LDCs will need to obtain regulatory approval and cost recovery from regulators. Third, it will take time to purchase portable compressors, train staff, and develop and implement procedures to integrate the technology into standard operating procedures. A pathway to BMP implementation could consist of the following steps:

- Year 1-2 Tracking, Data Collection and Reporting
- Year 3 Data Evaluation, Strategy Development and PUC Approval
- Year 4-5 Phased Implementation and Continued Tracking, Data Collection and Reporting

As outlined in the Supplementary Technical Information document, the total potential emissions would consist of calculated emissions from all planned maintenance activities in a calendar year assuming the pipeline is mechanically evacuated or mechanically displaced using non-hazardous means down to atmospheric pressure and no mitigation is used. DSI members agree with this approach and agree with EPA that potential emissions would vary from year to year. Subpart W calculation Method 1 or 2 are appropriate to use to estimate potential annual methane emissions. However, method 1, based on the volume of the pipeline segment between isolation valves and the pressure and temperature of the gas within the pipeline, will likely be the dominant method used by LDCs.

DSI members support the reporting elements for this BMP as outlined by EPA in the Supplemental Technical Information document. LDC partners would report the annual number of planned blowdowns and potential emissions per year. In addition, LDCs would report the mitigation approaches utilized and resulting emission reductions. EPA should consider the use of pressure control fittings as a mitigation option to reduce blowdown volumes rather than the use of existing valves. This data will provide a transparent accounting of the progress made by LDC partners implementing this BMP. Finally, EPA should provide quantification guidance for the use of flares in order to maintain consistency between LDCs.

Excavation Damages

DSI members support the mitigation approaches EPA has proposed with this BMP option: to shorten average time to shut-in for all damages, reduce the number of damages per thousand locate calls, undertake targeted programs to reduce excavation damages, and conduct incident analyses to inform process improvements and reduce excavation damages. While methane emissions associated with damages are uncertain and difficult to quantify, making progress in this area will improve safety, save money and result in methane emission reductions.

EPA should focus on all damages on the LDC system regardless of pressure. The number of damages is relatively even between services and distribution mains although the volume of methane that is emitted from service damages is very small. According to PHMSA data, excavation damages account for approximately 12 percent of all leaks from mains and 16 percent of all leaks from services. However, excavation damages account for over one third of all hazardous leaks from mains and one third of all hazardous leaks from services. For some DSI members, these values are much greater.

DSI members do not believe that quantifying methane emissions associated with excavation damages or setting emission reduction targets is appropriate for this source. Setting an emission reduction target for this BMP would be challenging due to the fact that emissions quantification is difficult due to the varying level of damages to mains and services. While LDCs do estimate the quantity of gas lost from significant excavation damages for billing purposes, quantifying methane emissions reliably from all damages would be a challenge. Quantifying emissions associated with damages would require the development of a standardized methodology and would likely involve considerable uncertainty. Other targets, including reducing the number of damages, reducing average shut-in time for all damages, or other qualitative targets are in line with what LDCs are already doing which will result in greater participation from LDCs.

Reducing excavation damages is a priority for LDCs. LDCs use a variety of strategies to educate customers, contractors, and the general public on excavation safety. For example, the Gold Shovel Standard Program of PG&E is designed to enhance safe excavation practices in the field and to reduce dig-ins and damage-inducing activities. In order to contract with PG&E, companies must be Gold Shovel Standard certified. LDCs are also working to get response times shorter and shorter. One issue EPA should be aware of is the impact that LDC service territory geographic size, geography, and makeup (i.e., rural versus urban) has on shut-in time. In addition, several DSI members have hit a plateau based on location of service centers and number of crews available.

EPA should allow each individual LDC to develop and implement a commitment unique to their own company given the differences between service territories and the fact that damages to their systems are largely outside their control. Similar to blowdowns, EPA should permit LDCs the flexibility to identify a pathway to BMP implementation over a 5 year implementation horizon beginning with recordkeeping and reporting and establishing a baseline for average time to shut-in for all damages and the number of damages per thousand locate calls.

DSI members support the reporting elements for this BMP as outlined by EPA in the Supplemental Technical Information document. However, as indicated above, we do not believe that quantifying methane emissions associated with excavation damages or setting emission reduction targets is appropriate for this source. Therefore, the data elements regarding the estimated volume of methane released, methane emission reduction goals, progress towards those goals and emission reductions from voluntary efforts would not be applicable. These data elements include the following: approximate size of mechanical puncture, estimated volume of methane released (mt CH_4), total estimate of natural gas released in a calendar year, company-specific goal for reducing methane emissions, progress in meeting company-specific goal, and emission reductions from voluntary action (mt CH_4).

BMPs- Areas of Future Focus

Mains and Services - Vintage and Century Plastic

DSI members agree with EPA's decision not to include vintage or Century plastic in the mains or services BMP at this time. Most LDCs do not have sufficient available inventory data such that they can commit to and track replacement levels. Furthermore, emission factors do not exist for these main or service material types. In fact, plastic is not differentiated between plastic types at all with the current emission factors. Therefore, when LDCs replace vintage or Century plastic mains and services, this is not currently reflected in Subpart W reporting.

DSI members propose that EPA work with LDCs and other stakeholders to add vintage and century plastic as a BMP option in the future. This will require improved understanding of the main and services inventory as well as methane emissions from leaks and cracks in this material. As part of the Methane Challenge Program, EPA should establish a group of LDCs and other interested stakeholders to address these issues. We suggest that EPA engage stakeholders in AGA's Plastic Pipe Data Collection Initiative. Their goal has been to create a national database of information related to the in-service performance of plastic piping materials. Members include AGA, the American Public Gas

Association, the Plastics Pipe Institute, NARUC, the National Association of Pipeline Safety Representatives, and PHMSA.

Customer Meters
As LDCs replace and rehabilitate leak prone pipe and modernize facilities, EPA should consider adding other BMP sources to the Methane Challenge Program. For example, for some LDCs, customer meters are estimated to be one of the most significant sources of methane emissions. As such, EPA should work with LDCs and other stakeholders to evaluate the development of a BMP focused on customer meters. The mitigation options for this BMP could include the repair or replacement of a specified percentage of customer meters annually.

Leak Backlogs
Many LDCs have a backlog of nonhazardous leaks on their systems. These leaks are typically classified as Grade 3 leaks and reported to PHMSA. LDCs are using increasingly more sophisticated leak detection equipment and are collaborating with NYSEARCH to quantify methane emissions from leaks. EPA should work with LDCs and other stakeholders to evaluate the development of a BMP focused on reduction of leak backlogs and the repair of leaks. The mitigation options for this BMP could include the repair of a specified percentage of leaks annually based on the size of the leak backlog. In addition, this BMP could also include increased surveys, emissions quantification of leaks found and repaired.

Methane Emissions Quantification
The current methane emissions quantification methodology for LDCs consists of default methane emission factors per mile of main and number of services. While the WSU research represents an improvement to the default emission factors currently used by EPA in the Greenhouse Gas Inventory and Subpart W, a transition to leak based emission factors should be considered. This alternative approach will more accurately reflect the efforts by LDCs to find and fix leaks by creating a public record of reduced methane emissions. Under the currently methodology, even LDCs who eliminate all leaks from their gas distribution networks would be unable to demonstrate methane emission reductions for best in class performance. EPA should work with LDCs and other stakeholders to evaluate the development of an alternative methodology to quantify emissions and emission reductions.

Sunset Dates for Mitigation Options
Similar to Natural Gas STAR, it is reasonable for the Methane Challenge Program to create a structure to establish sunset dates for mitigation options. DSI members recommend that EPA maintain consistency between the Natural Gas STAR program and Methane Challenge as much as possible. As EPA notes in the Supplemental Technical document, liners have a 10 year emission reduction benefit lifetime in the Natural Gas STAR program. This emission reduction benefit lifetime could also be applied to inserts and internal and external joint sealing under the Methane Challenge Program.

Recognizing Historic Action
The Methane Challenge Program should recognize previous actions by LDC partners for one or more BMP sources. This would likely be attractive to partners that have undertaken mitigation efforts to address a source identified by EPA (such as M&R stations) but is not selecting that BMP as part of its implementation plan. Background data and information on a partner's mitigation efforts and recognition by EPA would improve transparency and inform stakeholders as the program is launched. EPA could acknowledge these actions within the implementation plan of the LDC along with fact sheets and other materials prepared for the launch of the program in early 2016.

EPA should develop a standardized list of data elements and qualitative information that LDC partners would be required to provide regarding the actions taken and an estimate of the methane emission reduction benefits achieved. However, EPA should avoid making the data required a burden to Methane Challenge Program partners which could result in LDCs forgoing this opportunity. Finally, EPA may want to limit the recognition of historic action to 10 years to maintain consistency with the sunset dates for mitigation actions.

Thank you for the opportunity to provide this feedback and we look forward to continued engagement in the development of this important program.

Sincerely,

Brian Jones

COMMENTER:

Environmental Defense Fund (EDF)

Comments on EPA's Natural Gas STAR Methane Challenge Program: Proposed Framework:

November 13, 2015

U.S. EPA Natural Gas STAR Program
MC 6207J
1200 Pennsylvania Ave., NW
Washington, DC 20460

Attention: Carey Bylin, Natural Gas STAR Program Manager

Re: Comments on Proposed Framework for U.S. EPA's Natural Gas STAR Methane Challenge Program

I. INTRODUCTION

The Environmental Defense Fund (EDF) appreciates the opportunity to provide feedback on EPA's Methane Challenge Program Proposed Framework and Supplementary Technical Information (STI) to recognize voluntary efforts to reduce methane emissions from the oil and natural gas sector. Methane is a powerful climate pollutant over 80 times more potent than carbon dioxide over a 20 year period.[1] The oil and natural gas sector is responsible for 29% of U.S. methane emissions,[2] and the Administration has estimated that U.S. methane emissions from this sector could rise by 25% by 2025 if no additional action is taken to reduce emissions.[3] These emissions will accelerate climate change and are associated with harmful co-pollutants that contribute to ground level ozone and elevated cancer risks. Significant reductions in emissions of methane and other harmful pollutants from the oil and gas sector are technically feasible and highly cost-effective using current technologies, and EDF strongly supports sensible regulations under the Clean Air Act to ensure these solutions are rigorously deployed. Such standards are necessary to protect our climate and public health, and to meet the Administration's commitment to reduce methane emissions by 40–45% below 2012 levels by 2025.

Voluntary programs have played an important role in developing and deploying technologies for reducing emissions from the oil and gas sector. Over the past 20 years, EPA's Natural Gas STAR Program has encouraged partner companies to achieve meaningful methane

[1] IPCC, Climate Change 2013: The Physical Science Basis (2013), *available at* www.ipcc.ch/report/ar5/wg1/.
[2] *Overview of Greenhouse Gases*, EPA, http://www.epa.gov/climatechange/ghgemissions/gases/ch4.html (last visited Sept. 26, 2014).
[3] The White House, Fact Sheet: Administration Takes Steps Forward on Climate Action Plan by Announcing Actions to Cut Methane Emissions (Jan. 14, 2015).

emission reductions and identified over 50 cost-effective techniques for methane reduction.[4] The program has gathered data that advances EPA's work to protect the environment and public health, and has encouraged industry to develop, deploy, and document best practices.

The Methane Challenge Proposed Framework presents an opportunity to build on this foundation. We emphasize, however, that voluntary programs alone cannot secure the urgent substantial methane reductions needed from the oil and gas sector given the large number of companies in the sector and the need to assure that these companies comprehensively and effectively deploy best practices to protect human health and the environment. While voluntary programs can encourage companies to develop and implement the next generation of methane mitigation solutions, rigorous and comprehensive regulations will ultimately be needed to ensure protections are in place for communities across the country.

Our detailed comments are divided into four sections. First, we present principles that should inform the proposed Methane Challenge Program and identify ways the program can serve as an important complement to existing and future regulatory requirements. Second, we discuss the options described in the Methane Challenge Proposed Framework, providing recommendations to clarify and strengthen certain key elements. Third, we respond to some of the questions raised by EPA in the Proposed Framework and STI. Finally, we address certain of EPA's specific descriptions of emission sources and quantification methodologies, and we recommend other emission sources EPA should include when finalizing the program.

We make the following general recommendations:

- The Methane Challenge Program should create a framework that rewards true leadership, continuous improvement, and technological innovation in methane emission reduction that go well beyond compliance with existing state or federal requirements.

- The program should include rigorous requirements for reporting and verification, utilizing EPA's Greenhouse Gas Reporting Program (GHGRP) to the maximum extent possible as a means of providing accountability and transparency, and developing mechanisms within EPA's GHGRP reporting tool, e-GGRT, to collect supplemental data needed to verify reductions reported through the Methane Challenge.

- The program should incentivize good management practices and policies.

- The Methane Challenge Program should promote innovative approaches to emissions measurement, monitoring and reduction technologies and practices, and encourage emission reductions from a wide range of sources across the natural gas value chain.

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[4] EPA, Natural Gas STAR Methane Challenge Program: Proposed Framework, *available at* http://www.epa.gov/gasstar/documents/methane_challenge_proposal_072315.pdf.

II. COMMENTS ON THE OVERALL DESIGN OF THE METHANE CHALLENGE

We agree with EPA that the Methane Challenge Program can be a complementary part of the Agency's—and the Administration's—ongoing commitment to address methane emissions and global climate change. As such, the Methane Challenge must establish rigorous standards that reward true leadership, continuous improvement, and innovation in reducing emissions. To achieve this goal, it is essential that the program require participating companies to make specific and ambitious commitments that are reported annually using the GHGRP (with some modifications), and deepen those commitments over time. We also agree with EPA that the Methane Challenge Program can "serve as a catalyst for broad industry adoption of best practices to reduce emissions."[5] But to do so, the program must be transparent and forward-looking.

A. Each Programmatic Option Finalized by EPA Must Be Ambitious, Forward-Looking, Fast-Acting, and Transparent

In the Methane Challenge Program's Proposed Framework, EPA proposes two options for how companies could voluntarily reduce methane emissions, as well as a third possible approach that is under consideration, but not proposed. We believe the Methane Challenge Program will best drive additional reductions if the framework requires partners to be ambitious, forward-looking, fast-acting in implementing their strategies and delivering their reductions, and fully transparent in reporting on their progress. Specifically, partner actions under the Methane Challenge must be:

- **Ambitious**: The final options must ensure that partner commitments are ambitious and reflect stretch goals in the spirit of embracing the "methane challenge." Under the Best Management Practice (BMP) options, for example, partners should be expected to select multiple BMPs that go beyond actions the company has already taken. Under the One Future option, partners should commit to meaningful emissions intensity reductions regardless of whether they are already close to the One Future target for their segment of the industry.

- **Forward-Looking**: Company commitments must be forward-looking; they should drive future action and not implicitly or explicitly include reductions that were undertaken under the Natural Gas STAR Program or required under local, state or federal regulations. We appreciate EPA's clarification in the STI confirming that the intent of the Methane Challenge "is to promote voluntary methane emission reductions for operations not subject to emission control regulations, and to spur actions beyond those regulatory requirements (e.g., State regulations and New Source Performance Standards (NSPS))."[6]

- **Deliver Near-Term Reductions**: Commitments under the Methane Challenge Program must be "fast-acting," by which we mean that initial goals under any of the options

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[5] *Ibid*., p. 4.

[6] U.S. EPA, *Natural Gas Star Methane Challenge Program: Supplementary Technical Information: Proposal for Stakeholder Feedback*, October 19, 2015, p. 3. *Available at*: http://www3.epa.gov/gasstar/documents/MC-Supp-Tech-Info-Draft-10-19-15_508.pdf.

should be completed within five years (and preferably sooner). Voluntary programs allow companies to make and implement commitments quickly, and we urge EPA to fully leverage this benefit of voluntary frameworks given the critical importance of near-term methane reductions.

- **Transparent and Fully Verified**: Company performance under the Methane Challenge Program must be fully transparent and assured through rigorous verification procedures. All data related to emission reductions, activity data, and progress toward corporate commitments must be made publicly available. Further, the details of all protocols used to implement methane reduction technologies and practices, as well as underlying analysis supporting baseline calculations and subsequent adjustments should also be available to the public. Without transparency and verification, program integrity cannot be assured.

1. *Recommendations on the BMP Commitment Option*

EPA has significant experience implementing voluntary programs based on best management practices, and the BMP option EPA proposes, with key improvements, could meet the objectives of the new Methane Challenge Program. First, we urge EPA to expand the list of eligible BMPs found in Appendix 1 of the Proposed Framework. EPA developed this list based on contribution to national emissions and stakeholder interest, but the list excludes certain effective strategies that companies could readily implement. Accordingly, we urge EPA to provide a more comprehensive list of emission sources in Appendices 1 and 2 and to develop protocols for these additional sources consistent with the approach taken for sources covered in the STI. Further, we urge EPA to expand the list of covered sources on an ongoing basis, rather than delaying further action for a year or more, to ensure timely implementation of the Program.

Second, we urge EPA to require partners to implement more than one emission reduction option at a time. EPA should encourage ambitious action from partners both in terms of which and how many sources they include in their initial commitments. We note that the 2012 Subpart OOOO NSPS required implementation of emission reductions within 3 years or less, depending on the emission source. State-level emission requirements affecting existing sources have had similar compliance deadlines. Given the large number of potential reduction options available to partners in the Methane Challenge Program, partner companies should be expected to implement at least two voluntary emission reduction options (or more) over a few years.

Third, we urge EPA to require swift implementation of these commitments. We agree that timing is critical and that voluntary frameworks, given their flexibility, can enable near-term reductions. We believe that allowing five years to fully implement the BMPs, as stated in the Proposed Framework, should be the outside limit for implementation. We urge EPA to adopt an approach that encourages companies to complete commitments as quickly as feasible (ideally within 3 years), and to take more time (no more than 5 years) only when circumstances necessitate.

Fourth, we urge EPA to focus sharply on securing prospective commitments that achieve real additional reductions. In the Proposed Framework, EPA acknowledges the possibility that partner companies could report emission reductions achieved through BMPs adopted prior to joining the Methane Challenge, and seeks comment on "specific program design options that encourage partners to make source-specific commitments that would recognize progress and yield significant additional emission reductions."[7] The purpose of the Methane Challenge is to deliver real methane reductions, and accordingly, we have concerns with an approach that would conflate Methane Challenge reductions with those previously secured as part of the Natural Gas STAR Program or through other regulatory or voluntary initiatives. Accordingly, we recommend that EPA require partners to clearly report whether progress toward BMP commitments occurred before or after joining the Methane Challenge Program. Moreover, to ensure these commitments secure real reductions, we urge EPA to require partners to commit to BMPs for which they have not already made substantial progress in their operations (for instance, less than 50% of eligible operations implementing the BMP). Most of the companies that have made significant progress already are industry leaders, and they should be encouraged to continue to lead by example as they expand their efforts.

Fifth, it is essential that partner companies in the Methane Challenge Program be encouraged to demonstrate continuous improvement by deepening their commitments over time. We recommend that EPA require Methane Challenge partners to add new BMPs over time in order to remain in the program (for instance, one new BMP commitment each year).

We believe that the BMPs EPA has proposed to recognize are broadly applicable to sources in the oil and gas sector. Should EPA allow partner companies to determine that particular BMPs cannot be implemented at particular sources or facilities, we support EPA's development of a rigorous process for identifying such situations. In particular, we recommend that EPA require the partner, in its annual Methane Challenge report, to identify all such sources. Further, for each such source, the partner should explain why it was not possible to implement the emission reduction measure at the source, estimate the annual emissions from the source, and commit to equivalent reductions by deploying another BMP at any of its sources. This data element is not currently reflected in the Reporting Tables in the STI, and we recommend that EPA include it. If there is no such process for tracking these situations, it will be difficult to fully understand what the partners are doing and how effectively they are reducing their emissions. Similarly, EPA should include the proposed data element on acquisitions and divestitures in the Reporting Tables.[8]

Finally, we support EPA's recommendation that commitments include interim milestones, and EPA's statement that partner companies should "submit, within 6 months of joining the Program, an Implementation Plan to specify milestones for achieving their commitments."[9] We urge EPA to publicize progress made toward both the overall goal and the

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[7] U.S. EPA, *Natural Gas STAR Methane Challenge Program: Proposed Framework*, July 2015, p. 8.
[8] U.S. EPA, *Supplemental Technical Information*, p. 4.
[9] U.S. EPA, *Supplemental Technical Information*, p. 5.

interim goals. We believe that annual reporting of progress and results is fundamental to the integrity and success of the Methane Challenge Program.

2. Recommendations on the One Future Emissions Intensity Commitment Option

EPA's second option under the Methane Challenge Program is a program administered by One Future, Inc. EPA explains this option as follows:

> One Future companies make a commitment to achieve a specified average rate of emissions intensity across all facilities within a specific segment by 2025. Each company has the flexibility to determine the most cost-effective pathway to that goal – and agrees to demonstrate progress according to specific reporting protocols.[10]

EPA's BMP approach, described above, builds from the Agency's experience with the Natural Gas STAR Program, which itself was focused on technologies and practices available to reduce emissions. Conversely, the One Future approach is performance-based, and as a result, may create an opportunity for greater emission reductions at lower costs. There are, however, complexities associated with implementing a performance-based approach, which, when coupled with the current lack of key details concerning the One Future Initiative, make meaningful comparison with EPA's proposed BMP option difficult at present. For instance, it appears that the "specified average rate of emissions intensity" for each segment of the industry has not yet been established along with other key program features.

Moreover, EPA acknowledges that there is "a possibility that companies are already near their target intensity, and their commitments therefore would not yield significant additional methane reductions."[11] EPA seeks feedback on how to address this issue, which could include "reducing emissions below levels necessary to achieve One Future's target." To assure the program secures meaningful methane reductions, we recommend that partners selecting the One Future option meet the more stringent of either the One Future target or a meaningful percentage reduction in intensity.

For other aspects of the One Future Initiative where details are available, we urge EPA to ensure that commitments made under that program are consistent with key features in the proposed BMP framework. Notably, the One Future Initiative requires companies to achieve commitments by 2025 but under the BMP option EPA proposed implementation over a 5-year period. If EPA intends to recognize One Future commitments under the Methane Challenge program, companies should be required to accelerate their commitments consistent with the need for near-term methane reductions. Further, as some commitments are completed, the One Future process should assist companies in identifying others on a rolling basis to maintain momentum and deliver significant methane reductions.

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[10] U.S. EPA, *Proposed Framework*., p. 8.
[11] U.S. EPA, *ibid*., p. 9.

We urge EPA to continue working with the industry leaders who have been developing the One Future Initiative to help identify rigorous intensity targets, to address technical implementation issues, including those associated with monitoring and verification, to surface innovative technologies and practices, and to help fully realize the promise of performance-based approaches, whether or not One Future is formally recognized under the Methane Challenge Framework. EPA should also ensure the public has a meaningful opportunity to comment on these program details in advance of any decision to incorporate One Future into the Methane Challenge Program.

3. Recommendations on the Emission Reduction Commitment Option

EPA raises the possibility of an "Emission Reduction Commitment" as a third option under the Methane Challenge Program. According to EPA, this approach would allow companies to "commit to reducing their methane emissions by a certain percentage from an agreed company-wide emissions baseline by a future date (to be determined by the company)."[12] This option has not been fully developed by EPA, and the proposed Methane Challenge framework raises some significant implementation concerns associated with this approach – including the difficulty of maintaining a consistent baseline over time for large companies with significant divestments and acquisitions. In light of these concerns, we agree with EPA's proposed determination that this option should not be part of the Methane Challenge Program at this time.

B. All Finalized Options Should Foster Continuous Improvement in Methane Management Through Focus on Additional Emission Sources, Innovative and Advanced Monitoring and Measurement Approaches, and Updated Protocols

It is critical for the Methane Challenge Program to include mechanisms for expanding and amending the list of BMPs over time to encourage technological innovation and the deployment of improved methods for mitigating methane emissions. As noted above, the current list of BMPs reflects only a subset of the well-established practices and technologies that have been shown to effectively control methane emissions. EPA should include additional practices and technologies in the final Methane Challenge Program Framework. Such an approach will support partner efforts toward continued progress and additional emission reductions.

In addition, if a partner wants to use an alternative practice or technology that is not included in the final list of BMPs, EPA should allow the company to submit a request that includes a detailed description of the practice or technology, and a test protocol for quantifying and verifying emission reductions. EPA should make proposed BMPs and test protocols publicly available, and encourage both Methane Challenge partners and technology developers to submit such proposals. Such efforts to encourage innovation can take advantage of – and further stoke – the dynamic methane technology space. This arena includes multi-stakeholders efforts such as the EDF-led Methane Detectors Challenge, a partnership with 8 leading oil and gas companies to

[12] U.S. EPA, *ibid*., p. 9.

bring to market new, cost-effective continuous methane detection systems, and the ARPA-E MONITOR initiative.

Where a new practice or technology is proposed as an alternative means of controlling an emission source that is covered by an EPA-approved BMP, EPA should also review proposals to ensure they achieve equal or greater emission reductions than the approved BMP. If EPA determines that the request is acceptable, then it can grant a temporary exemption that allows use of the alternative BMP and requires the partner to demonstrate rigorous compliance. After verifying the efficacy of an alternative BMP, the Agency could allow for its use at other partner facilities and ultimately integrate it into the Methane Challenge framework.

C. It is Essential that the Methane Challenge Program Distinguish between Regulatory and Voluntary Actions

As noted previously, we support EPA's decision to include only voluntary methane emissions reductions in the Methane Challenge Program, and we agree that EPA should require the reporting of information on "applicable air regulations for included facilities, including a list of sources covered in the partner's Methane Challenge commitment that are affected by each regulation."[13] Given the current focus on methane regulation in several states and at the federal level, it is increasingly important to track the level of emission reductions from voluntary actions and regulatory requirements separately.[14] Further, we do not support counting methane reductions required under a local, state, or federal regulation toward meeting program commitments. Such reductions are not "additional," because reductions achieved as a result of compliance with regulatory frameworks would occur even in the absence of the Methane Challenge.

To the extent that companies are reporting under the BMP option, we recommend that EPA publish the total ***voluntary*** emission reductions per BMP implemented. Achievement of a BMP commitment should be based on a demonstration that the BMP has been fully implemented for all (or a majority of) sources that are not regulated. In some cases, it may be possible for companies to exceed emission reduction requirements at regulated sources; any such over-compliance could be counted toward the commitment as a voluntary reduction.

It is also important to distinguish between regulatory and voluntary actions under the One Future option, and to ensure that only voluntary reductions are counted toward One Future's Methane Challenge goals. We urge EPA and One Future to work together to ensure that the One

[13] U.S. EPA, *Supplemental Technical Information*, p. 4.

[14] EPA should also continue to increase transparency surrounding how Gas STAR data is used to quantify voluntary emission reductions in the U.S. Greenhouse Gas (GHG) Inventory. Because many reports are not specific enough to identify particular source categories, the 2014 GHG Inventory classified over 40% of the reductions in the "other" category. We encourage EPA to make the Gas STAR and Gas STAR Gold reporting requirements more detailed and transparent so that the EPA Inventory program can more readily use the data to quantify reductions from specific sources.

Future and Methane Challenge goals are set in such a way as to encourage ambitious partner commitments through voluntary action.

D. EPA's Methane Challenge Program Must Contain Rigorous Standards for Reporting and Verification

We support the annual reporting requirement contained in the Proposed Framework, and have several suggestions to strengthen its rigor. We agree with EPA's proposal to rely on GHGRP Subpart W data to track progress in meeting commitments, and appreciate EPA's recognition that voluntary supplemental data will also be needed to comprehensively track progress.

In response to EPA's call for comment on specific mechanisms for reporting such supplemental data, we recommend that EPA develop a new module in the e-GGRT data-reporting tool used for the GHGRP. Companies participating under the Methane Challenge Program are already familiar with e-GGRT, having submitted data under Subpart W for several years. We support EPA's efforts to leverage Subpart W and create a user-friendly system with similar references and language, as this will help streamline reporting. In addition to the data provided through Subpart W, we encourage EPA to continue working with partner companies to better understand the costs of innovative methane mitigation practices.

We appreciate the additional detail provided by EPA on the types of information that would be submitted under the different Methane Challenge options. We agree with EPA that the One Future or Emission Reduction (ER) commitments would need to provide supplemental data for all sources, whereas the BMP option would require supplemental information only for the selected BMPs. We also support a requirement that comprehensive supplemental data be provided under the One Future and ER commitments related to past year baseline emissions data. We note that the reporting protocols in the STI do not currently include any detail on the data elements to be reported related to past year baseline emission data, and EPA should require companies to provide such information as a required reporting element.

We agree with EPA that all data that has not been determined to be confidential under the GHGRP should be made public. Further, data that is submitted voluntarily should be made public unless such data are in categories that are confidential business information (CBI) under the GHGRP. Voluntarily submitted data should not be treated as CBI if that same data would be made public under the GHGRP. Transparency of submitted data is important to assure the public that the voluntary reductions reported under the Methane Challenge program are real and verifiable. In addition, Methane Challenge program data could help supplement and enhance other oil and gas sector databases.

We stress that EPA must ensure that the level of detail in the data reporting mechanism is specific enough to confirm implementation of the protocols. In this regard, we believe that EPA has taken a significant step forward in the STI for the emission sources covered in Appendix A. As previously noted, we urge EPA to consider expanding the number of covered emission sources and related protocols. Because the adequacy of existing reporting mechanisms varies by the individual source, EPA may initially focus on mechanisms most in need of improvement rather than updating all protocols.

In addition to annual reports, we urge EPA to include a verification component, which would require occasional site visits by EPA or an independent, accredited third-party auditor. Further, photographic or video documentation or electronically recorded measurements could feature in the verification process where appropriate. The Center for Sustainable Shale Development (CSSD) auditor qualification guidelines provide a potential model.[15] These guidelines include qualification requirements for audit teams, individual auditors, lead auditors, and subject matter experts. Requirements include education, experience, training completion, and maintenance of competence through continued certification and participation in at least one CSSD audit every twelve months. The auditing firm must maintain records for at least six years, identifying which audit team members fulfilled the various competency requirements for the audit team.

To assure the independence of third party auditors, the protocol should require that verifiers have no conflict of interest and receive no financial benefit from the outcome of verifications. EPA can reference the Food and Drug Administration's requirements for accrediting third parties to review certain medical device certifications to identify potential conflicts of interest to avoid, including past or present personnel relationships with companies undergoing verification and past or present ownership or investments in these companies.[16] CSSD also models a protocol that auditors must follow when verifying protocols.

Finally, EPA should ensure that deliberately misreporting information or influencing verification has consequences for program participation. A company found to be deliberately misreporting information or influencing verification should be removed from the Methane Challenge Program. In addition, such a company should be barred from independently publicizing their performance under the Methane Challenge Program.

E. The Methane Challenge Program Should Include Incentives for Good Management Practices and Policies to Minimize Methane Emissions

EDF's experience working with industry partners suggests that achieving meaningful reductions in methane emissions requires a supportive corporate culture. This includes training managers and employees on how to reduce methane emissions and identify opportunities for further reductions; incentivizing employees to achieve emission reductions by making this a factor in compensation, performance evaluation, and/or similar management decisions or processes; and providing appropriate resources, training, incentives, and expectations for

[15] Center for Sustainable Shale Development, CSSD Auditor Qualification (Approved Aug. 19, 2013), *available at* https://www.sustainableshale.org/wp-content/uploads/2014/01/Qualifications.pdf.
[16] *See* Food and Drug Administration, Implementation of Third Party Programs Under the FDA Modernization Act of 1997; Final Guidance for Staff, Industry and Third Parties 11-12 (Feb. 2, 2001), *available at* http://www.fda.gov/downloads/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm094459.pdf.

contractors. Accordingly, we suggest that EPA add a "Good Management" protocol or module that encourages Methane Challenge Program partners to spread best practices in terms of steps taken to create a corporate culture conducive to minimizing emissions – regardless of whether the partners have selected the BMP or emissions intensity approach. This Good Management protocol would serve as a foundation for the efforts being undertaken under the Methane Challenge Program to reduce emissions. Over time, this requirement could support more ambitious commitments in the program, as well as continued active participation over an extended time period.

III. FEEDBACK ON CERTAIN QUESTIONS FOR STAKEHOLDERS IN THE PROPOSED FRAMEWORK AND SUPPLEMENTAL TECHNICAL INFORMATION

A. Responses to Selected Questions in the Proposed Framework

<u>Question 4</u>*: For the BMP option, how can EPA encourage companies to make commitments for sources for which they have not made significant progress in implementing mitigation options? In other words, how can companies be encouraged to participate beyond the sources for which they have already made significant progress?*

EPA must ensure the Methane Challenge Program recognizes only ambitious, additional emission reduction activities that demonstrate genuine leadership. As noted above, we suggest that EPA put this goal into practice by discouraging companies that select the BMP option from selecting BMPs that have already been largely or substantially adopted. For companies selecting the One Future option, we further recommend that EPA require companies to meet the intensity target ahead of schedule and opt for a "stretch" target that reflects the *lower* of the applicable One Future intensity target or a meaningful reduction in emissions intensity.

As noted previously, EPA should also expand the list of BMPs and require that partners commit to implement at least two BMPs at a time. Finally, we urge EPA to require that partners can only remain in the Methane Challenge Program if they ensure that their commitments remain ambitious and deliver significant emission reductions on an ongoing basis. For the BMP program in particular, we believe EPA should require Methane Challenge partners to continue committing to at least one new BMP each year in order to remain in the program.

<u>Question 5</u>*: Please provide comments on the sources and corresponding BMPs that are provided in Appendix 2, including any recommendations for additions, deletions, and revisions.*

Additional information in response to this question is found in Section IV, below.

<u>Question 7</u>*: Is a 5-year time limit to achieve BMP commitments appropriate? If not, please provide alternate proposals. Would a shorter time frame limit or encourage greater reductions earlier?*

We believe that the 5-year time limit to achieve BMP commitments is outside a generally acceptable limit. As noted above, it is our view that a 3-year deadline is reasonable for most companies, with the option of extending the commitment to 5 years if the company provides a transparent and compelling explanation as to why additional time is needed. We believe that a shorter timeframe will result in greater emission reductions earlier, and better serves EPA's goal of recognizing ambitious corporate action and catalyzing near-term reductions in emissions.

In addition, we believe that timelines for the One Future option should be similar to those we suggest for the BMP option.

Question 8: Should EPA offer the ER commitment option? If so, please provide specific recommendations for ways that EPA could address the implementation challenges outlined in this document. What is the minimum target company-specific reduction level that should be set for participation in this option?

As explained above, we agree with EPA that the ER Commitment faces a number of implementation challenges. We recommend that EPA continue to evaluate the ER Commitment option in light of lessons learned from implementing the other two program options.

Question 9: To what extent is differentiating the voluntary actions from regulatory actions important to stakeholders? What are the potential mechanisms through which the program could distinguish actions driven by state or federal regulation from those undertaken voluntarily or that go beyond regulatory requirements?

As described above, distinguishing voluntary and regulatory actions is fundamental to the integrity of the program. The goal of the Methane Challenge Program should be to spur corporate leadership by recognizing ambitious, additional steps to reduce methane emissions from the oil and gas sector. For this reason, companies that are doing no more than is required of them under regulatory programs should not be recognized under the Methane Challenge Program.

Above, we suggest several modifications to the Methane Challenge framework that would ensure all participants are undertaking substantial additional actions to reduce emissions. To further protect the integrity of the program, we also believe it is vital that EPA require Methane Challenge partners to publicly disclose in their annual reporting which actions and reductions result from regulatory requirements, and which actions and reductions can be considered voluntary. We note that EPA has incorporated this approach into the STI.

Question 10: EPA plans to leverage existing reported data through the GHGRP (Subpart W) in addition to supplemental data that partners would submit to EPA. Would the e-GGRT system be an appropriate mechanism to collect the voluntary supplemental data?

As described above, we believe that EPA should develop a module for the voluntary supplemental data within the e-GGRT platform. We believe such an approach will be more quickly implemented, less burdensome for reporters, and will facilitate ready integration of the Subpart W and supplemental data.

<u>Question 12</u>: EPA seeks feedback on potential mechanisms for encouraging continued active participation in the Program once a company's initial goals have been achieved.

It is our view that companies that do not renew their commitments to reflect continuous improvement, as recommended above, should exit the program.

B. Responses to Certain Questions in the Supplemental Technical Information.

<u>Question 1</u>: Are potential partners interested in reporting measured methane emissions for any sources that currently don't include measurement in the quantification options? Please comment on this, and if, so, provide information on recommended measurement protocols for sources of interest.

EDF strongly encourages EPA to include additional emission sources in the Methane Challenge Program. As discussed in Section IV below, the present list of sources omits several important methane reduction opportunities.

<u>Question 2</u>: Should intermittent pneumatic controllers be included in the Pneumatic Controllers source? EPA seeks recommendations on whether and how to include intermittent controllers.

Among different controller types, intermittent pneumatic controllers are responsible for the largest share of methane currently reported to Subpart W. A recent report by ICF International suggests certain of these devices can be replaced by low- or zero-bleed controllers and additional scientific research suggests that malfunctioning intermittent devices can be responsible for substantial emissions. Accordingly, we urge EPA to develop protocols for these sources.

<u>Question 17</u>: The Natural Gas STAR Program Annual Reporting Forms specify Sunset Dates (the length of time a technology or practice can continue to accrue emission reductions after implemented) for mitigation options. Should the Methane Challenge Program create a similar structure to establish Sunset Dates for designated mitigation options?

From our review of the sunset dates under the Natural Gas STAR program,[17] it appears that there are three broad categories: sources that must be implemented annually, sources that sunset after 7 years, and sources that sunset after 10 years. EDF supports the use of sunset dates as a means of ensuring that partners are monitoring all facilities where emission reductions have

[17] U.S. EPA, *Natural GasSTAR: Table of Sunset Dates/Technologies and Practices by Industry Sector*, *available at*: http://www3.epa.gov/gasstar/documents/table_sunset_dates.pdf.

been implemented and ensuring that the emission reductions are delivered over the reduction's expected life. We urge EPA to require that partners document via site visits or instrumentation that previously implemented technologies or practices are, in fact, effective at least until the EPA sunset date.

Question 18: Should the Methane Challenge Program create a mechanism to specifically recognize historic action for certain sources? If so, how could the Program recognize such previous action (for example, by allowing these companies to join the Program and collecting and posting relevant details on previous action prior to joining the Program)?

As discussed previously, it is essential that the Methane Challenge Program differentiate past from forward-looking actions. Forward-looking commitments should form the foundation of any commitment under the Program, though, for companies making such commitments, EPA could develop an appropriate, and fully-transparent, methodology for recognizing past actions.

IV. COMMENTS ON PROPOSED BMP COMMITMENT OPTIONS

Below we offer several suggestions on EPA's approach for identifying the BMP commitment options that could apply to the different oil and gas segments. First, we urge EPA to implement a more inclusive BMP approach, as an alternative to the more limited list of BMPs listed in Appendices 1 and 2 of the Proposed Framework. Second, we provide recommendations to strengthen both mitigation measures and reporting requirements for the identified sources.

A. EPA Should Encourage Companies to Consider Multiple BMP Options by Providing a Comprehensive List of BMPs for Each Industry Segment.

We recommend EPA expand the list of available BMPs, including adding several BMP options reflected in the Natural Gas STAR Program and/or reported under Subpart W of the GHG Reporting Program but not currently recognized under the Methane Challenge Program. EPA could consider reorganizing Appendices 1 and 2 of the Proposed Framework with a focus on the specific BMPs, as opposed to the industry segments, along the lines suggested below:

Best Management Practice	Applicable Industry Segments
Pneumatic Device Venting	Production, Gathering & Boosting, Transmission
Pneumatic Pump Venting	Production, Gathering & Boosting, Transmission, Storage
Liquids Unloading	Production
Flare Stack Emissions	Production, Gathering & Boosting, Processing
Vented Storage Tanks	Production, Gathering & Boosting, Transmission
Reciprocating Compressors Seal Emissions	Production, Gathering & Boosting, Processing, Transmission, Storage
Centrifugal Compressor Seal Emissions	Production, Gathering & Boosting, Processing, Transmission, Storage

Dehydrator Vents	Production, Gathering & Boosting, Processing
Acid Gas Removal	Production, Gathering & Boosting, Processing
Blowdown Vent Stacks	Production, Gathering & Boosting, Processing, Transmission, Storage
Equipment Leaks	Production, Gathering & Boosting, Processing, Transmission, Storage, Distribution
Pipelines – Leaks and Blowdowns	Gathering & Boosting, Transmission
Metering and Regulating Stations	Distribution
Pipeline Main Equipment Leaks	Distribution
Service Line Equipment Leaks	Distribution
Excavation Damages	Distribution

For most of these BMPs, the means of reducing emissions should be consistent across industry segments. Further, it is likely that many upstream companies operate across more than one segment (e.g., production, gathering & boosting, and/or processing). In these cases, organizing emission reduction efforts around the BMP could result in broader, more consistent application of certain BMPs and larger emission reductions.

B. EPA Should Ensure That Development of the Methane Challenge BMP Protocols Are Rigorous

In the STI, EPA has provided additional information on mitigation options and reporting requirements for certain sources. Below, we provide comments on several of EPA's proposed protocols.

1. Gas-Driven Pneumatic Controllers

The STI offers a number of mitigation options for continuous, high-bleed pneumatic controllers, including replacement with low- or zero-bleed devices or removal from service. These mitigation options can secure substantial emission reductions and we support their inclusion in the STI. For example, based on emission factors derived from Subpart W data, ICF International determined that an individual pneumatic controller replacement can reduce emissions by approximately 97%, at a *negative* annual cost of -$3.08/Mcf of methane—even when assuming a relatively high capital cost of $3,000 per device. (The ICF figures were based on replacement of high-bleed with low-bleed devices).[18] Given these swift financial returns, EPA should encourage companies to implement this BMP as swiftly as possible.

EPA should strengthen these mitigation options, however, in several respects:

- <u>First</u>, operators should be required to first consider whether removal or replacement with a zero-emitting device is feasible before deciding to replace a continuous high-emitting controller with a low-emitting controller. Zero-emitting devices (and removal) are associated with substantially greater emissions

[18] ICF International, *supra* note 14, Tbl. 3-7.

reductions and EPA's mitigation options should reflect a preference for these options.

- Second, we urge EPA to include intermittent controllers in the source description. A study by ICF International concluded that replacement of certain intermittent devices could achieve substantial emission reductions, and EPA could retain the same narrow exemption already proposed for continuous high-bleed controllers to ensure intermittent controllers could continue to be used where operational characteristics require.
- Finally, as noted below in our discussion of equipment leaks, we urge EPA to require regular monitoring of any natural gas-driven pneumatic controller – especially intermittent pneumatic controllers, which are known to malfunction frequently. For example, a recent study commissioned by the City of Fort Worth examined emissions from 489 intermittent pneumatic controllers.[19] The study found that many of these controllers were emitting constantly and at very high rates, even though these devices were used to operate separator dump valves and were not designed to emit between actuations. The study authors concluded that these emissions were frequently caused by malfunctioning or failed controllers. A recent study of pneumatic controller emissions in British Columbia also noted that maintenance issues can lead to abnormally high bleed rates,[20] and a 2014 study of pneumatic controller emissions by UT-Austin similarly found that many high-emitting pneumatic controllers were bleeding continuously in a manner inconsistent with the manufacturer's design.[21] Application of regular leak detection and repair (LDAR) techniques to pneumatic controllers and pumps—especially as part of a comprehensive LDAR program applied to all components of an oil and gas facility—is a cost-effective way to identify maintenance issues and malfunctioning devices.

2. *Equipment Leaks and Fugitive Emissions*

EPA suggests it will delay development of a commitment option for equipment leaks and fugitive emissions due to "on-going regulatory actions." Equipment leaks are the most significant emissions source in the inventory and likewise represent a substantial mitigation opportunity. Accordingly, we urge EPA to move forward now with a commitment option addressing LDAR, which will enable companies to pursue these actions as part of their initial commitments under the Methane Challenge Program. Below, we provide more detailed recommendations on the dimensions of such a program.

- Scope. EPA should require all equipment and components at facilities—not just valves and connectors—to be monitored, including pneumatics, compressors,

[19] ERG and Sage Environmental Consulting, LP, *City of Fort Worth Natural Gas Air Quality Study, Final Report.* (July 2011) [hereinafter "Fort Worth Study"], *available at* http://fortworthtexas.gov/gaswells/default.aspx?id=87074.

[20] The Prasino Group, *Determining bleed rates for pneumatic devices in British Columbia; Final Report* at 19 (Dec. 2013) ("Certain controllers can have abnormally high bleed rates due to operations and maintenance; however, these bleed rates are representative of real world conditions and therefore were included in the analysis.").

[21] David T. Allen et al., *Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers,* 49 Environ. Sci. Tech. 633, 639 (2014).

pressure relief valves (PRVs), thief hatches, and separator dump valves. Further, the protocol should require monitoring of any malfunctioning components that vent emissions in excess of their normal operating rates. These requirements should apply to sources across segments.

- Frequency. EPA should require frequent monitoring. Colorado's Regulation 7 requires a tiered approach for leak inspection frequency of well sites, with certain sites being required to perform monthly monitoring.[22] Under the Methane Challenge Program, EPA should require monitoring to be performed at least quarterly for all facilities or at least as frequently as required by Regulation 7.
- Repair. EPA should require swift repair. In addition, EPA should consider requiring that low-leak technology be used for repairs in order to achieve greater emissions reductions, especially when a repair is delayed. "Low leak" or "leakless" valve packings, gaskets, and other equipment can be certified to operate with minimal fugitive emissions. Certain low-leak technologies, such as "low-E" valves and valve packings, have been used for over fifteen years, have been found to leak infrequently and at minimal rates, and are available at a moderate cost premium of 10–35% relative to standard valves.[23] Manufacturers of this equipment have begun issuing warranties that assure the equipment will not emit fugitives in concentrations greater than 100 ppm, and several standard industry test protocols are available for certifying low-leak equipment.[24] As a result, over the last several years EPA has included provisions in consent decrees with petroleum refineries and chemical facilities that require replacement of leaking valves and valve packings with low-leak technology.[25] In addition, EPA's proposed Uniform Standards for equipment leaks would require that low leak technology be used to repair or replace valves and connectors for which a repair cannot be completed within the standard 15-day deadline provided in the proposed rule.[26] Accordingly, low-leak replacement technology should be considered as a mitigation technology in the program.

Finally, the protocol should consider the rapidly evolving field of continuous monitoring technologies. For example, EDF has launched the "Methane Detectors Challenge," a competition meant to incentivize development of innovative new technology that will allow for continuous detection of methane emissions.[27] EPA could use the Methane Challenge Program to incentivize development and deployment of these and other promising new leak detection technologies. Colorado's Regulation 7 allows for innovation by permitting an owner or operator to use (Division approved) continuous emission monitoring, in which case the Division may also approve a streamlined inspection and reporting program.[28]

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[22] Colo. Dep't of Pub. Health & Env't Reg. No. 7 (5 CCR 1001-9), Unofficial Draft (Feb. 23, 2014) § XVII.F.3.
[23] Kosta Loukeris, *Low Leak Valve and Valve Packing Technology (Low-E Valve)*, 4 (EPA, Aug. 16, 2011); *See also* Joseph Wilwerding, *Fugitive Emissions From Valves: Update, Hydrocarbon Processing V-81, V-82* (June 2010) (indicating that costs for low-leak valve packings are "similar and sometimes less than costs for similar equipment").
[24] Loukeris, *supra* note 16, at 10.
[25] *See id*. at 14 (listing seven consent decrees signed as of August 2011); James Drago, Legislating Leak Detection: How U.S. Regulations Are Impacting the Rest of the World, 18 FLOW CONTROL 11, 16-18 (Nov. 2012).
[26] 77 Fed. Reg. 17,897 (Mar. 26, 2012).
[27] *Methane Detectors Challenge*, ENVTL. DEF. FUND, http://www.edf.org/energy/natural-gas-policy/methane-detectors-challenge (last visited July 22, 2014).
[28] *Id.* § XVII.A.

3. Liquids Unloading

EPA's proposed liquids unloading protocol requires minimizing venting during the process of liquids unloading through use of several technologies. We recommend EPA require direct measurement of venting during liquids unloading in order to more accurately track the performance of measures to avoid venting. In addition, the Agency's proposed reporting requirements are largely directed at collecting information on the efficacy of plunger lift systems. EPA should require partners to submit additional reporting data, beyond what is included in Subpart W, to assess other mitigation options such as velocity tubing and artificial lift systems.

4. Hydrocarbon Liquid Storage Tanks

As with pneumatic controllers, proper monitoring practices are a necessary component of a strategy to reduce emissions from storage tanks. In addition to the mitigation options EPA proposes, the Agency should ensure tanks are subject to a rigorous LDAR program, which should address instances of open thief hatches. Open thief hatches are likely responsible for a large proportion of storage tank emissions. [29]

The methane reduction source should apply to existing storage tanks with emissions below the threshold contained in the NSPS. We support EPA's proposal to route gas to a capture system (e.g., VRU) for beneficial use with at least a 95% reduction in methane emissions. Alternatively, companies could route gas to a flare or control device. In this case, however, flares or control devices must be required to achieve 98% DRE, which has been feasibly demonstrated and is required in many jurisdictions.[30]

5. Reciprocating Compressors Rod Packing

In the STI, EPA outlines several mitigation options to reduce methane emissions at reciprocating compressors. EDF urges EPA to encourage Methane Challenge partners with existing gas capture systems to route all rod packing emissions to beneficial use as a measure of first resort. Gas capture can result in greater methane reductions than rod packing replacements, especially in situations where rod packing deteriorates at an unexpectedly rapid rate. However, we note that it is also possible for operators *without* existing gas capture systems to install closed vent systems that route rod packing emissions to compressor suction or the fuel intake (an approach that EPA recently amended Subpart OOOO to include). EPA should require partners

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[29] AIR QUALITY CONTROL COMM'N, COLO. DEP'T OF PUB. HEALTH & ENV'T REG, INITIAL ECONOMIC IMPACT ANALYSIS PER § 25-7-110.5(4), C.R.S, at 9 (2013), *available at* http://www.colorado.gov/cs/Satellite/CDPHE-AQCC/CBON/1251647985820 ("Field observations using infra-red (IR) cameras and other methodologies indicate that in actuality emissions from controlled storage tanks often escape through the thief hatches and pressure relief valves (PRV) and therefore are not being combusted in the flare.").

[30] *See* Colo. Dep't of Pub. Health & Env't Reg. No. 7 (5 CCR 1001-9) (2014) § XVII.C.1 (requiring combustion devices to have a design hydrocarbon destruction efficiency of 98%); Wyo. Dep't of Envtl. Quality, Oil and Gas Production Facilities: Chapter 6 Section 2 Permitting Guidance (June 1997, Revised Sept. 2013) (requiring 98% control of flash emissions from storage tanks and separation vessels as well as emissions from glycol dehydrators, pneumatic pumps, and produced water tanks); 78 Fed. Reg. 17,836 (March. 22, 2013) (requiring flares for the Fort Berthold Indian Reservation in North Dakota to have minimum 98% DRE).

to implement such an approach unless there are safety or operational reasons that preclude it, or the expected emission reduction benefits would be demonstrably lower than with rod packing replacement.

EPA should also require regular LDAR at compressor stations to optimize the continuing effectiveness of the rod-packing replacement protocol. A corresponding LDAR requirement will encourage operators to perform regular maintenance and inform them of when rod-packing must be replaced. This requirement would also allow operators to quickly identify equipment failures and mitigate the significant emissions that result from those events.

6. Transmission and Distribution Pipeline Blowdowns

In the STI, EPA provides several mitigation options for transmission and distribution pipeline blowdowns. EPA further proposes that partners implementing the BMP option would "commit to maximize blowdown gas recovery and/or emission reductions through utilization of one or more of these options to reduce methane emissions from non-emergency blowdowns by at least 50% from total potential emissions each year."[31]

We support EPA's decision to encourage reduced venting of methane during blowdowns. We are less convinced that setting a fixed 50% requirement for reducing methane emissions from blowdowns is the best approach. In Appendix B of the STI, EPA seeks feedback on this proposal and notes that under certain situations, potential emissions could be overstated. EPA also asks for comment on whether the minimum 50% commitment "should be adjusted to serve as an appropriate stretch goal for companies."[32] We believe that all Methane Challenge Program commitments should be stretch goals, and we urge EPA to consider increasing the fixed percentage requirement by a reasonable amount every year.

7. Cast Iron/Unprotected Steel Pipeline Mains

In the STI document, EPA identifies two mitigation options for reducing methane emissions from distribution mains: replacing cast iron mains with plastic or cathodically protected steel, or rehabilitating cast iron and unprotected steel pipes with plastic pipe inserts.

The proposed BMP would call on local distribution companies (LDCs) to replace or otherwise seal a minimum percentage of pipelines each year, but does not require that replacements be directed to the leakiest portions of each system. We also note that EPA has proposed using emission factors to estimate the emission reductions associated with upgrading or rehabilitating cast iron and unprotected steel mains. We recommend that EPA require Methane Challenge partners to monitor all pipelines in their network using mobile leak detection technology similar to that used by EDF in its methane mapping project, on at least an annual basis.[33] Further, LDCs should make this data publicly available in real-time. Most importantly, EPA should require LDCs to eliminate their backlog of Class 2 and 3 leaks within three years,

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[31] U.S. EPA, Supplemental Technical Information, p. 13 and p. 15.
[32] *Ibid.*, p. 22 (Question 8).
[33] *Air pollution mapping enters a new tech era*, ENVTL. DEF. FUND, http://www.edf.org/climate/methanemaps/partnership (last visited Sept. 26, 2014).

and require that new Class 2 and Class 3 leaks be repaired within a reasonable period of time, not to exceed 1 year. Such a requirement would reward LDCs for actually finding and repairing leaks, and encourage strategic use of pipeline replacements and other leak reduction strategies.

8. Associated Gas

EDF urges EPA to include an option to reduce emissions of associated gas that is co-produced with oil and other hydrocarbon liquids. Venting and flaring of associated gas represents a tragic waste of natural resources, in addition to having harmful impacts on climate and public health. Flaring of associated gas in particular has become a significant problem in many areas of the country. We recommend that EPA craft a BMP that would call on partner companies to eliminate venting of associated gas, and gradually phase out flaring, by capturing the gas and either routing it to a sales line or directing it to beneficial use.

9. Flares

As noted for several of the preceding emission sources, EDF urges EPA to require flares to have a minimum 98% destruction rate efficiency (DRE). Also, the "reliable and continuous ignition system" required by the proposal should be equipped with a malfunction alarm and remote notification system to address instances of pilot flame failure. EPA has already effectively introduced these requirements for the Fort Berthold Indian Reservation in North Dakota.[34] Finally, all of the flare standards should apply to any source employing a flare as an emission control device under any of the covered emission sources.

V. CONCLUSION

EDF supports the development of an ambitious, forward-looking, fast-acting, and transparent program to reduce methane emissions from the oil and gas sector, which can serve as a complementary part of the Agency's—and the Administration's—ongoing commitment to address methane emissions. We believe that EPA's Methane Challenge Program is a significant first step toward this objective. In our comments, we have urged EPA and future partners participating in the Methane Challenge to be ambitious in commitment-setting, to act more quickly to fulfill these commitments, and to pursue additional, voluntary measures (as opposed to required actions under state and federal regulations).We appreciate the opportunity to comment on EPA's proposal, and look forward to working with the agency and interested stakeholders on the final design of the Program.

Sincerely,

Peter Zalzal
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Environmental Defense Fund
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[34] 78 Fed. Reg. 17,836 (Mar. 22, 2013).

COMMENTER:

Interstate Natural Gas Association of America (INGAA)

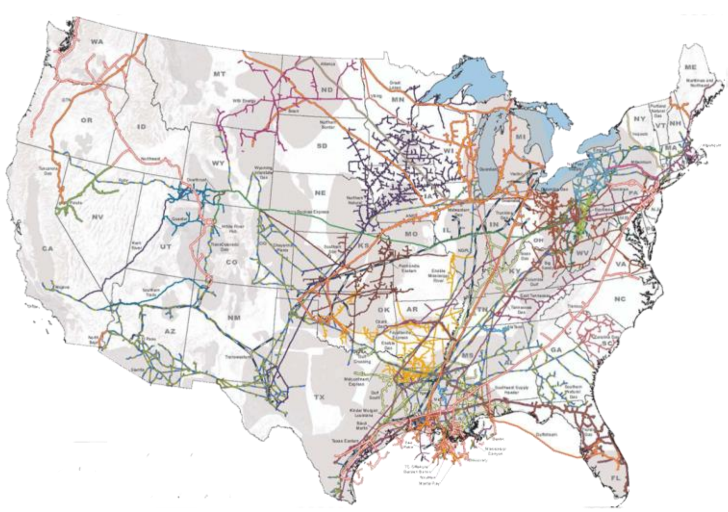
November 13, 2015

Via email
Ms. Carey Bylin
Natural Gas STAR Program
Global Methane Initiative (Oil & Gas)
U.S. EPA
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460

Comments of the Interstate Natural Gas Association of America (INGAA) on the Natural Gas Star Methane Challenge Program: Proposed Framework

Dear Ms. Bylin:

The Interstate Natural Gas Association of America (INGAA) is a trade organization that advocates regulatory and legislative positions of importance to the natural gas pipeline industry in North America. INGAA is comprised of 25 members, representing the vast majority of the interstate natural gas transmission pipeline companies in the U.S. and comparable companies in Canada. INGAA's members, which operate approximately 200,000 miles of pipelines, provide an indispensable link between natural gas producers and natural gas consumers in the residential, commercial, industrial and electric power sectors. INGAA's members are committed to providing safe, efficient and reliable transportation services to their diverse customers and to maintaining a high level of customer service.



INGAA and its member companies have a long history of working collaboratively with a variety of stakeholders on greenhouse gas (GHG) issues, including methane issues. INGAA appreciates the opportunity to comment on the Environmental Protection Agency's (EPA) Natural Gas

STAR Methane Challenge (Methane Challenge), a voluntary program designed to "reduce emissions and realize significant voluntary reductions in a quick, flexible, cost-effective way."[1] INGAA may supplement its comments at a later date should EPA issue additional technical documents, papers or Memorandum of Understanding (MOU) for Methane Challenge Participants**.**

Thank you for your consideration of these comments.

Sincerely,

Theresa Pugh
VP, Environment, Health & Construction Policy

[1] EPA's announcement of Methane Challenge on Natural Gas STAR website http://www.epa.gov/gasstar/methanechallenge/

I. EXECUTIVE SUMMARY

INGAA supports EPA's decision to propose a voluntary methane emission reduction program, rather than a prescriptive regulatory program, with the stated goal of achieving significant emission reductions in a cost-effective manner. INGAA also supports EPA's decision to offer three emissions reduction options, rather than prescribing uniform program criteria. Providing multiple options will enable each company to select the emissions reduction approach that best suits its business units.

- Program should be truly voluntary.
- Flexibility is critical.
- Program should focus on the largest sources of methane.
- Reducing Methane emissions from blowdowns events is unrealistic.

INGAA's decision to comment does not necessarily mean that its individual member companies will choose to participate in the Methane Challenge. While INGAA's comments highlight areas that may affect the willingness of member companies to participate in the program, that ultimate decision is entirely at the discretion of the individual operators of natural gas transmission pipelines.

INGAA supports voluntary measures to reduce methane emissions from Transmission and Storage (T&S) compressor stations and pipeline operations. INGAA developed and has proposed Directed Inspection and Maintenance (DI&M) guidelines for EPA's inclusion as a Best Management Practice (BMP) under the Methane Challenge program. Implementation of these DI&M guidelines has the potential to achieve significant emission reductions from existing T&S compressor stations that would not be achieved under existing regulatory programs (or the recently proposed OOOOa New Source Performance Standards). Including INGAA's DI&M as an approved BMP will encourage companies to participate in the voluntary Methane Challenge program.

INGAA urges EPA to accept the DI&M approach advocated by INGAA as a BMP for leak monitoring and repair. **INGAA's DI&M has the potential to address over 80 percent of leak emissions from natural gas transmission and storage compressor stations**.[2,3] (See Figures 1 and 2 on page 5 for illustration of the 80 percent). DI&M also can help to identify "super emitters"[4] that offer the best opportunity for cost-effective methane emissions reductions. Modification of the Methane Challenge to incorporate DI&M as a BMP would encourage gas pipeline participation.

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[2] EPA Natural Gas STAR, Lessons Learned, "Directed Inspection and Maintenance at Compressor Stations," EPA430-B-03-008 (October 2003); http://www.epa.gov/gasstar/documents/ll_dimcompstat.pdf
[3] Picard, D., 2005. In Proceedings: Modern Technologies Of Detection And Elimination Of Methane Leakages From Natural Gas Systems. Akademgorodok, Russia (2005).
[4] Recent literature has referred to these sources as "super emitters," "gross emitters," or "long tail" emissions, with the latter term based on the appearance of a cumulative distribution plot of emissions.

INGAA believes its DI&M meets the criteria for a BMP, and it recognizes that individual pipeline companies may choose to propose to EPA other arrangements governing the frequency of inspection and the criteria for repair.

EPA was not completely clear in the call for comments as to whether it would seek a Leak Detection and Repair (LDAR) program or might accept the interstate pipeline's DI&M as a BMP[5]. Should EPA expect use of a LDAR program in the Methane Challenge (as it proposed in the OOOOa or New Source Performance Standard) it would discourage program participation. Companies have two primary concerns about a traditional LDAR program:

1. Unnecessary costs associated with the frequency of monitoring and
2. The lack of operator flexibility to prioritize fixing leaks based on magnitude and risk.

LDAR works on the principal of robotically repairing leaks no matter how small or expensive rather than targeting repairs at the most common and serious leaks for maximum effect. By contrast, the DI&M approach focuses on finding and fixing 80 percent of the methane leaks from the T&S sector. It is common sense for EPA to use this DI&M approach as a BMP, especially since this is a program designed for existing sources.

Several INGAA member companies have participated actively in EPA's current Natural Gas STAR program and understand that flexibility is essential to a successful voluntary program that achieves meaningful reductions. Similarly, flexibility is critical for EPA's voluntary program to make significant methane reductions. Flexibility will afford operators the ability to focus resources on significant emission reduction opportunities in a cost-effective manner rather than following generically prescribed criteria. Accordingly, INGAA provides specific comments intended to enhance the incentives and avoid disincentives for companies to participate in the Methane Challenge program.

INGAA believes the most important aspect of a federal voluntary program is that the program remains truly *voluntary*. If EPA wants to ensure, as stated in the Proposed Framework that its Methane Challenge encourages "ambitious commitments" and "innovative approaches,"[6] then volunteering companies must be confident that they will not be penalized if they inadvertently underperform or fail to meet specific milestones or reduction goals. Further, volunteering companies must have assurances from EPA that their voluntary commitment to meet certain emission reduction targets does not create mandatory permit requirements once the voluntary program terminates.

Further, it is important to recognize that pipelines must, at times, emit methane through pipeline blowdowns to maintain and improve the safety of pipeline facilities. Specifically, in certain instances a pipeline operator must reduce the pressure within a pipeline and remove the gas in order to perform inspections and maintenance. In other instances, a pipeline operator must blow down gas to prevent a pipeline incident and ensure safety. Therefore, INGAA requests that EPA eliminate the presumption added on October 19 that program participants commit to reduce pipeline blowdowns by 50 percent and instead allow companies to decrease blowdown emissions

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[5] Footnote 17, page 17 of EPA Methane Challenge found at http://www3.epa.gov/gasstar/documents/methane_challenge_proposal_072315.pdf

[6] Proposed Framework at 5.

to the extent reasonably practicable, taking safety and other factors into consideration, without giving a percentage goal.

INGAA strongly encourages EPA to allow the companies to design their program participation with sufficient flexibility consistent with the Natural Gas STAR program. The details on flexibility are further addressed beginning on page 14. In particular, INGAA observes that some companies have other oil and gas sector segments in their businesses and may want to create different approaches for their different business segments that might go beyond the T&S sector.

II. DETAILED COMMENTS

A. Adopting INGAA's DI&M As a BMP Option Would Advance EPA's Goal of Reducing Emissions From the Largest Sources

A relatively small number of leak sources account for the vast majority of methane emissions in the T&S sector. The vast majority of the methane emissions are from reciprocating and centrifugal compressors and from tanks. EDF's February 2015 collaborative study with the Colorado State University (CSU) documents that a small number of leaks, termed, "super emitters" account for a large percentage of emissions from leaks. [7] These leaks have also been called either "gross emitters" or "long tail emitters." The CSU study concludes that, "…the highest emitting 10% of sites (including two super emitters) contributed 50% of the aggregate methane emissions, while the lowest emitting 50% of sites contributed less than 10% of the aggregate emissions."

INGAA members are committed through its DI&M to identify and reduce emissions from the largest emission sources. INGAA's DI&M is preferable to a conventional LDAR program as described by EPA in the proposed OOOOa rule because it targets the largest T&S emission sources. INGAA's DI&M focuses on compressor station equipment most likely to be the sources of the T&S sector's largest leaks. This approach allows pipeline companies to dedicate available resources to address the largest leaks. DI&M provides the ability to achieve reductions similar to leak detection programs while managing costs. EPA has said that they learned many things in response to its 2014 call for comments to its Methane White Papers and that it would be unnecessary to require program participants to include every methane source.

Figures 1 and 2 illustrate the Pipeline Research Council International's (PRCI) analysis of leak emissions using EPA's Subpart W data and supplemental data submitted by INGAA and PRCI. This analysis demonstrates that INGAA's DI&M will address 80 percent or more of the methane leak emissions at compressor stations.

Figure 1 (on page 5) shows leak emissions from the T&S sector by source category for 2011 reporting. Figure 2 shows the same information for 2012 reporting. The five categories of pipeline emissions include reciprocating compressors, centrifugal compressors, storage tank

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[7] Subramanian, R., et al., *"Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol"*, Environ. Sci. Technol., 49, 3252-3261, DOI: 10.1021/es5060258 (2015); http://pubs.acs.org/doi/pdf/10.1021/es5060258

(dump valve leakage), leaks in compressor units, and leaks in non-compressor units. For the four categories other than tanks, the total emissions are comprised of emissions from multiple sources, including:

1. Reciprocating compressors (typically released to atmosphere through elevated vents):
    a) Rod packing;
    b) Isolation valve; and
    c) Blowdown valve.
2. Centrifugal compressors (typically released to atmosphere through elevated vents):
    a) Wet seal degassing vent (this is more a vent source than a leak source, but is grouped with centrifugal compressor leak emissions for tracking purposes);
    b) Isolation valve; and
    c) Blowdown valve.
3. Compressor or non-compressor unit leaks generally are accessible at or near ground level for surveying. The total emissions estimate is based on emissions from the following five component types:
    a) Connectors;
    b) Valves;
    c) Open ended lines (OELs);
    d) Pressure relief valves (PRVs); and
    e) Meters.

The figures show each of the categories (i.e., the primary bullet in this list), as well as the emissions from the specific leak sources associated with each category (i.e., the sub-bullets in this list). The percentage of total leaks for each source or category is shown in the figures. Where total emissions for the five component types are a small overall contributor to leak emissions, the percentage for the total is shown rather than emissions by component types.

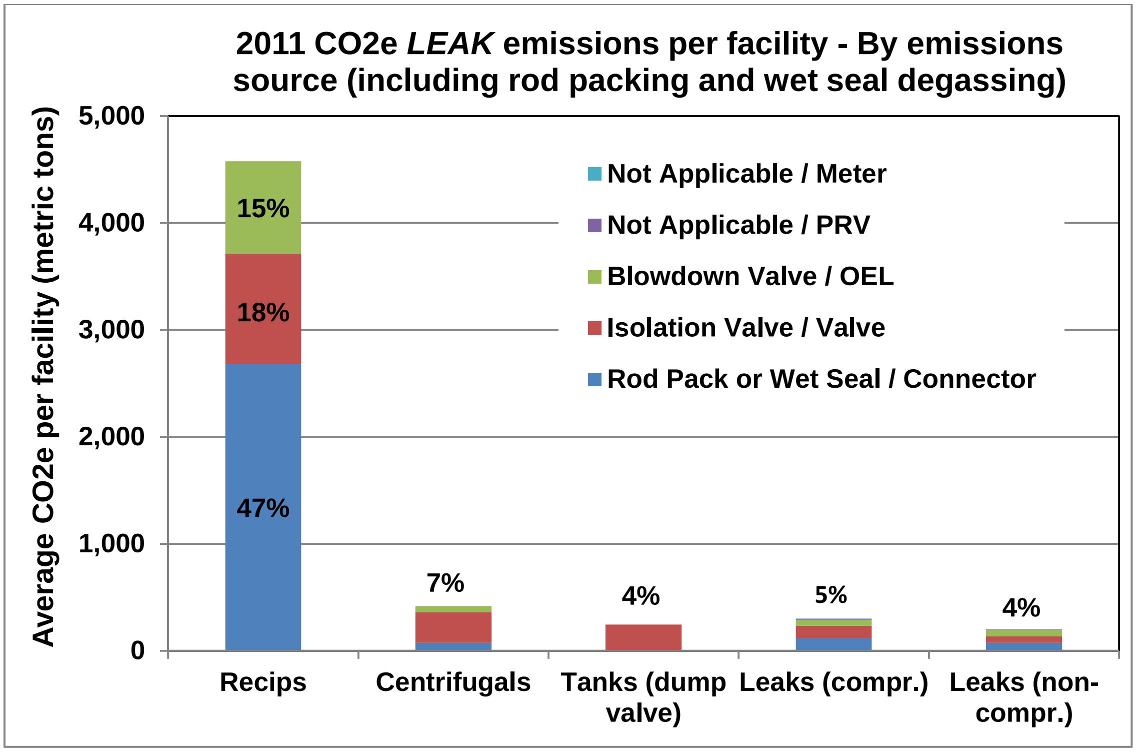

Figure 1. Leak emissions by category and emissions source for Subpart W reported emissions compiled for PRCI project – 2011.

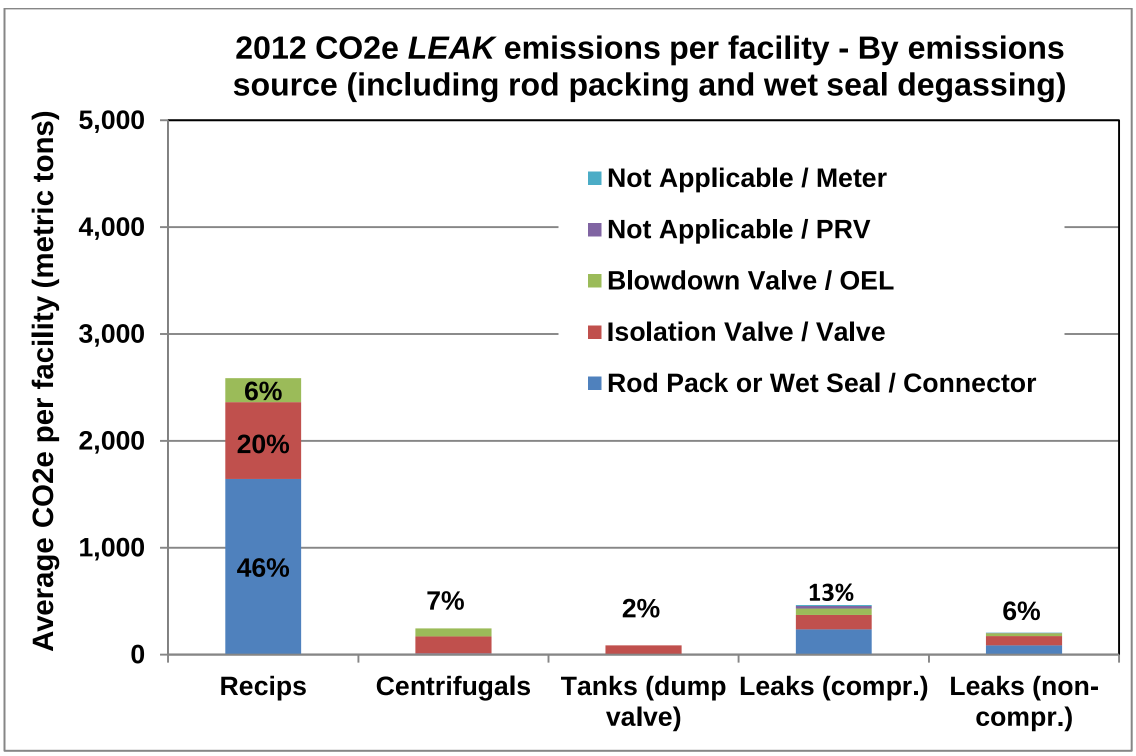

Figure 2. Leak emissions by category and emissions source for Subpart W reported emissions compiled for PRCI project – 2012.

The first three leak categories – reciprocating compressors, centrifugal compressors, and storage tank dump valves – are included in INGAA's DI&M. and the latter two are not included. In addition, the three categories included in INGAA's DI&M require surveying a limited number of potential leak sources – e.g., a reciprocating compressor (see items 1(a), 1(b) and 1(c) in the list above) will include rod packing leakage, two isolation valves (suction and discharge side of the compressor) and a blowdown valve. Thus, a limited number of vent lines need to be surveyed to identify leakage for the three sources in INGAA's DI&M. In contrast, the other potential leak sources (see five component types in items 3(a) through 3(e) in the list above) are comprised of *hundreds or thousands* of components throughout the compressor station that would require surveying.[8]

For 2011, reciprocating compressors, centrifugal compressors, and storage tank dump valves comprise 91 percent of the total leak emissions from the T&S sector. The three sources emitted 5,240 metric tons CO_2 equivalent emissions on average for all facilities in the PRCI dataset. The two leak categories not included in INGAA's DI&M (other equipment leaks in compressor or non-compressor units) comprise only 9 percent of the total T&S sector emissions and resulted in less than 500 metric tons of emission.

For 2012, total leak emissions are lower, which is likely due to repair of some of the larger leaks discovered in 2011 (e.g., reciprocating compressor leak emissions). Reciprocating compressors, centrifugal compressors, and storage tank dump valves comprise 81 percent of the total leak emissions from the T&S sector. The three sources emitted 2,915 metric tons CO_2 equivalent on average for all facilities in the PRCI dataset. The two leak categories not included in INGAA's DI&M (other equipment leaks in compressor or non-compressor units) comprise 19% of the total emissions, or approximately 665 metric tons.

INGAA's White Paper titled, "Directed Inspection and Maintenance for Reducing Leak Emissions from Natural Gas Transmission and Storage Compressor Stations: Greenhouse Gas Reporting Program Data Supporting a Focused Leak Mitigation Program" is submitted as an attachment to these comments (see Appendix) and provides supporting data to INGAA's conclusions regarding sources of T&S sector emissions. The White Paper (WP) demonstrates in greater detail that on a volume basis, the vast majority of emissions from natural gas transmission and storage operations are attributable to a relatively small percentage of leaks. As page 14 shows, the vast majority of the emissions (80 percent) are from a small number of leaks (20 percent or fewer). These "cumulative distribution" plots show the cumulative emissions associated with adding the emissions from each measured leak for reciprocating compressors (WP, Figure 4), centrifugal compressors (WP, Figure 5) and storage tanks (WP, Figure 6). As examples:

- There were approximately 950 "non-zero" measurements of reciprocating compressor rod packing leakage in 2011. About 10 percent of the leaks (by count) were responsible for 65 percent of the leak emissions; 22 percent of the leaks (by count) were responsible for 80 percent of the leak emissions.
- There were approximately 425 "non-zero" measurements of reciprocating compressor isolation valve leakage in 2011. About 15 percent of the leaks (by count) were responsible

[8] EPA's OOOOa model compressor station includes over 3,800 components. Table 5-11 from EPA's Background Technical Support Document indicates that model storage station has over 7,900 total components.

for 80 percent of the leak emissions; 27 percent of the leaks (by count) were responsible for 90 percent of the leak emissions.

- There were 122 "non-zero" measurements of centrifugal compressor isolation valve leakage in 2011. About 12 percent of the leaks (by count) were responsible for 80 percent of the leak emissions; 20 percent of the leaks (by count) were responsible for 90 percent of the leak emissions.

These assertions by INGAA are validated by EPA's Subpart W data. Although the entire EPA dataset includes additional facilities (and associated leak measurements) that are not included in the PRCI project data collected from its members, INGAA contends that EPA's review of the entire data set will result in similar conclusions.

For context on potential reductions, in EPA's Technical Support Document (TSD) for the recently proposed revisions to the oil [9] and gas NSPS, Subpart OOOOa, EPA references information from a Colorado rulemaking that estimates an LDAR program would achieve 40 percent to 60 percent reduction for an annual or quarterly survey frequency, respectively. The figures and discussion above show that over 80 percent of leak emissions are covered by focusing on the sources in the Subpart W program with a higher potential for large leaks – reciprocating compressors, centrifugal compressors, and storage tanks (leaking dump valve). For these categories, the White Paper figures discussed above show that a large percentage of the emissions are from 10 percent to 20 percent of the leaks. Thus, DI&M provides the opportunity for similar reductions as LDAR reductions as estimated from EPA's Subpart OOOO TSD.

DI&M capitalizes on the opportunity to achieve cost-effective and efficient emissions reductions with procedures that focus on repairing the largest leaks on a timely basis. The White Paper provides additional technical support and description of the figures and data discussed in these comments based on data and analysis from the PRCI project. The data from measurements conducted for the Subpart W program demonstrates that T&S leak programs, focusing on the emission sources in INGAA's DI&M can achieve significant reductions while focusing on a subset of potential leak sources and larger leaks from these sources. This approach supports allowing the T&S sector to use DI&M as a BMP to effectively address gross emitters.

EPA acknowledged DI&M as an established method for reducing the vast majority of compressor station leak emissions in an EPA STAR "lessons learned" document.[10] Consequently, there is a sound basis for recognizing DI&M as a BMP in the Methane Challenge.

As shown in the tables on page 5, INGAA's DI&M will address the same sources of methane emissions from natural gas compressors as the BMPs proposed by EPA in its Methane Challenge. DI&M leak surveys will focus on elevated vents associated with reciprocating compressors, centrifugal compressors, and storage tanks. For other equipment leaks not covered by DI&M, leak emissions are much smaller. Nonetheless, those leaks are still addressed through

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[9] EPA Docket Document Number EPA-HQ-OAR-2010-0505-5120. "Oil and Natural Gas Sector: Standards for Crude Oil and Natural Gas Facilities, Background Technical Support Document for the Proposed New Source Performance Standards, 40 CFR Part 60, subpart OOOOa." (August 2015)

[10] EPA Natural Gas STAR, Lessons Learned, "Directed Inspection and Maintenance at Compressor Stations," EPA430-B-03-008 (October 2003); http://www.epa.gov/gasstar/documents/ll_dimcompstat.pdf

Pipeline and Hazardous Materials Safety Administration (PHMSA) requirements, and facility approaches such as safety walk-throughs that use "audio-visual-olfactory" (AVO) approaches to identify and address leaks. Often, these leaks can be repaired easily (e.g., tighten a connector or valve bonnet) and are addressed through standard compressor station operations and management programs. These practices are a likely reason that the "other equipment leaks" are a relatively small contributor to total T&S leak emissions.

EPA BMP	**INGAA DI&M Guidelines as BMP**	**How DI&M Addresses Emissions**
Centrifugal Compressor – Wet Seal Degassing Vent	Centrifugal Compressor – Wet *or Dry* Seals	DI&M addresses centrifugal compressors with wet seals or dry seals. Need for mitigation depends on emissions rather than pre-determination that degassing vent is problematic.
Reciprocating Compressor – Rod Packing	Reciprocating Compressor – Rod Packing	DI&M may supplement prescribed maintenance interval with approaches such as condition-based maintenance.
Equipment Leaks	Equipment Leaks	DI&M covers many easy to repair leaks (e.g., AVO approach) and surveys focused on sources with potential for large leaks – e.g., compressor isolation valves and blowdown valves; scrubber dump valves.

The remaining leaks, resulting in significantly fewer emissions among a significantly larger source of emissions, are much less cost-effective or efficient to repair. Moreover, methane emissions would likely increase from pre-repair levels due to the fact that the pipeline would need to blowdown gas from the pipeline in order to conduct such repairs.

INGAA's key points are detailed in the following responses to EPA's specific questions set out in the Methane Challenge proposed framework (July 23 and October 19, 2015).

B. INGAA's Responses to EPA's July 23, 2015 Questions

EPA Question 1: Please indicate whether your company has specific interest in one of the commitment options presented, included the possibility or likelihood of your company marking that commitment.
INGAA response: INGAA believes that some member companies are likely to participate in the Methane Challenge; however, INGAA defers to its members companies to respond on an individual basis. INGAA believes that the program's disincentives must be addressed in order for participation to be broadly considered.

EPA Question 2: In addition to recognition through the Program, what are the key incentives for companies to participate in this Program? Should EPA offer some partners extra recognition, such as awards?
INGAA Response: INGAA believes EPA should incentivize participation by making the

program and BMP commitments flexible, and by ensuring reasonable reporting. INGAA believes the ability to participate in decision-making and to craft industry-lead voluntary guidelines rather than a prescriptive program is a key incentive to participation.

Specifically, INGAA requests that: (1) EPA should continue to allow participants to choose whether they wish to have one company within their corporate family or a number of affiliated companies participate in the Methane Challenge. (2) EPA should continue to provide participants the opportunity to select among the three proposed methane reduction opportunities (i.e., BMPs, ONE Future or EPA's third option of Emissions Reduction through the use of a common baseline). (3) EPA specifically lists DI&M as an approved BMP; (4) EPA should provide participants with some flexibility in their repair schedules based upon season, operating conditions and worker safety concerns. (5) EPA provide assurances that it will not penalize volunteering companies for failing to meet interim emissions reduction targets as long as overall reductions commitments in the MOUs are met. (6) EPA specifically assures companies that it will not modify or ask the states to modify Title V or other air permits prospectively to mandate emission reductions that had been voluntary commitments. (7) While INGAA realizes that EPA wants the reporting program to be transparent and to assure the public that methane reductions are verifiable and documented, INGAA also wants EPA to avoid any risks of disclosure of Confidential Business Information (CBI). Companies may need to work with EPA to ensure that they are not disclosing any CBI information on their own processes and related to non-T&S business units (such as in the upstream or gathering sectors).

INGAA believes that the greatest incentives to participation in the program would result from EPA's elimination of a presumption that T&S companies can reduce compressor station blowdowns by 50 percent or greater as covered in EPA's October 19, 2015 Supplementary Technical Information Document. (See INGAA's response to EPA's Supplemental Document Question 8 on page 19)

Expecting companies to reduce blowdown events and the resulting volume of methane by 50 percent is unrealistic. Blowdown events at compressor stations are not frequent but are undertaken as a public safety protection measure to purge natural gas (methane) from its pipelines in order to address a repair. The best example for blowdown necessity is that, like water pipelines in a residence, the water pipeline must have its water contents drained before a pipeline repair can be made by a plumber. In some pipelines there may be no opportunity to redeploy the natural gas to another line or to recompress quickly enough to undertake the pipeline repair. In some new compressor stations there may be opportunities to reduce the natural gas in a pipeline through either moving the natural gas to another pipeline, recompression or by use of some portable devices. However, there are many locations where an arbitrary expectation of methane reductions of 50 percent from blowdowns would simply not be feasible or achievable without risking public safety.

Another major disincentive is in including any presumption that T&S pipeline companies should place methane reduction measures ahead of public and worker safety in excavation activities. INGAA notes that Common Ground Alliance (CGA)[11] is committed to saving lives and preventing damage to underground infrastructure by promoting effective damage prevention

[11] http://commongroundalliance.com/about-us#sthash.ApSPzaxb.dpuf

practices. While INGAA may encourage companies to reduce methane through a variety of activities, excavation actions are inherently dangerous and those safety concerns trump any goal of reducing methane. It is also outside the scope of normal business for INGAA member companies to require their construction contractor company employees engaged in excavation activities to reduce methane while undertaking their primary mission. Further, documenting this action by a construction company and linking this back to the pipeline company is onerous and a distraction for the construction company. INGAA finds EPA's description about excavation a bit unclear as to whether EPA intended to include the T&S sector. EPA should make it clear that excavation does not apply to the T&S sector. INGAA offers no comments addressing excavation for other sectors.

EPA should clarify that company-provided data and information marked as Confidential Business Information ("CBI") will enjoy a presumption by the agency that the information is CBI and, therefore, be protected from production under the Freedom of Information Act. Further, EPA should clarify the interaction between the Methane Challenge and potential future regulations so that a company that makes early voluntary investments in emissions abatement is not penalized by early action if in fact any future regulatory program requires different types of investments or does not provide credit for earlier company reductions.[12] By doing so, EPA can convert what is currently a *disincentive* to participation into a positive incentive.

Accordingly, INGAA urges EPA to commit in the Methane Challenge that any subsequent regulation of methane emissions from existing sources will set the baseline at the start of the Methane Challenge program and will provide full credit for any emissions reductions achieved under the Methane Challenge program. Such a non-binding statement of policy about the content of a future proposed rule is consistent with EPA's legal obligations for rulemaking under the Clean Air Act.

INGAA also suggests that EPA provide a process for companies to take credit for methane reduction under the Methane Challenge in the future for actions not yet identified or approved by EPA under the current BMPs. These might include, but are not limited to, the use of new technologies that might be commercially demonstrated or more cost effective in future years that are not currently available or affordable.

EPA Question 3: EPA is proposing to launch the Program with charter partners by the end of 2015, but will welcome new partners on an ongoing basis. Please comment on the likelihood of your company committing to join this Program as a charter partner, or at a future date.

INGAA Response: INGAA defers to its members companies to respond on an individual basis. Nonetheless, INGAA notes that given the timing of EPA's supplemental documents that detail its proposed program and the announcement of the Memorandum of Understanding and Implementation Plan only days before the deadline for comments make it very challenging for INGAA to comment fully. Further companies might find it difficult to make a commitment to the

[12] INGAA does not advocate future mandatory regulations under Section 111(d) of the Clean Air Act for reducing methane emissions from existing sources, because a well-crafted voluntary program, with sufficient flexibility, will achieve the same goal more efficiently. This is consistent with EPA's statements that they have no plans to propose a separate rulemaking under Section 111 (d) of the Clean Air Act.

Methane Challenge by 4Q 2015 given that the last two documents were only announced on November 9. EPA should consider allowing companies to enter the Methane Challenge after 2015, or to expand the program to other corporate business units, after the initial deadline rather than require a one-time sign-up deadline.

EPA Question 4: For the BMP option, how can EPA encourage companies to make commitments for sources for which they have not made significant progress in implementing mitigation options? In other words, how can companies be encouraged to participate beyond the sources for which they have already made significant progress?
INGAA Response: INGAA believes that it is unrealistic to expect participating companies to expand their commitment to additional business units or pipelines or additional emission sources (e.g., adopt additional BMPs) until they have had several years' experience with the Methane Challenge. EPA should provide participating companies an opportunity to gain experience operating under the framework of the Methane Challenge before expecting parties to commit to additional reductions prior to 2022 or the five year compliance period.

INGAA believes that "source" could mean a facility or additional emission sources within the facility. For example a participant could elect to implement the pneumatic BMP but not other BMPs for any other "sources" at that company.

The BMP option provides companies the ability to pick the BMP, or multiple BMPs, that work best for a particular company. INGAA supports EPA's proposal to allow submission of additional BMPs at a future date whether from INGAA, another industry association, or through individual companies. This allows companies to submit new innovative measurement, monitoring or emission reduction technologies for inclusion in the Methane Challenge program as those technologies or practices are developed.

EPA Question 5: **Please provide comments on the sources and corresponding BMPs that are provided in Appendix 2, including any recommended additions, deletions, or revisions.**
INGAA Response: As explained at the beginning of the comments, INGAA recommends that DI&M be included as a BMP. As already explained, INGAA's DI&M Guidelines would focus on key equipment that address 80 percent or more of methane leak emissions at compressor stations based on 2011 and 2012 data from Subpart W surveys. In addition, the vast majority of emissions from the focused list of sources in the INGAA Guidelines are attributable to approximately 10 to 20 percent of leaks from these key sources. See tables provided in IES Paper Appendix A.

INGAA appreciates EPA's consideration of DI&M as a BMP for the T&S sector as referenced in footnote 17 of the Methane Challenge. INGAA strongly recommends including DI&M, based on the INGAA DI&M Guidelines provided to EPA and discussed in recent meetings.

These findings are documented in a white paper that INGAA is providing as an appendix to these comments. Based on a review of EPA GHG reporting program (GHGRP) data, as well as supplemental data collected in a project undertaken by Pipeline Research Council International, the white paper concludes that the sources included in the INGAA DI&M Guidelines would address 80 percent or more of methane leak emissions at compressor stations. See table on page 30.

Other examples in the literature confirm the general trend that a relatively small percentage of leaks are responsible for the vast majority of leak emissions. A 2014 paper[13] that compiled and analyzed a number of technical papers from the last 20 years provides several examples. The collaborative EDF-Colorado State University shows similar findings. INGAA's White Paper[14] further demonstrates that a relatively small percentage of leaks account for the vast majority of emissions from natural gas transmission and storage operations.

INGAA's DI&M capitalizes on this opportunity to achieve cost effective and efficient emissions reductions with procedures that focus on repairing the largest leaks on a timely basis.

EPA acknowledged DI&M as an established method for reducing the vast majority of compressor station leak emissions in its EPA STAR "Lessons Learned" document[15]. Consequently, there is a sound basis for recognizing DI&M as a BMP in the Methane Challenge. EPA referenced INGAA's DI&M approach as BMP on page 17[16] by stating "EPA has received, and is considering, a proposal to structure BMP coverage of natural gas transmission and storage compressor stations as a Directed Inspection and Maintenance Program". INGAA seeks EPA's adoption of this BMP for those companies that wish to use it in their participation.

DI&M is preferable to conventional leak detection and repair (LDAR) programs with an approach that focuses on compressor station equipment more likely to be the source of a large leak, and prioritizes repairing those larger leaks. DI&M provides the ability to achieve similar reductions while better managing costs. The discussion above (see Figures 1 and 2 and related discussion) shows that significant reductions can be realized through DI&M. The costs savings are obvious. As discussed above, DI&M includes lower survey costs because the survey portion of the program is limited to select equipment with a higher potential for larger leaks. Repair costs are also lower because conventional LDAR requires repair of *all* leaks while DI&M focuses on larger leaks. While existing programs (e.g., PHMSA requirements, AVO walk-throughs for safety) will find many of the smaller leaks, LDAR would still trigger additional leak repairs for very minor leaks, thus resulting in higher costs. Increased emissions could also result if station piping blowdowns are required to accomplish the repair.

Figures 1 and 2 demonstrate through Subpart W data and pipeline company data for both 2011 and 2012 that more than 80 percent of the leak emission which come from three source categories-reciprocating compressors, centrifugal compressors and tanks.

As shown in Figures 1 and 2 (pages 5 and 6) and discussed in the related text as well as the attached White Paper, data from a PRCI project to collect and analyze members' data from

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[13] Brandt, A.R., et al., *"Methane Leaks from North American Natural Gas Systems"*, Science, 343, 733-735 (2014).
[14] Subramanian, R., et al., *"Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol"*, Environ. Sci. Technol., 49, 3252-3261, DOI: 10.1021/es5060258 (2015); http://pubs.acs.org/doi/pdf/10.1021/es5060258
[15] http://www3.epa.gov/gasstar/documents/ll_rodpack.pdf
[16] http://www3.epa.gov/gasstar/documents/methane_challenge_proposal_072315.pdf

Subpart W of the GHGRP shows that for the leak emissions sources, more than 80 percent (2012 data) to 90 percent (2011 data) of leak emissions are associated with three source categories – reciprocating compressors, centrifugal compressors and tanks. These sources would be addressed by the DI&M guidelines because these sources include components (e.g., isolation valves, rod packing, dump valves) with the greatest potential of being a large emission source. The DI&M guidelines address these sources through surveys that focus on a limited number of components with the greatest potential for large leaks. The leaks from other components require surveying hundreds or thousands of additional components throughout a facility, and the total emissions from those hundreds of potential leak sources comprise about 9 percent (2011 data) to 19 percent (2012 data) of total leak emissions. Requiring hundreds or perhaps a thousand of additional component surveys across a facility is not cost effective.

INGAA and PRCI members that submitted GHGRP data provided the PRCI project with Subpart W data along with related supplemental data on equipment, operations, and measurement methods. It includes well over half of the sources that reported to EPA. The emissions reported under EPA's Subpart W of the GHGRP provides a good basis for assessing the potential effectiveness of DI&M as a BMP because it includes far more facilities than included in other studies that assess leak emissions, and the DI&M guidelines focus on sources that require direct measurement under Subpart W (compressors, storage tanks).

In addition, Figures 1 and 2 (on page 5) and discussion above clearly demonstrates that reciprocating compressors are the largest sources of T&S methane emissions, and collectively with the other two source types measured in Subpart W (centrifugal compressors and storage tanks) 80 percent or more of emissions are addressed. Consequently, DI&M offers a BMP for addressing more than 80 percent of the methane leak emissions from compressor stations based on 2011 and 2012 PRCI data.[17]

The conclusion that a relatively small number of leaks account for the vast majority of methane emissions from reciprocating and centrifugal compressors and tanks is supported by the data in the White Paper. Thus, the GHGRP data reinforces the foundation for INGAA's development of DI&M as an alternative to LDAR: the vast majority if emissions (80 percent or more) are from a small number of leaks (e.g., 20 percent or fewer). The White Paper supports this conclusion with cumulative distribution plots of individual sources for reciprocating compressors and centrifugal compressors, and with plots of measurements from tanks. The GHGRP data confirms the premise for DI&M as an efficient strategy for reducing T&S sector methane emissions.

<u>EPA Should Provide Participating Companies the Flexibility to Define the Scope of BMP Implementation within Their Operations</u>

The current proposal requires a company-wide commitment to implement the BMP(s) selected by the reporting entity. In the proposal, EPA sought to find a balance between covering significant portion of the operations and widespread implementation of best practices. INGAA is

[17] The PRCI project is also compiling data for 2013, but the analysis of Subpart W and supplemental data is not complete.

concerned that a BMP might not achieve cost-effective emissions reductions if it must be implemented across the entire company. INGAA recommends that participating companies have the flexibility to define the scope of implementation of the BMP within its operations. For example, a BMP might be appropriate for implementation at only 75 percent of an operation because implementation at the remaining 25 percent of the operation might not achieve meaningful reductions. In such a case, a company should have the flexibility to replace the BMP with an alternative BMP that achieves comparable or better emission reductions. The CSU paper from the EDF-industry study discusses relative emission results in this manner – i.e., 10 percent of the facilities are responsible for more than 50 percent of methane emissions, and 50 percent of the lowest emitting facilities are responsible for less than 10 percent of emissions. This also would provide the opportunity to achieve cost-effective emission reductions as new leak identification or mitigation technologies are developed and incorporated within a participating company's implementation plan. As new technology is developed, opportunities may also be provided to achieve effective reductions at fewer sites. For example, figures above and in the White Paper show that reciprocating compressors are an important source. Advances that focus on reducing those emissions could support implementing a BMP for facilities with reciprocating compressors and not facilities that exclude those compressors.

Since the emissions and emission reductions will be reported to EPA, this approach would ensures transparency and continued progress in achieving methane emission reductions.
An example is that routing gas from rod packing vents to re-use is only viable at stations where other equipment is running and available to use the recovered gas. Further, pipeline blowdown recovery is another BMP that cannot be implemented for all maintenance activities due to customer scheduling demands, cost, and safety limitations. Companies should have the flexibility of not implementing the BMP at 100 percent of their facilities and/or to choose an alternative BMP that achieves meaningful emission reductions.

<u>While Blowdowns Can Be Minimized at 50 Percent Reduction of Blowdowns Is Not Achievable in All Cases</u>

Pipeline companies must have the ability to blowdown pipeline segments for public safety, and pipeline integrity purposes. PHMSA regulations[18] and initiatives to improve pipeline safety make it necessary for pipeline operators to blow down natural gas from a pipeline to either reduce the pressure within a pipeline or to evacuate the pipeline segment completely to perform inspections, maintenance and, in limited instances, to ensure safety in the event of an incident. INGAA supports minimizing pipeline segment blowdowns as a BMP. INGAA, however, is concerned that the BMP, as proposed, would apply to all pipeline segment blowdowns, except in emergencies. INGAA recommends that EPA redefine the BMP to "minimize pipeline segment blowdowns for maintenance activities."

<u>INGAA Believes That Pipeline Companies Must Be Able To Blowdown Pipeline Segments for Public Safety and Pipeline Integrity Purposes</u>

In addition, it is neither practical nor economic to install portable flares at all compressor stations to combust the residual gas once the operating pressure has been reduced using existing or

[18] 49 C.F.R. Sections 101, 102 and 103.

temporary compression. INGAA believes that reducing the operating pressure to the extent feasible using existing or temporary compression should be adequate for this BMP.

EPA Question 6: Please comment on the proposed definitions on the companies or entities that will make BMP commitments, per Appendix 3.

INGAA Response: INGAA agrees that reporting by an individual inter- or intra-state transmission pipeline system company is reasonable. However, for companies with some combination of production, gathering, processing, transmission, storage, and distribution operations, a more comprehensive, corporate-wide approach should remain an option. Reporting by the individual inter- or intra-state transmission pipeline system company is consistent with the current GHGRP reporting structure. INGAA believes that each company should determine the scope of the reduction measure and Methane Challenge participation level including whether a single pipeline, business unit or entire corporation participates.

INGAA also encourages EPA to provide the opportunity for companies to participate at the parent company level by combining multiple industry segments under the same parent company. This would provide the same flexibility as the One Future option.

EPA Question 7: Is a 5-year time limit to achieve BMP commitments appropriate? If not, please provide alternate proposals. Would a shorter time limit encourage greater reductions earlier?

INGAA Response: INGAA believes that the five-year period proposed by EPA for implementing BMPs or other program commitments (e.g., ONE Future intensity reductions, etc.) is reasonable. INGAA does not believe it is reasonable to expect achievement of the commitments in less than five years. It is important to recognize that companies likely will not be able to implement their commitments fully on day one, or even in year one. For example, pipeline companies likely will need time to train staff, hire third party contractors (to implement LDAR or DI&M program, to develop internal processes for pipeline pumpdowns and other recovery activities, to identify, to establish new maintenance schedules for rod packing replacements, etc.). Certain reduction measures might require one time replacements of equipment (e.g., pneumatic devices) while others might involve longer-term commitments (e.g., equipment component monitoring and repair programs, minimization of pipeline segment blowdowns, etc.). Memoranda of Understanding (MOUs) should reflect individual company milestones and final action dates. While many reduction measures can take place within the five years proposed by EPA, INGAA recommends that EPA not limit the Methane Challenge to a five year compliance period when a company may have reasons why it cannot complete the reductions within five years INGAA recommends that participating companies have a similar option addressing technical feasibly under the BMP option, where a progress update can be provided within 5 years but that complete implementation of the BMP be achieved within 10 years (i.e., by 2025).

EPA Question 8: Should EPA offer the Emissions Reduction (ER) approach? If so, please provide specific recommendations for ways that EPA could address the implementation challenges outlined in this document. What is the minimum target company-specific reduction level that should be set for participation in this option? Would your company use this option if it were offered?

INGAA Response: INGAA supports EPA offering the ER approach as a means to encourage greater participation. EPA should maintain flexibility for each company to define the reduction goals that make sense for that individual company or entity. INGAA does not prefer ER over the other two options but believes it gives more choices to potential program participants.

EPA Question 9: To what extent is differentiating the voluntary actions from regulatory actions important to stakeholders? What are the potential mechanisms through which the program could distinguish actions driven by state or federal regulation from those undertaken voluntarily or that go beyond regulatory requirements?

INGAA Response: INGAA believes the most important aspect of a federal voluntary program is that the program is truly *voluntary and flexible*. As stated in response to question 2, companies must have some ability to craft the best approach for participation. If EPA wants to ensure, as stated in the [Proposed Framework] that it Methane Challenge encourages "ambitious commitments" and "innovative approaches,"[19] then volunteering companies must have specific assurances that they will not face penalties under the program. To this end, INGAA urges EPA to clearly indicate that, in the event that there are discrepancies about a company's performance under the Methane Challenge or if a company wants to end its participation; such actions will not be enforceable or punishable in any way under the Clean Air Act.

INGAA also urges EPA to make clear that Methane Challenge commitments have no place in Title V permits, and that the Agency will neither issue nor approve a Title V permit (or any other regulatory permit) that requires inclusion of Methane Challenge commitments.

In addition to emphasizing that participating companies' commitments should not be included in Title V or other regulatory permits, EPA should clarify that the Agency will only use Methane Challenge data supplied by participating companies to assess performance under that program. We urge EPA to make clear that it will not use Methane Challenge data (including DI&M or other data) for purposes of evaluating compliance with *other* programs or regulations.

EPA Question 10: EPA plans to leverage existing reported data from GHGRP (Subpart W) and supplemental data from companies to EPA. Would e-GGRT system be appropriate mechanism to collect the voluntary supplemental data?

INGAA Response:

The Methane Challenge reporting system will need to interface with the current GHGRP reporting system (e-GGRT) and coordinate with reporting under the existing Natural Gas STAR program. INGAA believes it is important to keep the data separate and maintain different sets of data for the voluntary program and the GHGRP. INGAA members are concerned that too many supplemental reporting requirements beyond the current GHGRP could deter participation in the Methane Challenge Program. The e-GGRT system may be an appropriate mechanism for reporting under the Methane Challenge Program, but voluntary data should be reported separately from the mandatory data and clearly labeled. INGAA believes that in order to maximize participation, the reporting system must be easy to use and confidential data must remain confidential. The reporting requirements should not be overly burdensome or companies may be deterred from participating in the program.

[19] Proposed Framework at 5.

INGAA respectfully requests an opportunity to review and further comment on the reporting structure once it has been developed and proposed by EPA.

EPA Question 11: Would companies be willing and able to make commitments related to emissions sources where EPA has proposed, but not finalized, new GHGRP Subpart W requirements?
INGAA Response: INGAA companies will need to evaluate a more detailed proposal from EPA regarding supplemental data requirements under the Methane Challenge program, both for emission sources similar to those reported under the GHGRP, as well as for new emission sources, such as pipeline emissions and the gathering and boosting segment, which are not yet a part of the GHGRP.

EPA Question 12: EPA seeks feedback on potential mechanisms for encouraging continued, active participation in Program once a company's initial goals have been achieved.
INGAA Response: INGAA believes that the best encouragement for continued and active participation is for EPA to recognize accomplishments in the MOUs with individual companies. INGAA defers to individual company participants for feedback on other mechanisms for encouraging active participation.

As new technologies are developed and commercially deployed, EPA should encourage the implementation of new BMPs, if these technologies are commercially demonstrated, widely deployed and cost-effective.

EPA released its model MOU and Implementation Plan documents less than a week from the deadline for the Methane Challenge Comments with a separate deadline of November 20, 2015. INGAA will not be able to provide comments back on those two documents as soon as November 20th because INGAA and many member companies will be attending a four day EPA meeting on methane in Pittsburgh, PA. INGAA believes it is regrettable that EPA did not issue all documents relevant to Methane Challenge in July and provide at least 60 days for comments on all documents and materials. In fact, INGAA requested a minimum of 30 days for filing comments after all Methane Challenge documents were publicly available. INGAA retains the right to file additional comments after Nov. 20, 2015 to address any additional concerns with those documents.

As already stated in response to questions 2 and 9, INGAA believes that companies should have the ability to participate in the decision-making and to craft industry-lead approaches that allow for flexibility. Voluntary programs are preferred over prescriptive regulatory requirements.

EPA Question 13: EPA is proposing to call this new voluntary effort the "Natural Gas STAR Methane Challenge Program", and welcomes comments and suggestions on this name.
INGAA Response: INGAA believes the name is suitable.

C. INGAA's Responses to EPA's October 19, 2015 Questions

EPA Question 1: Are potential partners interested in reporting measured methane emissions for any sources that currently don't include measurement in the quantification options? Please comment on this and, if so, provide information on recommended measurement protocols for sources of interest.
INGAA Response: Because the Methane Challenge program is a voluntary program intended specifically to achieve real and quantifiable methane reductions while minimizing the reporting burden on the partner companies, the additional measurement or data elements beyond those specified under the GHGRP or in the Methane Challenge Technical Support documents would only add more reporting burden to participating companies without providing any information that would be considered relevant for demonstrating methane reductions.

EPA Question 2: Should intermittent pneumatic controllers be included in the Pneumatic Controllers source? EPA seeks recommendations on whether and how to include intermittent controllers.
INGAA Response: Intermittent pneumatic controllers should not be included as a source. Intermittent pneumatic controllers are used to assure safe operation of critical valves and other compressor station components that must operate in emergency situations. Intermittent pneumatic controllers operated by natural gas pressure provide greater reliability and safety than alternative energy driven devices. Companies should be allowed to include reductions from the replacement of intermittent pneumatic controllers if these controllers are replaced utilizing the existing BMP.

EPA Question 3: For Tanks, EPA seeks comment on whether additional elements collected under GHGRP should be considered for tracking purposes for the Methane Challenge Program.
INGAA Response: With the exception of the data elements already listed on the table provided on Pages 7 and 8 of the Methane Challenge Supplementary Technical document, INGAA does not see the need to require the reporting of any additional data elements collected under the GHGRP for the applicable facilities. Because the Methane Challenge program is a voluntary program intended specifically to achieve real and quantifiable methane reductions while minimizing the reporting burden on the partner companies, the additional data elements specified under the GHGRP would only add more reporting burden to the companies without providing any information that would be considered relevant for demonstrating methane reductions.

EPA Question 4: What types of situations require operators to vent to the atmosphere instead of capturing emissions during liquids unloading? How could this information best be captured in the reported data?
INGAA Response: The liquids unloading provisions do not pertain to the T&S sector.

EPA Question 5: For liquids unloading, are there additional supplemental data elements or quantification methods needed to demonstrate that operators are minimizing emissions during liquids unloading?
INGAA Response: The liquids unloading provisions do not pertain to the T&S sector.

EPA Question 6: EPA seeks feedback on methodologies for calculating and tracking centrifugal compressor seal oil degassing and reciprocating compressor rod packing methane emissions for the following operational situations:

a. **Compressors that route seal oil degassing/rod packing vents to manifolded vents that include sources other than seal oil degassing (e.g., blowdown vents) or seal oil degassing/rod packing emissions from multiple centrifugal compressors.**
b. **Compressors that route seal oil degassing/rod packing vents to flare, a thermal oxidizer, or vapor recovery for beneficial use other than as fuel.**

INGAA Response: INGAA's members represent the vast majority of the natural gas pipeline operators in the U.S. Installation and operation of vapor recovery systems, thermal oxidizers or flares for seal oil degassing and rod packing vents is not a common practice within the natural gas transmission and storage. This technology may be applied in limited situations (e.g., Alaska operations), but it is not a typical industry practice. Rather, this technology is not yet deemed to be a proven technology for the transmission and storage sector.

EPA Question 7: EPA seeks feedback on methodologies for calculating methane emission reductions for centrifugal compressors that convert from wet seals to dry seals.
INGAA Response: INGAA supports the option to include methane reductions when converting to dry seals during centrifugal compressor upgrade or routine maintenance. INGAA recommends use of the Subpart W wet and dry seal emission factors for calculating the associated emission reductions. Wet seal emission factors are available in current Subpart W reporting methodologies. Companies would simply report the number of wet seal to dry seal conversions covered under the program and the associated methane emission reductions. INGAA also recommends that EPA leave flexibility for a "before" and "after" measurement should a T& S company want to use a different reduction factor.

EPA Question 8: For transmission and distribution blowdowns, EPA requests feedback on the proposal of 50% as the minimum reduction percentage commitment, and whether the minimum commitment should be adjusted to serve as an appropriate stretch goal for partner companies. Is the proposed methodology for calculating potential emissions from this source appropriate? The proposed methodology assumes full evacuation of the pipeline to atmospheric pressure; are there circumstances in which companies don't lower pipeline pressure all the way to atmospheric levels, such that using this basis for calculating potential emissions could overstate potential emissions?
INGAA Response: INGAA supports voluntary measures to reduce methane emissions from pipeline blowdowns. Pipeline segment blowdowns are required to perform maintenance, testing, pipe replacements and for safe pipeline operations. Specific Pipeline and Hazardous Materials Safety Administration (PHMSA) regulations[20] require pipeline blowdowns for class location changes (that is, population increases in the vicinity of the pipeline above specified thresholds) and hydrostatic testing (testing pipe using water under high pressures) and for other pipeline safety purposes. The ability to reduce the pipeline pressure to minimize blowdown emissions is limited by the pipeline configuration (single pipeline or multiple pipelines adjacent to each other), available compression (either existing pipeline compression or temporary rental compression), timeframes required to draw down the pressure, impacts to customers, weather and multiple other factors. EPA must be cognizant of the fact that pipeline operators frequently cannot always control the timing and need for blowdowns in emergency situations to maintain pipeline integrity and assure safety. Pipeline operators must evaluate and address all of these

[20] 49 C.F.R. Parts 191, 192 and 193

factors in determining whether a pipeline can be drawn down or must be blown down. Even when a pipeline is drawn down, some residual gas remains in the pipeline that must ultimately be blown down. Therefore, the ability for any pipeline operator to achieve a specific minimum blowdown reduction goal will vary. Therefore, establishment of a specific minimum percentage reduction threshold could deter companies from participating in the Methane Challenge program. Rather, the 50 % reduction should be an overall program goal, but not a specific BMP or company requirement for participation.

Emission reductions can be calculated based on pipeline operating pressures, temperatures and other engineering factors. For pipelines that are drawn down but have a residual gas volume that is subsequently vented to atmosphere, the emission reduction calculation is the difference from the volume of gas at operating pressure minus the residual volume vented to atmosphere. For example, a pipeline may have an operating pressure of 1000 psi and is drawn down using compression to 300 psi. The emission reduction could be calculated assuming a 700 psi reduction volume using the same engineering calculation methodology.

As stated above, PHMSA regulations require pipeline blowdowns for pipeline integrity and public safety purposes. For example, one INGAA member company currently has to blowdown an average 8 to 10 segments per year under PHMSA's regulations for class location changes. *See* 49 C.F.R. § 192.611. Collectively, upgrading 10 segments of pipeline per year would result in approximately 200 million cubic feet (91,300 metric tons of CO_2e) of methane emissions.

INGAA member companies operate approximately 90 % of the nation's transmission lines, so nationwide the amount of methane released due to unnecessarily upgrading pipelines is significant. Instead, if PHMSA would adopt limitedly revised regulations allowing for integrity management in lieu of pipeline replacement, these tons of methane could be preserved each year. Revisions to provide an alternative to pipe replacement under the PHMSA class location rules to reduce pipeline blowdown should be promoted in lieu of a an extensive NSPS regulatory program imposed by EPA. Because such blowdowns are not required for safety, but instead are driven by existing regulations (as described above), the Obama Administration should adopt limited revisions under PHMSA's regulatory program to reduce the frequency of those blowdowns and still attain its goal of reducing methane emissions. Implementation of pipeline integrity management practices to reduce unnecessary blowdowns results in a win-win for pipeline safety and the environment.

EPA has called for comments on the supplemental document that included an expectation that for participants in Methane Challenge to reduce blowdowns by 50%. Most importantly, INGAA believes the greatest incentive to participate in the program would result in EPA's elimination of a presumption that T&S companies can reduce blowdowns by 50% of greater. Expecting companies to reduce blowdown events and the resulting volume of methane by 50% is unrealistic. Blowdown activities are undertaken as a part of a company's safety management program or required maintenance activities. The intent of a blowdown is to purge the methane from the pipeline, similar to water in a residential water pipeline, and that pipeline must have the water removed before a pipeline repair can be made by a plumber.

In some natural gas pipeline system there may not be an opportunity to transfer the natural gas (methane) from one pipeline to a secondary pipeline which could elevate the need for a blowdown. Blowdowns along the pipeline are infrequent because of the improvement in pipeline repair techniques. In comparison, compressor station blowdowns occur on a more regular basis for maintenance activities. Companies are currently working on best management practices to mitigate the amount of methane released during these maintenance activities. There are many locations where an arbitrary expectation of methane reductions of 50% from blowdowns would simply not be feasible or achievable without risking public safety.

EPA Question 9: For distribution mains, EPA requests feedback on the proposed percentage replacement rates, which include a new proposed category for companies with an inventory of >3000 miles of cast iron and unprotected steel mains.
INGAA Response: These provisions do not pertain to the T& S sector.

EPA Question 10: EPA seeks feedback on the proposal to use the plastic pipe EF for "Distribution Mains – Cast Iron or Unprotected Steel with Plastic Liners or Inserts" and "Distribution Services – Cast Iron or Unprotected Steel with Plastic Liners or Inserts."
INGAA Response: These provisions do not pertain to the T&S sector.

EPA Question 11: For distribution mains and services, should "vintage" plastic pipe or "Century" plastic pipe be included with cast iron and unprotected steel in this category (Aldyl A and LDIW Aldyl A Polyethylene gas piping manufactured from 1965 through 1972 and plastic piping extruded by Century Utility Products Inc. from Union Carbide Corporation's DHDA 2077 manufactured between 1970 and 1973 respectively)? In particular, EPA seeks input on whether companies have sufficient available activity data (e.g., known inventories of vintage plastic pipe and annual information on plastic pipeline material) such that they can commit to and track replacement levels, and if so how emissions of this type of pipe should be quantified (e.g., are material- or age-specific emissions factors available?).
INGAA Response: These provisions do not pertain to the T&S sector.

EPA Question 12: For cast iron services, EPA seeks comment on how to quantify methane emissions, and requests quantification methodology suggestions, including any available data.
INGAA Response: These provisions do not pertain to the T&S sector.

EPA Question 13: For distribution mains, EPA seeks feedback on whether to include as a mitigation option use of internal or external joint sealants for cast iron pipes greater than 20" in diameter. In particular, EPA seeks feedback about the ability to implement other mitigation options for these pipes (e.g., slip-lining), which reinforce the joints as well as the pipeline. EPA requests commenters to provide relevant supporting data with their response, if available.
INGAA Response: These provisions do not pertain to the T&S sector.

EPA Question 14: For excavation damages, EPA seeks comment on whether to limit the scope of this source to pipe operating at 15 psi or greater, or whether it should cover excavation damages on all pipe.
INGAA Response: See response to Question 8.

EPA Question 15: Because many excavation damages are technically out of the control of companies, EPA is proposing company-specific goal setting to participate in the Program. We request feedback on this approach, in particular whether companies would be able to set emission reduction targets versus other targets (e.g., reducing number of damages, reducing average shut-in time for all damages, other qualitative targets).
INGAA Response: See response to Question 8. Since excavation damages are outside the control of pipeline operators, it would be impossible to set company goals and emission reduction targets. Pipeline operators must implement immediate corrective actions to address excavation damage and emergency situations in accordance with PHMSA regulatory requirements and to assure public safety.

EPA Question 16: EPA requests feedback on how to quantify methane emissions/gas releases from excavation damages. Is there publically available data on recommended calculation methods for quantifying emissions from this source? Are there any circumstances under which it would be appropriate to use an emission factor (e.g., GRI/EPA or Lamb et al.)?
INGAA Response: Refer to comments in Question 8. Since excavation damages are outside the control of pipeline operators, it would be impossible to set company goals and emission reduction targets.

EPA Question 17: The Natural Gas STAR Program Annual Reporting Forms specify Sunset Dates (the length of time a technology or practice can continue to accrue emission reductions after implemented) for mitigation options (http://www3.epa.gov/gasstar/tools/program-forms.html) Should the Methane Challenge Program create a similar structure to establish Sunset Dates for designated mitigation options?
INGAA Response: INGAA does not support a Sunset Date. Emission reductions should be available throughout the length of the Methane Challenge commitment period.

EPA Question 18: The Methane Challenge Program seeks to stimulate new action to reduce methane emissions while also recognizing past actions undertaken by partners. For some sources, such historic action will be clear through proposed reporting (e.g., facilities that have converted high-bleed pneumatic controllers will show a low number of high-bleeds relative to low-bleed and zero emitting controllers). For other sources, such as cast iron pipe, a low level or nonexistent cast iron could reflect a historic replacement program or the fact that the facility never had such pipe. For practice-based programs, such as that proposed for excavation damages, companies may already have taken steps to reduce damages such that they cannot expect to achieve significantly lower levels. Should the Methane Challenge Program create a mechanism to specifically recognize historic action for certain sources? If so, how could the Program recognize such previous action (for

example, by allowing these companies to join the Program and collecting and posting relevant details on previous action prior to joining the Program)?
INGAA Response: If a company desires to submit historic reductions, the company should report them under the existing Natural Gas STAR program. EPA should provide a mechanism for member companies to report historic emissions reductions from a BMP. Companies can use the same data elements to report past emissions reductions, which can be identified as occurring prior to the start of the Methane Challenge commitment.

III. Conclusion

Addressing methane through a voluntary program is preferred over a regulatory system under section 111(d) of the Clean Air Act (or as those measures proposed in "OOOOa"). A properly structured voluntary program will encourage the gas transmission industry to identify the greatest sources of methane emissions (the "super emitters") and reduce methane emissions more efficiently and cost-effectively.

INGAA supports having all of the three options offered to prospective Methane Challenge program participants yet strongly encourages EPA to add INGAA's DI&M to its BMP option. Allowing companies to select from several BMPs, ONE Future, or the Emissions Reduction option will increase the likelihood of voluntary program participation. **INGAA recommends its DI&M as a Best Management Practice (BMP) to identify and respond to 80 percent of the T&S sector's methane leaks in a responsible manner.**

INGAA does not believe it is currently feasible to achieve a reduction 50 percent of the methane from blowdown events given the design of many pipelines that cannot avoid blowdowns. INGAA believes that excavation measures should not apply to the T&S sector because it is not appropriate to interfere with the core mission of excavation work and public safety protection.

INGAA respectfully requests an opportunity to further comment on the additional implementation or MOU documents released by the EPA on November 11, 2015.

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Directed Inspection and Maintenance for Reducing Leak Emissions from Natural Gas Transmission and Storage Compressor Stations: Greenhouse Gas Reporting Program Data Supporting a Focused Leak Mitigation Program

Prepared for:

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September 2015

INTRODUCTION AND BACKGROUND

It has been shown that a relatively small percentage of leaks contribute the vast majority of leak emissions for natural gas operations. For example, 95% of methane emissions from equipment leaks are from 20% of the leaks at natural gas transmission compressor stations.[21] Directed Inspection and Maintenance (DI&M) is a leak mitigation practice that leverages this characteristic of compressor station leaks through procedures that focus repairs on larger leaks while limiting resources expended on inconsequential leaks. This White Paper provides background and technical support for implementing DI&M, as described in the INGAA DI&M Guidelines, to mitigate natural gas transmission compressor station equipment leaks.

The INGAA DI&M Guidelines provide the structure, program elements, and procedures for a company-specific DI&M program. The Guidelines focus on key leak sources within a facility that have a higher probability of being large leaks – referred to as "gross emitters" in recent EPA documents. The focused list of sources is based on previous studies, company experience, and available information, including data from the EPA Greenhouse Gas Reporting Program (GHGRP). The key leak sources are discussed further below, and GHGRP data collected for an industry research project are analyzed to demonstrate that the INGAA DI&M Guidelines focus on the appropriate leak sources.

INGAA members operate compressor stations that are required to report GHG emissions under the GHGRP. An ongoing project is being conducted by the Pipeline Research Council International (PRCI) to collect data submitted to EPA through its electronic greenhouse gas reporting tool (e-GGRT). The PRCI project is also collecting supplemental data that provides additional information on associated facility and equipment operations, and on vent measurements. Data from the PRCI project was analyzed to document that the sources included in the INGAA DI&M Guidelines represent the vast majority of equipment leak emissions from natural gas transmission compressor stations. Data and associated analysis is presented in this document.

INGAA GHG GUIDELINES – EQUIPMENT LEAK SOURCES AND RELATIONSHIP TO SUBPART W LEAK SOURCES

Leak sources included in the INGAA DI&M Guidelines are similar to emissions sources that require measurement in Subpart W of the GHGRP. The primary interest is compressor related leak sources, and the INGAA DI&M Guidelines go beyond the requirements of Subpart W by including leak sources and operating modes that are not included in GHGRP reporting. The sources included in the INGAA DI&M Guidelines are shown in Table 1.

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[21] "Directed Inspection and Maintenance at Compressor Stations." U.S. EPA Natural Gas STAR, Lessons Learned (see http://epa.gov/gasstar/documents/ll_dimcompstat.pdf), EPA430-B-03-008 (October 2003).

Table 1. Affected Equipment / Component List for DI&M Program.

<table>
<tr><td>• Reciprocating compressor blowdown valve leakage through blowdown vent in any mode as found:
1. Leakage during “Operating” mode
2. Leakage during “Standby Pressurized” mode</td><td rowspan="2">• Reciprocating rod packing leakage[A] in any mode as found:
1. Reciprocating rod packing emissions during “Operating” mode
2. Reciprocating rod packing emissions during “Standby Pressurized” mode</td></tr>
<tr><td>• Reciprocating compressor unit isolation valves (suction and discharge) leakage through the associated vent during “Not Operating, Depressurized” mode</td></tr>
<tr><td rowspan="2">• Centrifugal compressor blowdown valve leakage through the blowdown vent in any mode as found:
1. Leakage during “Operating” mode
2. Leakage during “Standby Pressurized” mode</td><td>• Centrifugal compressor unit isolation valves (suction and discharge) leakage through the associated vent during “Not Operating, Depressurized” mode.</td></tr>
<tr><td>• Centrifugal compressor wet or dry seal leakage through associated vent(s) in any mode as found (see modes listed above for rod packing).</td></tr>
<tr><td colspan="2">• Storage tank vents to atmosphere from scrubber dump valve leakage.</td></tr>
</table>

[A] Reciprocating compressor rod packing is designed to leak, even when new.[22] Repair decisions and timing that considers condition-based maintenance for rod packing will be defined in the DI&M Plan.

The primary focus is on compressor emissions from large valves and other known leak sources, such as reciprocating compressor rod packing and centrifugal compressor wet seal degassing vents. The list of sources includes combinations of the emission source and the compressor mode that are not included in GHGRP reporting, including: reciprocating compressor rod packing leakage in standby-pressurized mode; centrifugal compressor dry seals; and centrifugal compressor sources in standby-pressurized mode. As discussed below, GHGRP data indicates storage tank emissions from scrubber dump valve leakage is not a significant source, but because this is a source of interest included in Subpart W, storage tanks are included in the INGAA DI&M Guidelines.

The equipment leak sources *excluded* from the INGAA Guidelines are components such as connectors, valves, and open ended lines associated with yard piping or compressor house gas lines. As discussed in the next section, evaluation of detailed data from the PRCI project demonstrates that these emissions are generally a small portion of overall leak emissions.

[22] EPA Natural Gas STAR Lessons Learned document, “Reducing Methane Emissions From Compressor Rod Packing Systems.” October 2006. http://www.epa.gov/gasstar/documents/ll_rodpack.pdf

PRCI GHG DATA COMPILATION PROJECT

Compressors stations that exceed the GHGRP annual emissions reporting threshold of 25,000 CO_2 equivalent (CO_2e) metric tons are subject to reporting under Subpart C (combustion emissions) and Subpart W (leaks, venting, blowdowns). Subpart W requires annual leak measurements for compressor-related sources and storage tanks. In addition, a leak survey that counts leaks by component types is required for other facility equipment. Since significant new data is being collected, PRCI is conducting an ongoing project to gather data from its members, and compile and analyze the data. This includes Subpart W data submitted to EPA and supplemental data on equipment, operations, and measurement methods. The project is analyzing the data to assess development of improved emission factors for compressors. The data can also be analyzed to provide technical support for ongoing dialogue related to GHG emission estimates and emission reduction opportunities.

The first year of Subpart W reporting was 2011, and data elements reported to EPA were broadened in January 2015. Since reporting was more limited in the initial three reporting years, the PRCI project supplemented the e-GGRT data with additional information. In addition to e-GGRT data, companies provided supplemental data on facility equipment, operations, and methods used for vent measurement. This supplemental data is needed to better understand the reported emissions and to support analysis such as emission factor development.

The PRCI data was collected from members and the dataset does not include all companies or facilities that report to EPA. However, the majority of facilities are included in the PRCI dataset: 70% of all EPA facilities are included for 2011 and over 60% are included for 2012. As discussed in the following section, the emission trends for each Subpart W source type are similar for the PRCI dataset and the entire EPA dataset.

The PRCI GHG dataset is being analyzed to assess whether updated emission factors can be developed for reciprocating compressors and centrifugal compressors. In addition, the data is available to support technical analysis on GHG issues such as source-specific emissions, emission trends, the distribution (by size) of measured leaks, the prevalence of "large" leaks, and measurement methods performance. At this time, the PRCI dataset includes 2011 and 2012 data. Final review is being completed for 2013 data, which will be added to the PRCI dataset. Data collection and compilation for the 2014 reporting year will occur in late 2015.

DATA ANALYSIS AND DISCUSSION

The figures presented in this document are based on PRCI 2011 and 2012 data, with one exception. Figure 2 includes the entire EPA dataset downloaded from EPA's website. Figure 1 presents PRCI data for 2011 and 2012 by Subpart W emissions source. Figure 2 shows all data from EPA for 2011, 2012, and 2013. Facility counts differ from year to year. Thus, to facilitate comparison, the emissions are presented as a facility average (i.e., total emissions for each source type divided by the total number of facilities for the respective datasets). Storage facility data is more limited (i.e., fewer facilities report and fewer emission sources are included in GHGRP reporting), so the data analysis focused on the transmission segment.

Data has been collected for 2011 – 2013 reporting years; PRCI data in this document is from 2011 and 2012. These data were reported based on a methane global warming potential (GWP) of 21, and this document does not correct the GWP to its current value (GWP = 25). The EPA website "all facility" data for 2011 – 2013 presented in Figure 2 is also based on a GWP of 21.

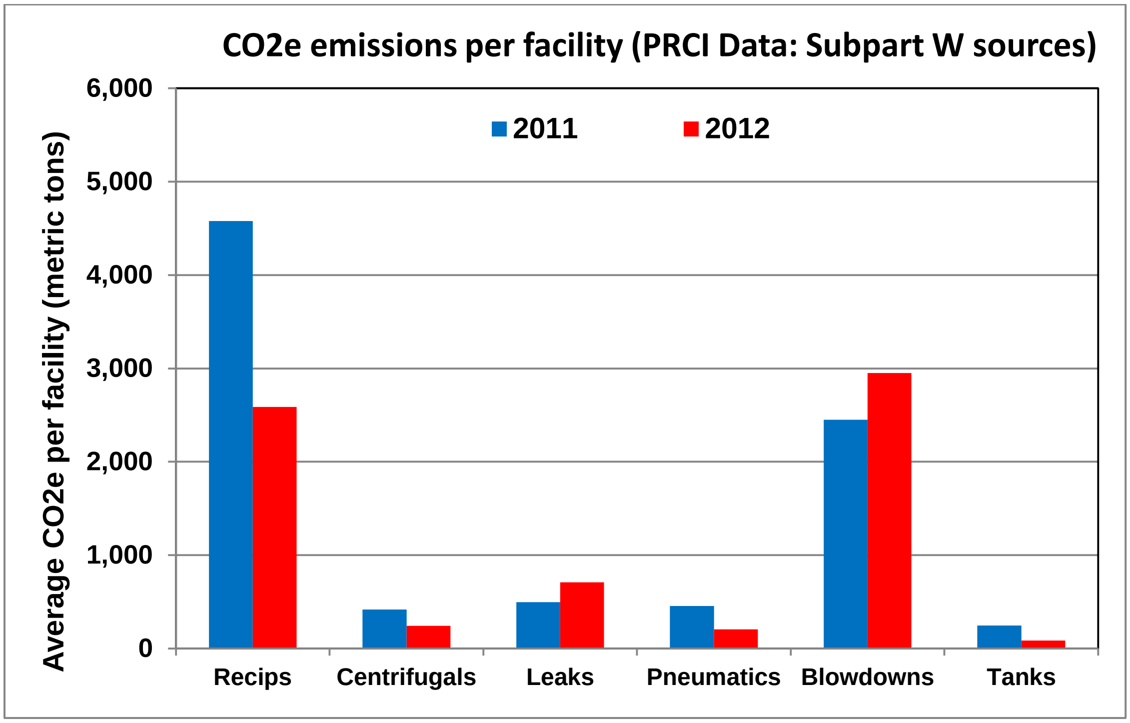


Figure 1. Emissions by Subpart W source type (PRCI data)

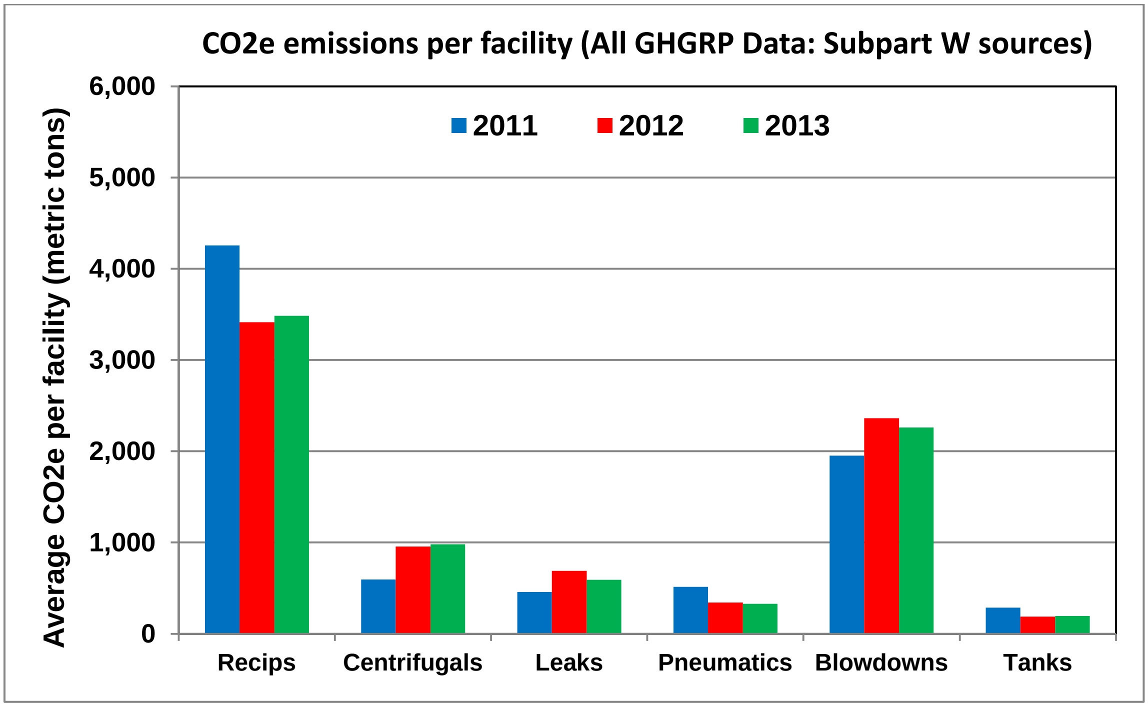


Figure 2. Emissions by Subpart W source type (All EPA data)

The two figures show similar reported emission levels and similar trends. Several observations follow:

- Reciprocating compressor emissions and blowdown emissions are more than 70% of the total emissions.
- Reciprocating compressor emissions decreased in the second year of the program. A larger decrease occurred for facilities included in the PRCI dataset compared to the entire GHGRP dataset. There are several factors that likely contribute to the decrease after the first year: 2011 allowed the use of "best available monitoring methods" (BAMM) when the program was launched; some large leaks were likely repaired following discovery in 2011; and, measurement method used may have changed.
- The 2013 data from EPA shows that emissions were similar in the second and third reporting years and generally differ from reported emissions for the first year.
- Vented emissions from pneumatic devices decreased in the second year of the program. That emission estimate is based on device count by type (high bleed, low bleed, intermittent) and emission factors. It is likely that categorization by device type improved in 2012 – e.g., in the first year of the program conservative estimates based on best available information classified devices as high bleed that were subsequently confirmed as low bleed devices.
- There is a difference between the PRCI data and "all EPA" data for centrifugal compressor emissions. The PRCI project will likely examine this data more closely to determine whether the reason for the difference can be discerned. However, the difference does not impact the discussion and conclusions that follow in the document regarding sources included in the INGAA DI&M Guidelines.

For the six Subpart W sources, four are leak-related sources where the reduction option is a leak mitigation program (e.g., LDAR, DI&M). Blowdowns are a separate category of emissions and emission reduction opportunities are generally based on the feasibility of alternative operating practices for select types of events. Pneumatic device venting is reduced by using low bleed devices or compressed air systems.

The other four source types are the candidate compressor station emission sources for leak mitigation:

- Reciprocating compressor emissions from rod packing, isolation valves, and blowdown valves.
- Centrifugal compressor emissions from isolation valves, blowdown valves, wet seal degassing vents, and dry seals. (The latter is not included in Subpart W reporting.)
- Emissions through storage tank vents from leaking condensate tank dump valves.
- Equipment leaks from equipment and components other than those listed above (i.e., "other" leak emissions).

Blowdowns are a separate category of emissions and a significant contributor to overall facility emissions. Because blowdowns are a different category than leaks and EPA has not included facility blowdown reductions in proposed mitigation programs, and compressor station methane leak mitigation is the focus of a DI&M program, blowdown emissions in Figure 1 are not included in analysis or discussion below. Pneumatic device vented emissions are also a different category than leaks, but EPA proposed programs include reducing pneumatic device emissions, so limited additional discussion on pneumatic emissions is provided below.

Pneumatic device emissions are relatively small for the transmission and storage segments. Pneumatic device emissions are included in Figure 3 to compare emissions for methane emission sources recommended as reduction opportunities in proposed EPA programs: the EPA voluntary Methane Challenge program for existing sources, and the proposed NSPS rule that regulates methane emissions from new facilities (Subpart OOOOa).

Figure 3 shows the same PRCI data as Figure 1, using a different bar chart format and excluding blowdowns. The "other" leak emissions (Subpart W leaks not from compressors or tanks) are presented in two categories consistent with Subpart W methodology, where leaks survey results track whether or not the leaking component is in compressor service (i.e., thermal cycling and vibration from compressors may affect leak size and frequency).

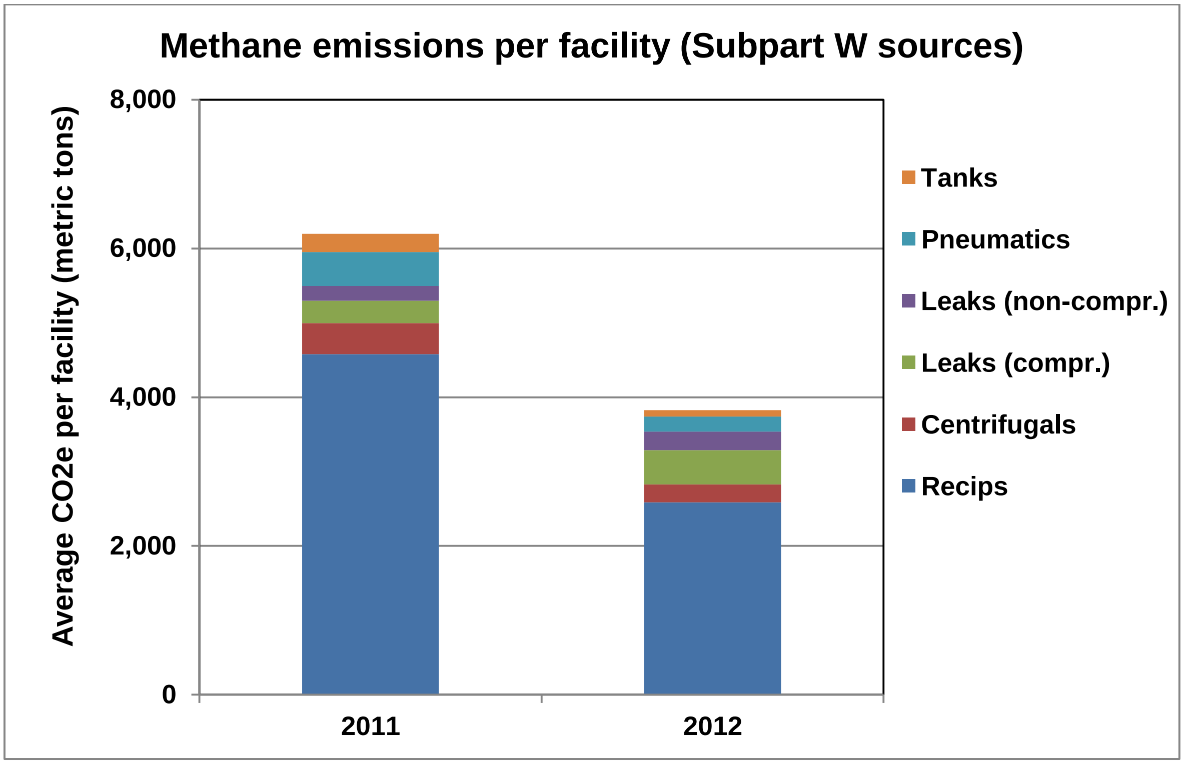


Figure 3. Subpart W emissions by source type for leaks and pneumatic venting.

Pneumatic device venting is 7% of these emissions in 2011 and 5% in 2012. For the remaining leak sources, reciprocating compressors, centrifugal compressors and tanks are included in the INGAA DI&M Guidelines. These sources comprise over 90% of the total leak emissions in 2011 and over 80% of the total in 2012. Addressing compressors and tanks requires surveying a limited number of vents, while the remaining 10 to 20% of leak emissions are associated with hundreds of components spread over the entire facility. Additional detail on leak emissions is provided in figures below.

In addition, the emission estimates from "other" leak sources excluded from the INGAA DI&M guidelines are based on a count of leaks detected in the annual survey and emission factors. The component-specific emission factors in Subpart W are based on 10 to 20 year old data, and it is likely that emissions have decreased as leak mitigation programs have become more common. Thus, if "other" leak emission estimates based on older data over-estimate emissions, then measured Subpart W leak data from compressors and tanks would comprise a larger percentage of the leak emissions than indicated by the Subpart W data.

The PRCI leak data from the figures is also presented in Figure 4 and Figure 5, which show additional details for the 2011 and 2012 Subpart W data for leak emission sources. Additional details associated with the leak sources that comprise total compressor leak emissions is available based on the emission source-operating mode combinations measured for Subpart W. The five categories include reciprocating compressors, centrifugal compressors, storage tank (dump valve leakage), and "other leaks" for components either in compressor service or non-compressor service. EPA usually groups the "other leaks" into a single category, but the Subpart W emission estimate uses different emission factors for each component type depending on whether or not the component is in compression service. For the categories other than tanks, the total emissions are comprised of emissions from multiple sources and different compressor modes, including:

4. Reciprocating compressors (typically released to atmosphere through elevated vents):
    d) Rod packing emissions when the unit is operating;
    e) Isolation valve emissions when the unit is shutdown and de-pressurized;
    f) Blowdown valve emissions when the unit is operating or in standby-pressurized mode.
5. Centrifugal compressors (typically released to atmosphere through elevated vents):
    a) Wet seal degassing vent emissions when the unit is operating (this is more a vent source than a leak source, but is grouped with centrifugal compressor leak emissions for tracking purposes);
    b) Isolation valve emissions when the unit is shutdown and de-pressurized;;
    c) Blowdown valve emissions when the unit is operating.
6. "Other leaks" in either compressor or non-compressor service, with the total emissions estimate based on emissions from each of five component types:
    f) Connectors;
    g) Valves;
    h) Open ended lines (OELs);
    i) Pressure relief valves (PRVs);
    j) Meters.

The figures show each of the categories (i.e., the primary bullet in this list), as well as the emissions from the specific leak sources associated with each category (i.e., the sub-bullets in this list). The percentage of total leak emissions for each source or category is shown in the figures. For "other leaks," where total emissions for the five component types are a small overall contributor to leak emissions, the percentage shown is for the total rather than for each of the five component types.

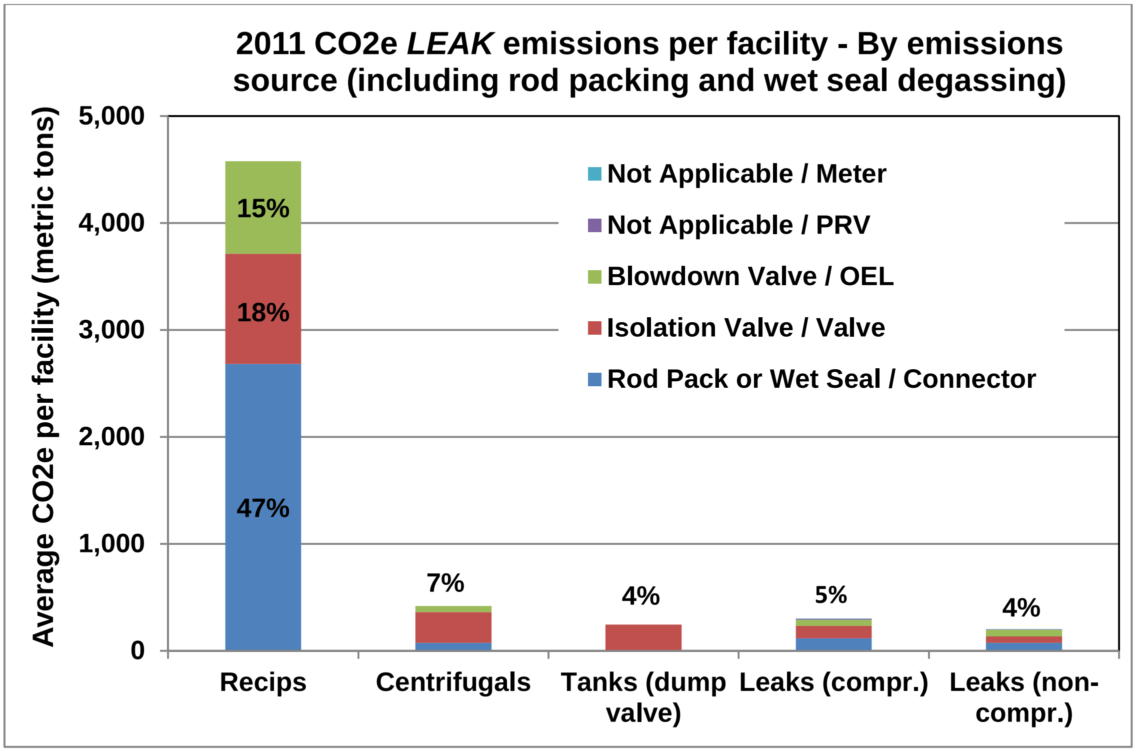


Figure 4. 2011 leak emissions by category and emissions source for Subpart W reported emissions compiled for the PRCI project.

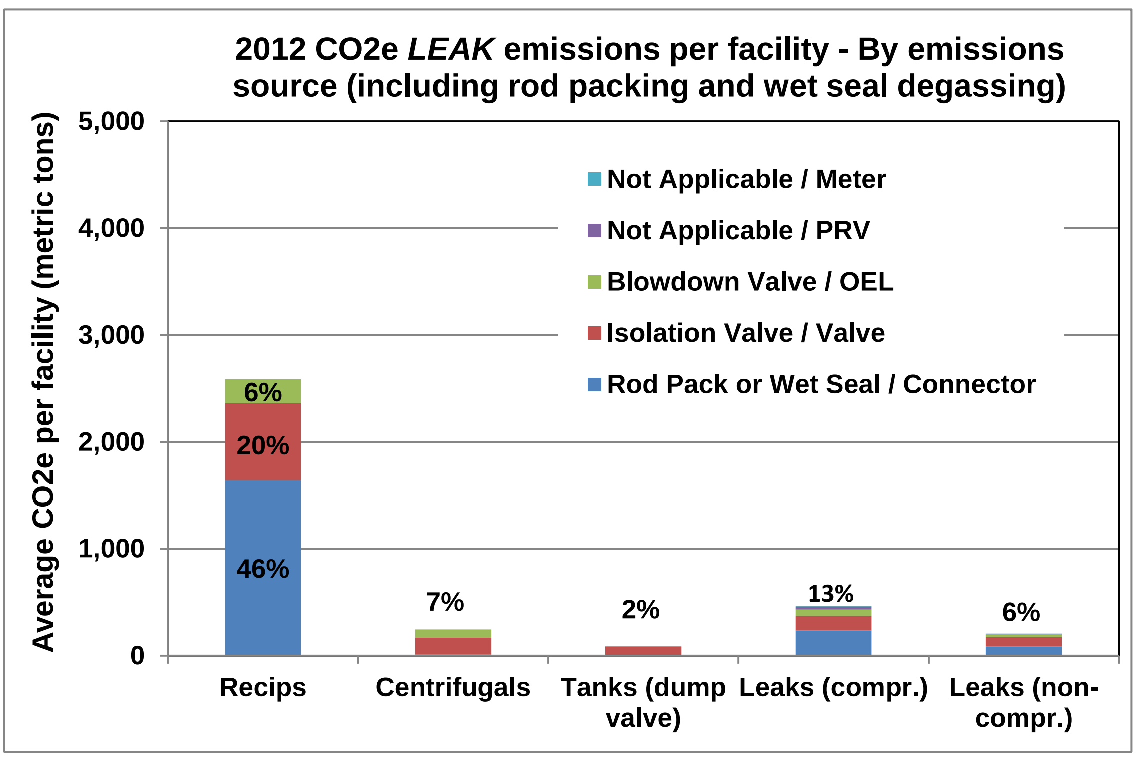


Figure 5. 2012 leak emissions by category and emissions source for Subpart W reported emissions compiled for PRCI project.

The first three leak categories – reciprocating compressors, centrifugal compressors, and storage tank dump valves – are included in the INGAA DI&M Guidelines and the latter two are not directly included in the program. Existing programs, such as walk-throughs that conduct audio-visual-olfactory (AVO) review for safety purposes will address "other leaks" within the facility, but those activities are not detailed in the INGAA DI&M Guidelines.

The number of potential leaks surveyed varies significantly for the first three categories compared to "other leaks." To reiterate, the three categories included in the INGAA DI&M Guidelines are based on sources that are measured for Subpart W and require surveying a minimal number of sources. The other leaks category requires surveying hundreds of additional components.

For example, potential leak sources for a reciprocating compressor (see items 1(a), 1(b) and 1(c) in the list above) will include rod packing leakage, two isolation valves (suction and discharge side of the compressor) and a blowdown valve. Thus, a limited number of vent lines need to be surveyed to identify leakage for the three leak categories in the INGAA DI&M Guidelines. In contrast, the other potential leak sources (see five component types in items 3(a) through 3(e) in the list above) are comprised of *hundreds* of components throughout the compressor station that would require surveying. About 80% or more of leak emissions are covered through the focused program in the INGAA DI&M Guidelines.

These two figures show the relative contribution of leak emissions by category and associated leak source for the first two years of Subpart W reporting. For 2011 (Figure 4):

- The three categories included in the INGAA DI&M Guidelines **comprise 91% of the total** leak emissions.
    - 5,240 metric tons CO_2 equivalent emissions on average for all facilities in the PRCI dataset.
- The two leak categories not included in the INGAA DI&M Guidelines – other equipment leaks in compressor service or non-compressor service – comprise 9% of the total emissions and less than 500 metric tons.

For 2012, total leak emissions are lower, which is likely due to repair of some of the larger leaks discovered in 2011 (e.g., reciprocating compressor leak emissions). From Figure 5:

- The three categories included in the INGAA DI&M Guidelines **comprise 81% of the total** leak emissions.
    - 2,915 metric tons CO_2 equivalent emissions on average for all facilities in the PRCI dataset.
- The two leak categories not included in the INGAA DI&M Guidelines – other equipment leaks in compressor service or non-compressor service – comprise 19% of the total emissions and approximately 665 metric tons.

Additional detail on individual measurements and the contribution of large leaks to the overall total is available for the three leak categories included in the INGAA DI&M Guidelines. Data presented in the figures below show that a DI&M program following the INGAA Guidelines may ultimately demonstrate that an even more focused program is warranted (e.g., the relative emissions from blowdown valve leakage compared to isolation valve leakage may have implications for requirements such as survey frequency).

Figures 6 and 7 present PRCI measured emissions by source type and compressor mode – e.g., rod packing emissions in operating mode, isolation valve emissions in shutdown de-pressurized mode. Figure 6 presents a cumulative distribution of reciprocating compressor emissions for the four unique source-operating mode combinations in Subpart W. In Figures 4 and 5 above, the blowdown valve emissions for two different compressor modes are combined for the portion of the bar chart that shows "blowdown valve" emissions. The blowdown valve emissions are separated by Subpart W mode in Figure 5. Figure 7 presents the same information for the three source-compressor mode combinations for centrifugal compressors.

For the cumulative distribution plots, all of the measurement data are ranked from largest to smallest and cumulatively added. Only the "non-zero" measurements are included in these figures (i.e., the tail would be longer if additional measurements showing no leakage were included). These data show that leaking blowdown valves and centrifugal compressor degassing vents are smaller contributors to facility emissions than isolation valves and reciprocating compressor rod packing.

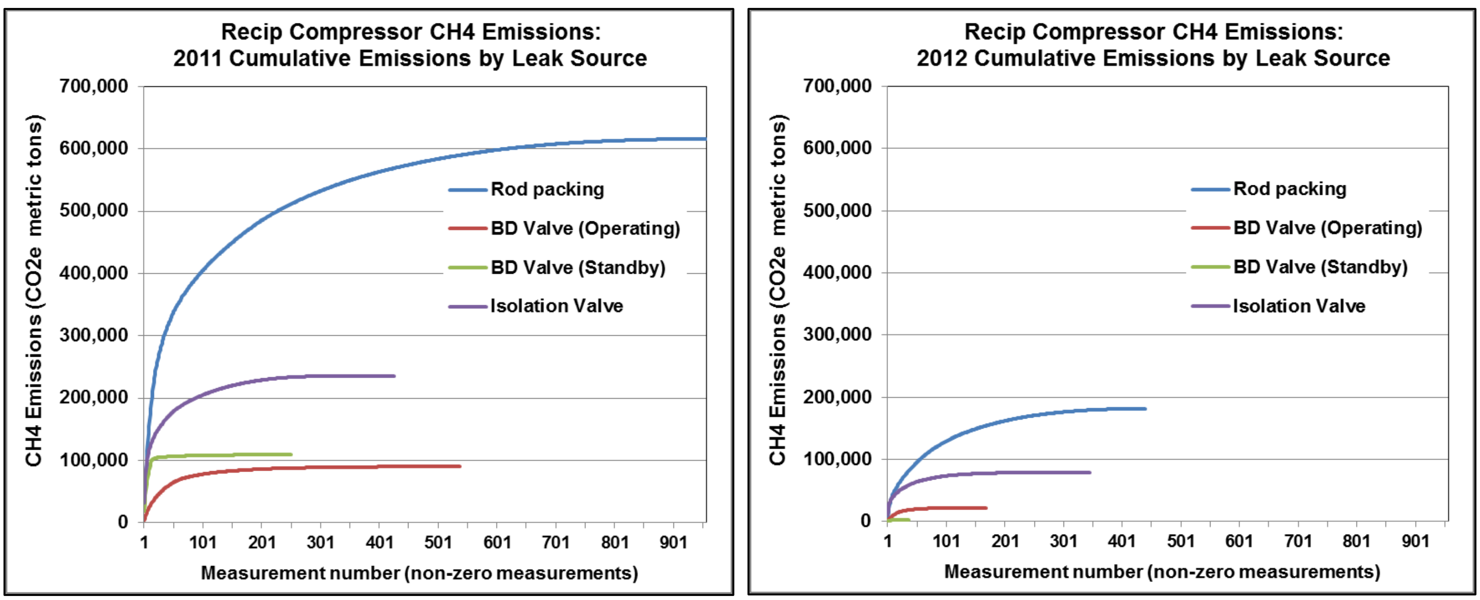


Figure 6. Reciprocating compress emissions by source – mode combination: Rod packing (operating mode), blowdown valve (operating mode or standby-pressurized mode) and isolation valve (shutdown-depressurized mode).

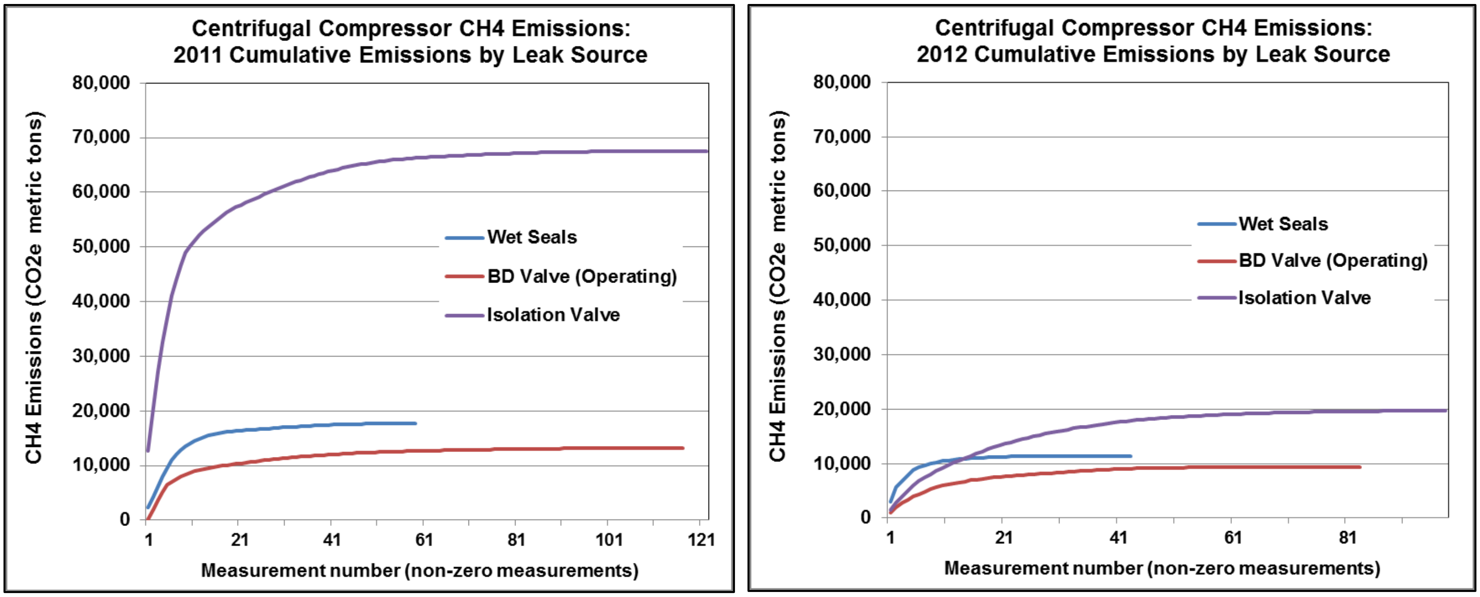


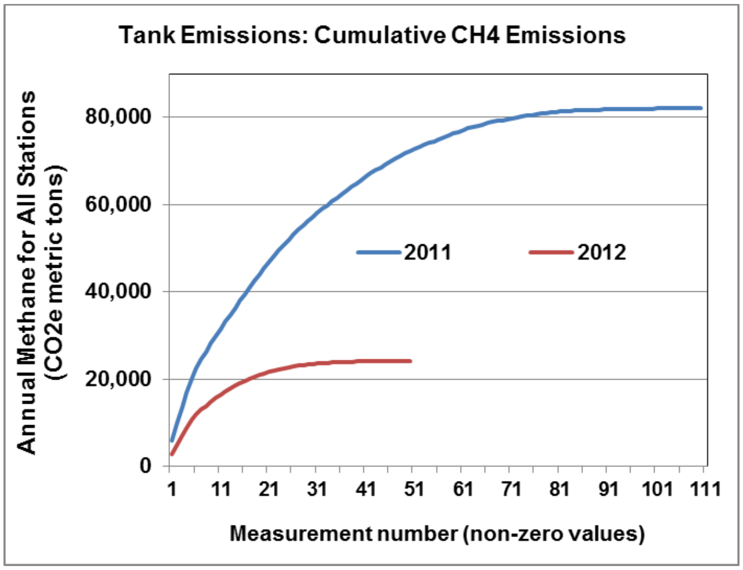
Figure 7. Centrifugal compress emissions by source – mode combination: Wet seal degassing (operating mode), blowdown valve (operating mode) and isolation valve (shutdown-depressurized mode).

For reciprocating compressors, rod packing leakage is a large contributor to total emissions. For both reciprocating and centrifugal compressors, isolation valves are an important source. In a DI&M program, repair decisions consider the leak size and the repair cost (or degree of difficulty). This approach is based on historical data that shows that a relatively small number of leaks comprise the majority of emissions. The same phenomenon is demonstrated in Figures 6 and 7. For example, in 2011 there were about 440 measurements of reciprocating compressor isolation valve emissions. The top 20% (about 90 measurements) comprise over 85% of the emissions from isolation valves. This trend is even more pronounced for the reciprocating compressor blowdown valves measured in standby mode in 2011. Several measurements (about 2% of the total) account for nearly all of the emissions from this source.

These figures, along with the storage tank figure below, show that the INGAA DI&M Guidelines include leak sources that PRCI Subpart W data shows as relatively small contributors. However, the INGAA Guidelines chose to include sources associated with Subpart W measurements, and additional sources not covered by Subpart W (e.g., rod packing in standby-pressurized mode) to provide the opportunity to develop a larger dataset and more clearly demonstrate larger leak sources. While total emissions for other leak sources are a larger percentage than some categories included in the INGAA Guidelines (e.g., Figure 5 shows that 13% of total leak emissions in 2012 are from other leaks for components in compressor service), those total emissions are from many components, while sources with smaller relative emissions included in the INGAA Guidelines (e.g., tanks are 2% in 2012) are associated with discrete sources that have a higher risk of large leaks.

A focus on the "gross emitters" is the most effective approach to reduce methane emissions. The data collected from a DI&M program, in conjunction with other ongoing data being reported for Subpart W (e.g., leak surveys for "other" leaks), will provide insight into program performance. As the program is implemented, performance will be defined, and the need to consider program adjustments (e.g., to focus on *more or fewer* potential leak sources) will be identified.

<u>Storage Tanks Emissions</u>
Although a relatively small source compared to compressor leaks, EPA has expressed concern regarding leaking dump valves, and Subpart W requires measurement of the associated tank vents. Thus, storage tanks are included in the INGAA DI&M Guidelines. Figure 6 shows PRCI data results from *non-zero* measurements in 2011 (111 non-zero measurements) and 2012 (51 non-zero measurements). *Cumulative* emissions for all tank measurements are shown in the left graph. The graph on the right shows each individual measurement. These data show that total tank emissions are relatively small and decreased from 2011 to 2012. Additional observations include: a relatively small number of facilities / measurement contribute most of the emissions; there were fewer leaks in 2012 than in 2011; and, there were fewer large leaks in 2012 than in 2011.



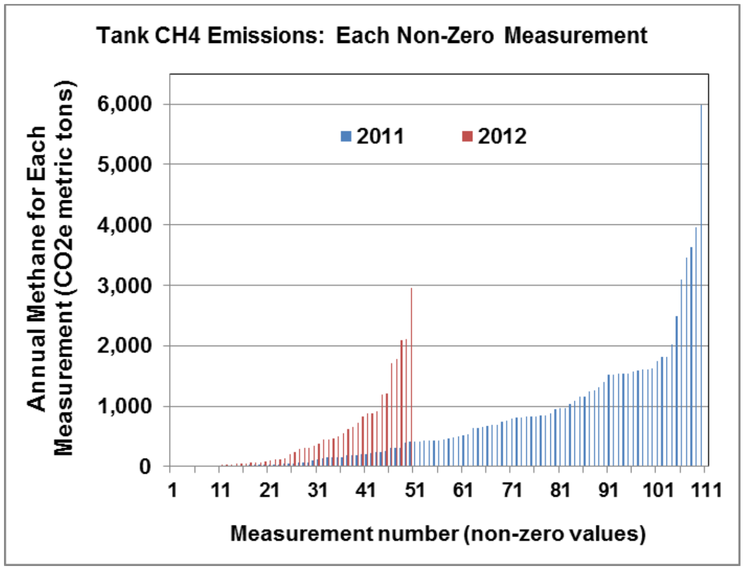


Figure 6. Storage tank emissions from leaking dump valves in 2011 and 2012. Cumulative distribution of all non-zero measurements (left graph) and leak rate for each non-zero measurement (right graph).

CONCLUSIONS

DI&M is a proven approach for reducing methane emissions from leaks at natural gas transmission and storage compressor stations. The INGAA DI&M Guidelines focus on compressor station leak sources that pose a higher risk of being a large leaker, include compressor and storage tank sources that require leak rate measurement under Subpart W, and include additional leak sources excluded from Subpart W (e.g., reciprocating compressor rod packing in standby-pressurized mode, centrifugal compressor dry seals).

Subpart W data and supplemental data from a PRCI project shows that the leak sources included in the INGAA DI&M Guidelines address more than 80% of emissions from compressor station leaks. Thus, a focused DI&M program provides an effective leak mitigation approach. Data gathered as a DI&M program is implemented also provides the ability to assess performance, ensure that the appropriate sources are included, and consider program adjustments to address insights gained from facility leaks and reduction opportunities.

COMMENTER:

Jan W. Mares

Jan W. Mares, Senior Policy Advisor at Resources for the Future provides his individual comments, since RFF takes no institutional positions, for consideration by EPA of its Natural Gas STAR Methane Challenge Program Proposal.

The Program's goals of ambitious commitments, transparency and flexibility are desirable and the six stated key objectives of the Proposed Program are very important and positive. However more consideration should be given to means of giving recognition or incentives to those firms that demonstrate consistently better than average emissions performance, or which are able to demonstrate significant progress in reducing their methane emissions, while providing more and higher quality data to EPA via the Challenge Program.

Properly structured, the Methane Challenge Program may prove particularly useful in helping to augment and improve emissions data. It is a challenge to ensure that emission estimation and measurement techniques are accurate and representative when dealing with the rapidly-changing natural gas sector. A voluntary program such as Methane Challenge may afford EPA the flexibility to promote data measurement techniques and reporting of sources, which would be infeasible in the near term under the mandatory Subpart W GHG Reporting Program (GHGRP). There are known deficiencies in data reporting that companies could be encouraged to address: few current direct measurements for certain equipment and processes, no data collection for sources that fall below the 25,000 ton GHGRP reporting threshold, and no data reported under GHGRP for gathering lines and some other potentially significant emission sources. EPA should use incentives to obtain such data through the Challenge Program.

Confirming the achievement of the emission reductions by the participating companies is important to the credibility of the program. While recognizing the added cost to provide such confirmation, EPA should consider in its protocols some form of confirmation system. Since a confirmation system would be an added expense for the participating companies while being a significant benefit for EPA and all stakeholders, some incentives should be provided by EPA to the participants who use such a system.

EPA should take advantage of the Methane Challenge Program to improve the basis for EPA's current methane emission estimates. They are based in large part on average emission factors that were developed twenty years ago and published by the Gas Research Institute. There has been work since then to estimate average emission factors but this is not yet reflected in EPA's national factors. Direct measurements of all sources in all locations is prohibitively expensive and not necessary given today's. However, direct measurements of some sources in some locations following agreed protocols could add significantly to the data base from which EPA could update its national emissions factors and related methane estimates. EPA should provide incentives in the Methane Challenge Program to encourage participants to conduct statistically robust direct measurements in accordance with principles established by EPA and report them as part of the Program.

Early action on reducing emissions could be given special recognition or incentives following the pattern in the Clean Power Plan rule for incentives for early reduction of CO_2 emissions. EPA has used incentives in prior programs and several seem appropriate in this Program. They include (a) allowing company commitments under the Program to be considered as an acceptable compliance mechanism for proposed EPA regulations; (b) depending on the amount of reduction and coverage by the company, treating its commitments as compliance under future section 111(d) methane regulation and/or (c) providing expedited processing of permits and regulatory actions on federal lands.

Because of the significant emissions reductions that can be obtained via practices such as Leak Detection and Repair and Directed Inspection and Maintenance, EPA should encourage these practices and not wait for finalization of the proposed relevant regulation to arrive at appropriate reduction estimates for the companies using these approaches.

COMMENTER:

Kinder Morgan (KM)

November 13, 2015

<u>Via email and online: methanechallenge@tetratech.com</u>

Carey Bylin
International Programs Leader
Oil and Gas at U.S. EPA
1200 Pennsylvania Avenue N.W.
Washington, D.C. 20460

RE: Kinder Morgan Comments on the Natural Gas Star Methane Challenge Program: Proposed Framework and Supplementary Technical Information

Dear Ms. Bylin:

Kinder Morgan, Inc. (Kinder Morgan) submits the following comments in response to EPA's proposed Natural Gas STAR Methane Challenge Program: Proposed Framework and Natural Gas STAR Methane Challenge Program: Supplementary Technical Information. Kinder Morgan appreciates EPA's efforts to propose a voluntary methane emission reduction program which could achieve significant emission reductions in a cost-effective manner as compared to a mandatory prescriptive regulatory program. Kinder Morgan endorses the comments submitted by the Interstate Natural Gas Association of America (INGAA) in full and endorses certain comments submitted by the American Petroleum Institute (API) on the Proposed Framework, as specifically identified below.

With interests in approximately 68,000 miles of natural gas pipelines and ownership of 1.3 trillion cubic feet (Tcf) of underground natural gas storage, Kinder Morgan is the largest natural gas transporter and largest storage operator in North America. Kinder Morgan's natural gas pipelines are connected to every important natural gas resource play, including the Bakken, Eagle Ford, Marcellus, Permian, Utica, Uinta, Haynesville, Fayetteville, Barnett, Mississippi Lime, and Woodford, that will play a significant role in meeting the nation's long-term natural gas supply. Kinder Morgan's operations serve the major natural gas consuming markets of the entire United States. Natural gas liquids production has also grown significantly in this business segment. Kinder Morgan also operates multiple gathering and boosting systems, over 15 gas processing plants, and two liquefied natural gas (LNG) terminals.

Kinder Morgan's natural gas transmission and storage pipeline companies have participated in EPA's Natural Gas STAR Program since 1993. Kinder Morgan's natural gas operations have achieved methane emissions reductions of over 80 Bcf since 1993. Kinder Morgan has achieved those reductions by implementing cost-effective measures to reduce methane releases from its transmission and storage operations and by repairing identified leaks. Various technologies have been implemented to reduce methane emissions including, but not limited to:

- Implementation of directed inspection and maintenance programs at various compressor stations and storage facilities;
- Replacing rod packing systems on reciprocating compressor engines when necessary;

- Replacing high-bleed pneumatics;
- Installing vapor recovery systems on storage tanks;
- Pumping or drawing down sections of pipe prior to conducting maintenance activities to minimize blowdown emissions;
- Installing full encirclement or composite sleeves for pipeline maintenance to eliminate the need for pipeline blowdowns; and
- Installing either gas turbines or electric motor driven compression, as appropriate, rather than installing reciprocating compressor engines.

Historically, one of Kinder Morgan's greatest methane reductions has come from preventing natural gas venting or "blowdowns" of natural gas pipeline sections prior to conducting maintenance activities. Drawing down pressures with existing compression, using portable compressors to recompress gas into other pipelines or pipeline sections, and the use of full encirclement or composite sleeves reduces the amount of natural gas that would otherwise be released into the atmosphere when conducting maintenance activities (when appropriately applied, considering safety and other concerns). Kinder Morgan's own efforts to voluntarily reduce methane emissions demonstrate that strict command and control regulatory regimes are simply not the best answer for reducing methane emissions from the oil and natural gas sector, and particularly the transmission and storage sector. The EPA should encourage industry to continue identifying high-impact, cost-effective mitigation options to achieve the greatest emission reductions.

Kinder Morgan will likely participate as a charter member in the Methane Challenge voluntary program. Kinder Morgan is a founding member of ONE Future and will likely participate through ONE Future. We encourage EPA to work with each company to make certain the MOUs remain flexible to provide for uniqueness of each company in terms of each commitment and to incentivize participation.[1]

Kinder Morgan supports the three options proposed in the Methane Challenge Program using BMP, joining ONE Future or making an Emission Reduction commitment to offer flexibility for participants. We fully support including INGAA's Directed Inspection and Maintenance (DI&M) BMP as an alternative to the currently proposed BMPs for reciprocating compressors, centrifugal compressors and equipment leaks. It is our experience through participation in EPA's Natural Gas STAR program that INGAA's DI&M addresses the most important compressor station sources, including "gross emitters" that offer the best opportunity for cost-effective methane emissions reductions.

Kinder Morgan appreciates the opportunity to comment on EPA's Natural Gas STAR Methane Challenge Program: Proposed Framework. We look forward to engaging with you and your staff on these initiatives.

Sincerely,

Gary Buchler
Chief Operating Officer, Natural Gas Pipelines

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[1] Kinder Morgan may respond to EPA once the MOU and Technical documents are made available and wishes to retain the opportunity to supplement our comments if warranted.

Answers to EPA's specific questions; Proposed Framework:

EPA Question 1: Please indicate whether your company has specific interest in one of the commitment options presented, included the possibility or likelihood of your company marking that commitment.

Response: Kinder Morgan will likely participate as a charter member in the Methane Challenge voluntary program. Kinder Morgan is a founding member of ONE Future and will likely participate through ONE Future.

EPA Question 2: In addition to recognition through the Program, what are the key incentives for companies to participate in this Program? Should EPA offer some partners extra recognition, such as awards?

Response: Kinder Morgan supports INGAA and API comments. EPA should include credit for emission reductions achieved in the voluntary program if a regulatory program is subsequently proposed. Kinder Morgan supports recognizing partners that join the program and those partners who actively participate and exceed their methane challenge targets. This recognition and/or awards program would be similar to those given under the existing Natural Gas STAR program.

EPA Question 3: EPA is proposing to launch the Program with charter partners by the end of 2015, but will welcome new partners on an ongoing basis. Please comment on the likelihood of your company committing to join this Program as a charter partner, or at a future date.

Response: Kinder Morgan will likely participate as a charter member in the Methane Challenge voluntary program. Kinder Morgan will respond to EPA once the MOU and Implementation Plan documents are made available. We also appreciate that EPA will welcome new partners on an ongoing basis.

EPA Question 4: For the BMP option, how can EPA encourage companies to make commitments for sources for which they have not made significant progress in implementing mitigation options? In other words, how can companies be encouraged to participate beyond the sources for which they have already made significant progress?

Response: Kinder Morgan supports INGAA and API comments.

EPA Question 5: **Please provide comments on the sources and corresponding BMPs that are provided in Appendix 2, including any recommended additions, deletions, or revisions.**

Response: Kinder Morgan supports INGAA and API comments. Kinder Morgan supports the addition of the INGAA DI&M BMP for reciprocating compressors, centrifugal compressors and equipment leaks.

EPA Question 6: Please comment on the proposed definitions on the companies or entities that will make BMP commitments, per Appendix 3.

Response: Kinder Morgan supports the comments submitted by INGAA.

EPA Question 7: Is a 5-year time limit to achieve BMP commitments appropriate? If not, please provide alternate proposals. Would a shorter time limit encourage greater reductions earlier?

Response: Kinder Morgan supports the comments submitted by INGAA and API.

EPA Question 8: Should EPA offer the Emissions Reduction (ER) approach? If so, please provide specific recommendations for ways that EPA could address the implementation challenges outlined

in this document. What is the minimum target company-specific reduction level that should be set for participation in this option? Would your company use this option if it were offered?

Response: Kinder Morgan is a founding member of ONE Future and will likely participate through ONE Future. However Kinder Morgan supports all the options presented in the Methane Challenge program in order to offer flexibility for companies and maximize participation.

EPA Question 9: To what extent is differentiating the voluntary actions from regulatory actions important to stakeholders? What are the potential mechanisms through which the program could distinguish actions driven by state or federal regulation from those undertaken voluntarily or that go beyond regulatory requirements?

Response: Kinder Morgan supports the comments submitted by INGAA and API.

EPA Question 10: EPA plans to leverage existing reported data from GHGRP (Subpart W) and supplemental data from companies to EPA. Would e-GGRT system be appropriate mechanism to collect the voluntary supplemental data?

Response: Kinder Morgan agrees the e-GGRT system may be an appropriate mechanism for reporting under the Methane Challenge Program, but voluntary data should be reported separately from the mandatory data and clearly labeled. Kinder Morgan also believes there is an opportunity to modify the existing Natural Gas STAR reporting mechanism. The reporting requirements should not be overly burdensome or companies may be deterred from participating in the program. Since EPA is not expected to propose an actual reporting system until 2016, Kinder Morgan reserves the right to submit additional comments on EPA's reporting system once it has been proposed.

EPA Question 11: Would companies be willing and able to make commitments related to emissions sources where EPA has proposed, but not finalized, new GHGRP Subpart W requirements?

Response: Kinder Morgan supports INGAA and API comments.

EPA Question 12. EPA seeks feedback on potential mechanisms for encouraging continued, active participation in Program once a company's initial goals have been achieved.

Response: Kinder Morgan supports the comments submitted by INGAA and API.

EPA Question 13: EPA is proposing to call this new voluntary effort the "Natural Gas STAR Methane Challenge Program", and welcomes comments and suggestions on this name.

Response: Kinder Morgan supports the comments submitted by INGAA and API.

Answers to EPA's specific questions; Supplemental Technical Information:

EPA Question 1. Are potential partners interested in reporting measured methane emissions for any sources that currently don't include measurement in the quantification options? Please comment on this and, if so, provide information on recommended measurement protocols for sources of interest.

Response: Kinder Morgan supports INGAA comments.

EPA Question 2. Should intermittent pneumatic controllers be included in the Pneumatic Controllers source? EPA seeks recommendations on whether and how to include intermittent controllers.

Response: Kinder Morgan supports INGAA comments.

EPA Question 3. For Tanks, EPA seeks comment on whether additional elements collected under GHGRP should be considered for tracking purposes for the Methane Challenge Program.

Response: Kinder Morgan supports INGAA comments.

EPA Question 4. What types of situations require operators to vent to the atmosphere instead of capturing emissions during liquids unloading? How could this information best be captured in the reported data?

Response: No Kinder Morgan comment.

EPA Question 5. For liquids unloading, are there additional supplemental data elements or quantification methods needed to demonstrate that operators are minimizing emissions during liquids unloading?

Response: No Kinder Morgan comment.

EPA Question 6. EPA seeks feedback on methodologies for calculating and tracking centrifugal compressor seal oil degassing and reciprocating compressor rod packing methane emissions for the following operational situations:

a. **Compressors that route seal oil degassing/rod packing vents to manifolded vents that include sources other than seal oil degassing (e.g., blowdown vents) or seal oil degassing/rod packing emissions from multiple centrifugal compressors.**
b. **Compressors that route seal oil degassing/rod packing vents to flare, a thermal oxidizer, or vapor recovery for beneficial use other than as fuel.**

Response: Kinder Morgan supports INGAA comments.

EPA Question 7. EPA seeks feedback on methodologies for calculating methane emission reductions for centrifugal compressors that convert from wet seals to dry seals.

Response: Kinder Morgan supports INGAA comments.

EPA Question 8. For transmission and distribution blowdowns, EPA requests feedback on the proposal of 50% as the minimum reduction percentage commitment, and whether the minimum commitment should be adjusted to serve as an appropriate stretch goal for partner companies. Is the proposed methodology for calculating potential emissions from this source appropriate? The proposed methodology assumes full evacuation of the pipeline to atmospheric pressure; are there circumstances in which companies don't lower pipeline pressure all the way to atmospheric levels, such that using this basis for calculating potential emissions could overstate potential emissions?

Response: Kinder Morgan supports INGAA comments.

EPA Question 9. For distribution mains, EPA requests feedback on the proposed percentage replacement rates, which include a new proposed category for companies with an inventory of >3000 miles of cast iron and unprotected steel mains.

Response: No Kinder Morgan comment.

EPA Question 10. EPA seeks feedback on the proposal to use the plastic pipe EF for "Distribution Mains – Cast Iron or Unprotected Steel with Plastic Liners or Inserts" and "Distribution Services – Cast Iron or Unprotected Steel with Plastic Liners or Inserts."
Response: No Kinder Morgan comment.

EPA Question 11. For distribution mains and services, should "vintage" plastic pipe or "Century" plastic pipe be included with cast iron and unprotected steel in this category (Aldyl A and LDIW Aldyl A Polyethylene gas piping manufactured from 1965 through 1972 and plastic piping extruded by Century Utility Products Inc. from Union Carbide Corporation's DHDA 2077 manufactured between 1970 and 1973 respectively)? In particular, EPA seeks input on whether companies have sufficient available activity data (e.g., known inventories of vintage plastic pipe and annual information on plastic pipeline material) such that they can commit to and track replacement levels, and if so how emissions of this type of pipe should be quantified (e.g., are material- or age-specific emissions factors available?).

Response: No Kinder Morgan comment.

EPA Question 12. For cast iron services, EPA seeks comment on how to quantify methane emissions, and requests quantification methodology suggestions, including any available data.

Response: No Kinder Morgan comment.

EPA Question 13. For distribution mains, EPA seeks feedback on whether to include as a mitigation option use of internal or external joint sealants for cast iron pipes greater than 20" in diameter. In particular, EPA seeks feedback about the ability to implement other mitigation options for these pipes (e.g., slip-lining), which reinforce the joints as well as the pipeline. EPA requests commenters to provide relevant supporting data with their response, if available.
Response: No Kinder Morgan comment.

EPA Question 14. For excavation damages, EPA seeks comment on whether to limit the scope of this source to pipe operating at 15 psi or greater, or whether it should cover excavation damages on all pipe.
Response: Kinder Morgan interprets the section on excavation damages to apply only to natural gas distribution. Since excavation damages are outside the control of pipeline operators, it would be impossible to set company goals and emission reduction targets. Pipeline operators must implement immediate corrective actions to address excavation damage and emergency situations in accordance with PHMSA regulatory requirements and to assure public safety.

EPA Question 15. Because many excavation damages are technically out of the control of companies, EPA is proposing company-specific goal setting to participate in the Program. We request feedback on this approach, in particular whether companies would be able to set emission reduction targets versus other targets (e.g., reducing number of damages, reducing average shut-in time for all damages, other qualitative targets).
Response: Kinder Morgan interprets the section on excavation damages to apply only to natural gas distribution. Since excavation damages are outside the control of pipeline operators, it would be impossible to set company goals and emission reduction targets. Pipeline operators must implement immediate corrective actions to address excavation damage and emergency situations in accordance with PHMSA regulatory requirements and to assure public safety.

EPA Question 16. EPA requests feedback on how to quantify methane emissions/gas releases from excavation damages. Is there publically available data on recommended calculation methods for quantifying emissions from this source? Are there any circumstances under which it would be appropriate to use an emission factor (e.g., GRI/EPA or Lamb et al.)?

Response: Kinder Morgan interprets the section on excavation damages to apply only to natural gas distribution. Since excavation damages are outside the control of pipeline operators, it would be impossible to set company goals and emission reduction targets.

EPA Question 17. The Natural Gas STAR Program Annual Reporting Forms specify Sunset Dates (the length of time a technology or practice can continue to accrue emission reductions after implemented) for mitigation options (http://www3.epa.gov/gasstar/tools/program-forms.html). Should the Methane Challenge Program create a similar structure to establish Sunset Dates for designated mitigation options?

Response: Kinder Morgan does not support a Sunset Date. The Methane Challenge program is expected to extend beyond 5 years so no need for a sunset date. For example, the ONE Future methodology, identified as an option in the Methane Challenge program, is targeting a period of 10 years to achieve their reduction goals. The ONE Future 2025 goal is consistent with the overall emission reduction targets established by the Obama Administration in its Climate Action Plan.

EPA Question 18. The Methane Challenge Program seeks to stimulate new action to reduce methane emissions while also recognizing past actions undertaken by partners. For some sources, such historic action will be clear through proposed reporting (e.g., facilities that have converted high-bleed pneumatic controllers will show a low number of high-bleeds relative to low-bleed and zero emitting controllers). For other sources, such as cast iron pipe, a low level or nonexistent cast iron could reflect a historic replacement program or the fact that the facility never had such pipe. For practice-based programs, such as that proposed for excavation damages, companies may already have taken steps to reduce damages such that they cannot expect to achieve significantly lower levels. Should the Methane Challenge Program create a mechanism to specifically recognize historic action for certain sources? If so, how could the Program recognize such previous action (for example, by allowing these companies to join the Program and collecting and posting relevant details on previous action prior to joining the Program)?
Response: Kinder Morgan supports INGAA comments.

COMMENTER:

ONE Future Coalition (OF)

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Tom Michels,
Executive Director
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November 13, 2015

Carey Bylin
U.S. Environmental Protection Agency
1200 Pennsylvania Ave., NW (6207-J)
Washington, DC 20460

Via e-mail: methanechallenge@tetratech.com

RE: The U.S. Environmental Protection Agency's Natural Gas STAR Methane Challenge Program Proposal.

Dear Ms. Bylin:

Our Nation's Energy Future Coalition, Inc. (ONE Future) appreciates the opportunity to comment on the U.S. Environmental Protection Agency's (EPA) Proposed Framework for the Natural Gas STAR Methane Challenge Program (Methane Challenge) issued on July 23, 2015, as well as the Supplementary Technical Information released on October 19, 2015, and the Draft Partnership Agreement and Draft Implementation Plan Guidelines released on November 10, 2015.

ONE Future is a unique coalition of leading companies with operations in one or more of the following four principal segments of the natural gas industry: (1) oil and natural gas production and gathering; (2) natural gas processing; (3) natural gas transmission and storage; and (4) natural gas distribution. ONE Future is a non-profit 501(c)(6) trade group that is focused exclusively on improving the management of methane emissions from the wellhead to the burner tip. By bringing together companies from every segment of the natural gas value chain, we aim to deploy innovative solutions to operational and policy challenges that will deliver better results to our customers, increase value to our shareholders, and improve the environment.

ONE Future's flexible and performance-based approach to the management of methane emissions begins with the establishment of an ambitious goal: by the year 2025, our member companies aim to achieve an average annual methane emission intensity[1] rate across our collective operations that, if achieved by all operators across the natural gas value chain would be equivalent to one percent or less of gross U.S. natural gas production. (To put this into perspective, natural gas sector emissions totaled

[1] In this paper, the term "emission intensity" refers exclusively to the average methane (CH4) emission rate over total methane throughput (as reported to the U.S. Energy Information Administration) in a given system.

approximately 1.49 percent of production in 2012.[2]) ONE Future established the one percent emission intensity goal for several reasons, not least of which is that while this goal is ambitious, we believe it is both technically and economically feasible using existing technology and practices. Additionally, recent peer-reviewed research has suggested that an average industry-wide emissions rate of one percent or less would ensure that using natural gas provides immediate greenhouse gas reduction benefits as compared to any other fossil fuel, in any other end-use application.[3]

Importantly, we believe that orienting our activities toward this specific and measurable outcome ensures a sustained focus on identifying the opportunities for emissions abatement that yield the greatest benefit for the least cost. It grants individual companies the flexibility to choose precisely how they can most cost-effectively and efficiently achieve their goal – whether that be by deploying an innovative technology, modifying a work practice, or in some cases, replacing a high-emitting asset with a low-emitting asset. The only essential aspect of our program is that companies transparently demonstrate progress toward their emission intensity goal. (To this end, ONE Future is developing a Methane Emission Intensity Estimation Protocol that will largely follow existing EPA methodologies. A summary of ONE Future's proposed reporting methods is included in Appendix I.)

ONE Future member companies believe strongly that the flexible, performance-based approach we have proposed will accomplish deeper emission reductions among participants at a lower cost than a one-size-fits-all mandatory program. We strongly encourage EPA to ensure that the proactive leadership of ONE Future member companies is acknowledged and recognized as they devise current and future regulatory actions in this arena.

Below, for your consideration, are ONE Future's detailed comments and recommendations on the proposed Methane Challenge program. Although we provide numerous suggestions, ONE Future strongly supports the proposed framework and believes that this innovative collaboration may one day serve as a template to address future challenges. We appreciate the agency's efforts and we are grateful for the thoughtful and professional constructive engagement that the EPA staff has displayed throughout our interactions over the past year. Thank you for your consideration.

Sincerely,

Tom Michels
Executive Director,
ONE Future Coalition

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[2] This figure is based on emissions data from the 2012 U.S. EPA inventory of GHG emissions (GHGI), accounting for co-allocation of emissions from associated gas originating at oil wells and lease condensates from gas wells, and 2012 natural gas gross withdrawals as reported by the U.S. Energy Information Administration (EIA).

[3] See for example: Alvarez et al. (2012) "Greater focus needed on methane leakage from natural gas infrastructure." Proceedings of the National Academy of Sciences. (http://www.pnas.org/content/early/2012/04/02/1202407109.abstract) Note that while ONE Future may not accept every conclusion of this study, we believe its findings are sufficiently robust to serve as a guidepost for our aspirational target.

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SUMMARY OF KEY RECOMMENDATIONS

ONE Future appreciates EPA's proposal to establish an official linkage between ONE Future and the Methane Challenge program. By supporting ONE Future as a Methane Challenge commitment option, EPA is promoting the deployment of an innovative, flexible and performance-based approach to managing methane emissions. We believe that the proposed public-private collaboration between EPA's Methane Challenge and the industry-led ONE Future coalition will achieve significant methane reductions at the lowest cost to industry and consumers. Thanks to EPA's support, results will be uniformly tracked and reported in public to assure transparency and credibility, while facilitating performance benchmarking. ONE Future member companies are fully committed to meeting a scientifically robust end-goal through deployment of cost-effective technologies and work practices. EPA's proposal to establish a direct and official linkage between ONE Future and the Methane Challenge program will add to our efforts to achieve meaningful reductions in a transparent manner.

The following is a brief summary of some of our key recommendations:

- An important objective of the Methane Challenge program should be facilitating the use of scientifically rigorous methods to measure and report up-to-date, accurate, and representative methane emissions data.
- EPA should, in partnership with other federal and state regulators, work to establish the regulatory conditions that will incentivize faster emission reductions across the industry.
- EPA should promote the use of simple but effective emission estimation methodologies that facilitate supplemental emissions reporting from Methane Challenge program partners.
- The Methane Challenge program should provide straightforward metrics to recognize and account for the significant reduction potential associated with widely practiced fugitive emission abatement work practices such as Leak Detection and Repair and Directed Inspection & Maintenance programs.
- EPA should ensure that there is a streamlined, science-based process in place to allow for rapid review and approval of proposed alterations to future Best Management Practices and Methane Challenge protocols, so that the program can adapt in pace with technological change.

DETAILED COMMENTS AND RECOMMENDATIONS ON EPA'S METHANE CHALLENGE PROPOSAL

Introduction

In January 2015, the Obama Administration specified an overarching goal of reducing methane emissions from the oil and gas sector by 40 to 45 percent below 2012 levels by the year 2025.[4] Based on our analysis and public statements, we conclude that a reduction goal of 40-45% equates to emission reductions of between 77 and 86 million metric ton of carbon dioxide by 2025[5] – even as the EIA projects that natural gas production will likely grow some 27 percent over that same period.[6] In addition to EPA's Methane Challenge, major components of the Administration's Strategy to Reduce Methane Emissions include the following regulatory actions:

- EPA's proposed performance standards for new and modified sources in the oil and gas sector (OOOOa), which EPA estimates will result in emission reductions equivalent to between 7.7 and 9 million metric tons of carbon dioxide[7];
- EPA's draft Control Techniques Guidelines (CTGs) for reducing VOC emissions from existing equipment and processes in the oil and natural gas industry, which EPA estimates will result in emission reductions equivalent to 5.5 million metric tons of carbon dioxide[8];
- BLM's Venting and Flaring rule, for which no estimates are currently available; and
- PHMSA's future rule for addressing the sector, for which no estimates are currently available.

From these projections, we conclude that a majority of the methane emission reductions associated with meeting the Administration's 40-45% goal are expected to be achieved via voluntary programs such as Methane Challenge. ONE Future has made a commitment to achieve a specific, measurable and ambitious performance target that, if adopted across the industry, would obviate the need for future regulation, while simultaneously improving the reliability of emissions data.

In addition to making specific recommendations surrounding program design and implementation, ONE Future's comments encourage EPA and other federal agencies to acknowledge the significance of our commitment and to consider providing a variety of incentives that would both incentivize participation and reward company achievements in improving their management of methane emissions.

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[4] See: The White House, "FACT SHEET: Administration Takes Steps Forward on Climate Action Plan by Announcing Actions to Cut Methane Emissions" January 15, 2015. Accessed on November 2, 2015 at: https://www.whitehouse.gov/the-press-office/2015/01/14/fact-sheet-administration-takes-steps-forward-climate-action-plan-anno-1

[5] Source: https://www.whitehouse.gov/energy/climate-change "...achieving this goal would save up to 180 billion cubic feet of wasted natural gas in 2025." Accessed on November 2, 2015. Our calculations indicate that 180 bcf of natural gas is equivalent to approximately 86 million metric tons of CO_2. (Utilizing a Global Warming Potential of 25 and assuming a factor of 19.2 g methane/scf of natural gas.)

[6] U.S. Energy Information Administration, "Annual Energy Outlook 2015", *Table: Natural Gas Supply, Disposition, and Prices*. Accessed on November 2, 2015 at: http://www.eia.gov/beta/aeo/#/?id=13-AEO2015&cases=ref2015

[7] See US EPA, "Proposed Climate, Air Quality and Permitting Rules for the Oil and Natural Gas Industry: Fact Sheet," August 18, 2015. Accessed on November 2, 2015 at: http://www3.epa.gov/airquality/oilandgas/pdfs/og_fs_081815.pdf.

[8] *Ibid.*

Recommendations for Establishing the Conditions that will Incentivize Early Action to Reduce Methane Emissions.

Voluntary programs such as the Methane Challenge have the potential to achieve greater emission reductions at lower cost to both industry and consumers than regulatory actions – if the appropriate incentives are in place to encourage robust industry participation. In many ways, the degree of industry participation in the Methane Challenge is likely to be contingent upon key features of the regulatory environment, such as whether taking early action to eliminate emissions could avoid a company's exposure to costly prescriptive regulations in the future, or conversely, whether taking early action might actually disadvantage a company vis-à-vis competitors who deferred action. We believe that EPA can and should establish straightforward and costless regulatory conditions and incentives that would encourage participation in Methane Challenge without diminishing the agency's ability to assure continuous improvement in the management of methane emissions. Further, we believe that EPA can structure incentives for those companies that go above and beyond minimum program expectations.

Regulatory incentives may be particularly important in the current context surrounding shale gas development, where low commodity prices drive companies to implement cost-cutting measures and avoid initiatives that could result in new costs. EPA should consider regulatory incentives whenever they effectively drive the industry to achieve desired outcomes (i.e. reduce emissions). We believe that enrollment in voluntary programs such as Methane Challenge would be greatly enhanced if EPA and other federal partners worked to deploy federal-level solutions to reduce the costs associated with complying with a patchwork of state and local regulations and requirements.

We look forward to working together with EPA to develop detailed proposals to provide regulatory incentives to companies that demonstrate consistently high performance in methane emissions management. Some current recommendations for consideration include:

Methane Challenge Commitments as Alternative Compliance Measures for proposed EPA regulations.

Given the commitment of Methane Challenge participants to achieve both near-term and long-term deep reductions in methane emissions from all sources – including *new, modified, and reconstructed* sources – it is appropriate for those commitments to serve as alternative means of compliance with currently proposed command-and-control regulations addressing methane and Volatile Organic Compounds (VOCs) from the same facilities:

a. *Methane Challenge commitments as alternative compliance measures under the proposed NSPS OOOOa rule.* In so far as companies participating in the Methane Challenge are adopting corporate-wide commitments, those commitments will apply to new, modified, and reconstructed sources owned and operated by those companies. Therefore, the participating companies should have the opportunity to demonstrate to EPA that implementation of their commitments will achieve reductions in methane (and, as applicable, VOCs) that are equivalent to those achieved by the traditional measures otherwise required under the OOOOa rule under Section 111(b) of the Clean Air Act. Where such a demonstration can be made, the Methane Challenge commitment should have the status of a valid alternative compliance measure. ONE Future will provide additional detail on this idea in our comments on the proposed OOOOa rule.

b. *Methane Challenge commitments as alternative measures for consideration in Control Technique Guidelines and/or State Implementation Plans*. For the same reasons discussed above with respect to the OOOOa rule, we believe that EPA should consider issuing revised guidance to states that would describe how states may use Methane Challenge commitments as Control Techniques Guidelines (CTGs), in lieu of CTGs, or in addition to CTGs in their State Implementation Plans (SIPs). In the past, EPA has issued guidance to states that suggested how states might consider incorporating voluntary programs into their SIPs so as to "encourage new control strategies for meeting CAA requirements." [9] We suggest that EPA consider updating this guidance to states, through workshops and other mechanisms, to describe how states could integrate Methane Challenge voluntary commitments into their State Implementation Plans for the ozone nonattainment areas and areas within ozone transport regions.

   A noteworthy precedent wherein EPA allowed states to employ voluntary programs as a means of complying with regulatory requirements in their SIPs is the usage of emission reductions from Voluntary Woodstove Changeout Programs.[10] Another innovative action that incentivized voluntary emission reductions can be seen in EPA's Voluntary Airport Low Emission (VALE) program, which provided guidance for generating emission reduction credits at airports under the General Conformity and New Source Review (NSR) programs.[11]

Methane Challenge commitments as an alternative to future Section 111(d) methane regulation of existing sources in the oil and gas sector.

Substantial participation of oil and gas companies in the Methane Challenge could result in a reduction in methane emissions or emissions rates in an amount that would obviate the need for additional regulation of methane emissions from the sector. For this reason, we encourage EPA to consider providing industry partners with assurances that if their proactive investments in emissions abatement measures achieve specified targets, it would obviate the need for future regulation under Section 111(d) of the Clean Air Act.

Such an approach has strong legal support. Courts have established that "an agency has broad discretion to choose how best to marshal its limited resources and personnel to carry out its delegated responsibilities."[12] In the recent case of *WildEarth Guardians v. EPA*, the D.C. Circuit

[9] US EPA, *Incorporating Emerging and Voluntary Measures in a State Implementation Plan,* September 2004. Accessed on Nov. 2, 2015: http://www3.epa.gov/ttn/caaa/t1/memoranda/evm_ievm_g.pdf

[10] US EPA, *Guidance for Quantifying and Using Emission Reductions from Voluntary Woodstove Changeout Programs in State Implementation Plans*, January 2006. Accessed on Nov. 2, 2015: http://www3.epa.gov/ttn/caaa/t1/memoranda/guidance_quantfying_jan.pdf

[11] US EPA, *Guidance on Airport Emission Reduction Credits for Early Measures Through Voluntary Airport Low Emission Programs*, Sept. 2004. Accessed on Nov. 2, 2015: https://www.faa.gov/airports/resources/publications/reports/environmental/media/AERC_093004.pdf

[12] *Massachusetts v. EPA*, 549 US 497, 527 (2007).

affirmed EPA's decision not to issue section 111 rules—including both new source rules under section 111(b) and existing source rules under section 111(d)—for methane emissions from coal mines.[13] The D.C. Circuit reasoned that EPA's justification— that EPA was "taking a common-sense, step-by-step approach intended to obtain the most significant greenhouse-gas-emissions reductions through using the most cost-effective measures first"—was a sufficient basis for the court to hold that EPA had not violated its obligations under the Clean Air Act by forgoing regulation.[14]

The commitment being undertaken by ONE Future and other Methane Challenge participants constitutes just such a common-sense approach to achieving significant GHG reductions via the most cost-effective mechanism possible. Therefore, we urge EPA to explicitly and publically recognize that, consistent with the *WildEarth Guardians* holding, sufficient industry participation and successful implementation of the Methane Challenge will reduce methane emissions from existing sources in the oil and gas sector to such a degree that agency resources would be better marshalled by regulating other sources of greenhouse gases. In which case, the agency will exercise its discretion to forgo regulation of existing sources of methane under section 111(d).

Methane Challenge Commitments as an acceptable means of compliance with any future Section 111(d) methane regulation.

Individual companies adopting ambitious commitments under the Methane Challenge should have assurances that their efforts will earn regulatory recognition under any future Section 111(d) methane regulation in the event that the total efforts are not sufficient to avoid such regulation. Absent such assurances, companies evaluating participation in the Methane Challenge will consider the risk that they effectively would be penalized for early action, i.e., by making an investment in voluntary action that their competitors have not made *and* then being required to make further investments under a future regulatory program. If not addressed, this risk could dissuade many companies from participating in the Methane Challenge.[15] In other words, if EPA does not provide such assurances, there is a strong risk that EPA will not achieve its objectives for the Methane Challenge.

EPA could provide assurances of regulatory relief to companies participating in the Methane Challenge in a number of ways. For ONE Future, the preferred way would be for EPA to provide assurances that it will propose in any future Section 111(d) methane regulation for the sector that a company's corporate-wide implementation of its Methane Challenge commitment will constitute compliance with the requirements under the regulation. We recognize that EPA is unlikely to provide binding assurances that will govern or constrain agency actions in future regulatory programs. However, we nevertheless urge the agency to issue a Statement of Policy outlining these elements, and to make clear that it will include them in any proposal for new regulation of existing

[13] *WildEarth Guardians v. EPA*, No. 13-1212, 2014 WL 1887372 (D.C. Cir. May 13, 2014).
[14] *WildEarth Guardians* at 6.
[15] To be sure, companies have a modest incentive to participate in the Methane Challenge if they have reason to believe that widespread participation in the Methane Challenge will forestall inefficient, command-and-control regulation of existing sources. However, this incentive is diminished by a collective action problem: an individual company can only control its own participation, not the participation of other companies. That is why it is important provide benefits of participation that a can company can secure through its own actions alone.

sources. EPA could also integrate them into a Memorandum of Understanding with each participating company.

'Baseline Protection' measures to ensure a level playing field for Methane Challenge participants. In the event that EPA cannot propose regulatory relief as described above, it should provide assurances that Methane Challenge participants will be recognized – not penalized – for their early voluntary actions. Such recognition could be achieved by providing "baseline protection." For example, the baseline year for any future regulatory program for existing sources of methane emissions in the oil and gas sector should be 2012, the benchmark year against which the Obama Administration is measuring the reductions it expects to achieve from its methane program. In any event, the baseline year should be no later than the launch date for the Methane Challenge program. If, for some reason, EPA is compelled to establish a later baseline year, the Agency at least should adjust upward the historic baseline emission levels for companies participating in the Methane Challenge. Such baseline protection is vital to ensure a level playing field between companies participating in the Methane Challenge and companies that do not. Otherwise, Methane Challenge participants will be penalized for their voluntary investments in methane abatement.

Mitigating or eliminating civil penalties for Methane Challenge participants.
For Methane Challenge participants, we encourage EPA to consider establishing criteria for the elimination or mitigation of civil penalties that result from minor enforcement actions brought under CAA Section 113(b). EPA has (for different reasons) established such criteria for certain small businesses, but in this case we suggest that EPA might justify alleviating civil penalties on the grounds that a company's commitment to make ambitious voluntary methane reductions should be considered a mitigating factor for minor enforcement actions. Alternatively, EPA could consider the Methane Challenge program as a Supplemental Environmental Project (SEP) that an unaffiliated settling party could consider in lieu of penalties under an enforcement action. The EPA's SEP Policy is designed to encourage environmental benefits beyond existing regulations, and is consistent with the design of the Methane Challenge program.

Facilitate the expedited review of related permits and regulatory approvals for Methane Challenge participants.
Utilizing cooperative interagency structures already in place, such as the Interagency Working Group to Support Safe and Responsible Development of Unconventional Domestic Natural Gas Resources, the Administration should consider linking emission reductions achieved under the Methane Challenge with expedited processing of permits and regulatory actions for related activities on federal lands, and streamlined National Environmental Policy Act reviews. Additionally, we encourage the EPA to consider providing expedited review for New Source Review (NSR) permit applications submitted by participants in the Methane Challenge that commit to and demonstrate a level of performance consistent with the ONE Future program's commitments.

Reduce paperwork burdens related to the demonstration of compliance with existing and proposed EPA emission rules.

Companies that achieve specified interim targets for their methane emission intensity should be relieved of many of the paperwork burdens associated with demonstrating their compliance with both the EPA's proposed OOOOa New Source Performance Standards, as well as those that may be associated with a future Existing Source Performance Standard for the oil and gas sector. EPA's own cost/labor estimates associated with the proposed NSPS requirements for industry record keeping and reporting (activities such as writing and submitting the notifications and reports, developing systems for the purpose of processing and maintaining information, and training personnel to be able to respond to the collection of information) indicate an estimated average annual burden of 92,658 labor hours with an annual average cost of $3,163,699.[16] Although some of the data and records are basic, many provisions are purely related to demonstrating compliance. (E.g. EPA requires digital photographs of operators physically performing monitoring surveys with embedded latitude and longitude positions). Stated differently, these reporting provisions exist to prove you committed no crime. We believe that this burden should be waived or mitigated for proactive operators who have good track records for compliance and safe operations and who by enrollment in ONE Future have demonstrated their interest in continuous improvement.

Recommendations on the Reporting Elements Associated with Methane Challenge.

ONE Future generally supports EPA's proposed facility definitions for Methane Challenge.

ONE Future proposes to have member companies report their emissions to EPA via the Methane Challenge reporting platform in order to demonstrate progress toward our emission intensity commitments. Under the ONE Future program, net emissions and emission intensities will be computed from emissions estimated and aggregated at the levels indicated in the table below for all covered emission sources.

Industry Segment	Reporting Facility
Production & Gathering	Consistent with Subpart W
Processing	Consistent with proposed Subpart W
Transmission & Storage	Reported at each Pipeline level[17]
Distribution	Consistent with Subpart W

[16] See "Oil and Natural Gas Sector: Emission Standards for New and Modified Sources" 80 Fed. Reg. 56,593 (Sep. 18, 2015).

[17] The reporting level for ONE Future's Transmission and Storage industry segment includes the aggregate of the covered emission sources included in the following facility definitions listed in Appendix C of the Methane Challenge Supplementary Technical Information: "Natural Gas Transmission Compression & Underground Natural Gas Storage" and "Onshore Natural Gas Transmission Pipeline".

EPA should facilitate the reporting of emissions from facilities that fall below the Subpart W reporting threshold.

For the relatively small number of facilities that fall below the Subpart W reporting threshold of 25,000 tonnes per year and have no default GHGRP emission factors, it is important that EPA permit emission estimations by means of engineering calculations based on process knowledge, company records, and best available data. For example, EPA has suggested that any voluntary reporting of ONE Future company facilities that are currently below the reporting threshold must be done with the exact same process and rigor as facilities that already must report under the GHGRP regulatory program. This approach could significantly restrict the number of participants in the Methane Challenge program if EPA were to require (for example) that they expand their leak detection, quantification, and reporting to the same level of an existing regulatory program in order to participate in a voluntary program. For those industry segments and emission sources for which appropriate data is available, the Methane Challenge program should allow participants to take advantage of the voluminous GHGRP activity data, leak surveys, measurements, and emissions data collected over the past several years. We recommend that participants also be permitted to utilize their own company-specific measured data (e.g. GHGRP data) or EPA's national emission factors from the GHGI for facilities that fall below the Subpart W reporting threshold. This approach would allow participants to utilize data that still meets the rigor of the GHGRP or GHGI or the direct measurement principles, but at a fraction of the cost and resources that would be needed to meet all the leak detection, quantification, and reporting requirements under certain sections of the GHGRP.

ONE Future encourages EPA to facilitate the use of direct measurements where it might improve data quality.

The ONE Future coalition is committed to working with EPA to help improve both the quantity and quality of emissions data. To this end we believe it is imperative that Methane Challenge participants be both permitted and encouraged to utilize updated emission factors that are based on the latest science or on representative surveys that utilize direct measurements. Although it is important that the Methane Challenge program avoid conflicting with, or unnecessarily overlapping the Greenhouse Gas Reporting Program (GHGRP), companies must have the flexibility to develop customized emission factors that are based on direct measurements employing generally acceptable protocols. Further, other voluntary programs, such as the Climate and Clean Air Coalition (CCAC), to which EPA is providing technical support and even EPA's own Gas STAR program have encouraged direct measurements. The EPA Gas STAR emission reductions are "backed off" from the EPA gross emissions to arrive at the net emissions from US natural gas systems. Employing similar logic, the ONE Future protocol for computing the net emissions intensity solves the concern related to potential conflicts between the data reported under GHGRP using default factors versus direct measurements. The ONE Future protocol for computing net emissions intensity solve the concern related to potential conflicts between the data reported under GHGRP using default factors versus direct measurements. ONE Future provides detailed discussion and recommendations surrounding the usage emissions calculations based on direct measurements in Appendix I entitled "Detailed

Recommendations for Reporting Emissions under the ONE Future Commitment Option of the Methane Challenge Program."

EPA should recognize and account for the reduction potential of fugitive emissions abatement practices such as LDAR and DI&M.

Although it is widely known that work practices such as Leak Detection and Repair (LDAR) and Directed Inspection and Maintenance (DI&M) have been demonstrated to be effective in reducing equipment leaks and fugitive methane emissions, the GHGRP does not account for any reductions achieved via the application of these work practice standards. EPA has indicated that they will recognize reductions related to these programs but has proposed to await finalization of pending regulatory actions before specifying abatement options (or defining emission factors for such options) for fugitive emissions and equipment leaks.

ONE Future opposes such a delay as we believe that there is no reason to link pending regulatory requirements governing fugitives from new sources with voluntary actions on both new and existing sources. To the contrary, one of the key features of a voluntary program is the fact that it can accommodate and encourage the deployment of innovative and customized approaches to emissions abatement. We encourage the EPA not to wait for finalization of the proposed OOOOa to arrive at appropriate reduction estimates for companies utilizing these work practice standards; rather we urge EPA to provide a clear methodology that allows companies to quantify their reductions by implementation of these voluntary practices.

We urge the EPA to refrain from collecting non-pertinent information from ONE Future Methane Challenge partners in an effort to differentiate voluntary actions from mandated actions.

EPA has proposed requesting that Methane Challenge participants submit "Applicable air regulations for included facilities, including a listing of the sources covered in the partner's Methane Challenge commitment that are affected by each regulation." ONE Future opposes this element of EPA's proposal, as it is neither reasonable nor practical to require participants in the Methane Challenge to differentiate voluntary actions from regulatory actions.

As noted throughout, the ONE Future approach was built around identifying a robust, scientifically-determined performance target that is consistent with optimal performance. Even in the unlikely event that a company was to achieve and sustain such a level of performance exclusively by adhering to state and federal mandates, the outcome is what's important: optimal performance.

ONE Future's ambitious one percent goal was adopted before EPA proposed the pending OOOOa rule and Control Techniques Guidelines guidance. The fact that EPA might subsequently mandate some portion of emission reductions through regulation does not diminish the commitment by ONE Future. Even for companies that commit to ONE Future *after* the promulgation of regulations, it is reasonable for EPA to conclude as a matter of policy that the ONE Future commitment is sufficiently ambitious without requiring further reductions to account for regulatory mandates.

EPA should ensure that reporting deadlines for Methane Challenge do not compound workloads related to mandatory EPA reports.

EPA has proposed that annual data submittals would be collected annually in spring of each year. ONE Future recommends a June 30th deadline to submit annual emissions reports under the EPA Methane Challenge program. Companies are currently required to submit their mandatory GHG reports under Subpart W by the end of the first quarter. We encourage EPA to establish a June 30th deadline for Methane Challenge reporting so as to avoid needlessly compounding workloads.

Recommendations on Methane Challenge program administration and design.

Submittal of implementation plans.

ONE Future supports the EPA's proposed Guidelines for Methane Challenge Implementation Plans. ONE Future agrees with the simple and straightforward plan information requirements collected in this plan. We do not believe it prudent or necessary to ask ONE Future companies to identify in advance the timing or nature of specific abatement actions, as a key feature of our performance-based approach is its flexibility to adapt to operational and commercial circumstances. Our program should be judged by its results, not by the processes which led to those results. EPA's proposed plan template matches our needs and expectations.

Branding the Methane Challenge Program.

EPA solicited comment on the proposed name "Natural Gas STAR Methane Challenge Program". It is obviously a minor point, but we would suggest that the proposed Methane Challenge program holds little resemblance or relationship to EPA's Natural Gas STAR program, and in fact marks a significant departure from other approaches to voluntary programs. In order to mark the significance of this new program, we respectfully suggest eliminating "Natural Gas STAR" from the title of the effort, in favor of simply "Methane Challenge."

APPENDIX I. Detailed Recommendations for Reporting Emissions Under the ONE Future Commitment Option of the Methane Challenge Program.

As discussed briefly in the Introduction to these comments, the ONE Future framework calls for tracking company progress and program progress by computing CH_4 emission intensities from natural gas systems at the national industry level, segment level,[18] and participating company level. At the national level, ONE Future's overall program goal is to reduce CH_4 emissions by 2025 to one percent of gross U.S. natural gas production. This is ONE Future's National Intensity Target. The target will be based on emissions data from the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI) and production data from the U.S. Energy Information Administration (EIA). Based on 2012 emissions and production data, emissions from the natural gas sector were approximately 1.49 percent of production in 2012.[19] By the year 2025, it is ONE Future's collective goal to achieve an average annual methane emission intensity[20] rate across our operations that, if achieved by all U.S. operators across the natural gas value chain would be equivalent to one percent or less of gross U.S. natural gas production.

To enable diverse companies involved in different segments of the natural gas supply chain to report CH_4 emissions in a manner that is both consistent and transparent, ONE Future will develop a Methane Emissions Intensity Estimation Protocol.[21] In order to minimize reporting burdens and provide consistent and transparent reporting, this protocol will rely in large part on existing EPA estimation and reporting mechanisms – principally the U.S. EPA's Greenhouse Gas Reporting Program, 40 CFR Part 98 Subpart W (GHGRP) and the national Greenhouse Gas Inventory (GHGI). The focus of this Appendix is to summarize key elements of our proposed Methane Emissions Intensity Estimation Protocol and provide recommendations to EPA specifying both which emissions sources ONE Future's framework would track and how we recommend that companies be permitted to measure and report their emissions under Methane Challenge. In this manner, the ONE Future framework would significantly streamline reporting requirements consistent with existing U.S. reporting requirements and minimize additional burdens for participating companies.

What follows are ONE Future's specific recommendations as to the delineation of emissions sources and the proposed method by which emissions be reported for each of the four principal industry segments. We look forward to feedback from the EPA and plan to incorporate necessary revisions to our final Methane Emissions Intensity Estimation Protocol.

[18] The four principal industry segments are: (1)production and gathering; (2) processing; (3)transmission and storage; and (4)distribution.

[19] This figure is based on emissions data from the 2012 U.S. EPA inventory of GHG emissions (GHGI), accounting for co-allocation of emissions from associated gas originating at oil wells and lease condensates from gas wells, and 2012 natural gas gross withdrawals as reported by the EIA.

[20] In this paper, the term "emission intensity" refers exclusively to the average methane (CH4) emission rate over total methane throughput (as reported to the EIA) in a given system.

[21] The scope of this protocol is limited to CH_4 emissions reporting and progress tracking. Specific program elements for company engagement in the EPA Methane Challenge Program, such as memorandums of understanding (MOU) between participating companies and the EPA, implementation plans, and specific data submission and management software to support emissions reporting, will be defined by EPA or are outside the scope of this document.

TABLE OF CONTENTS –EMISSIONS REPORTING APPENDIX

1. Production Segment

Table 1 outlines the emission sources applicable to natural gas production operations and included in the GHGI for Natural Gas Systems. Table 1 provides a reference to the rule language that addresses the sources included in the GHGRP and indicates which sources are not included in the GHGRP.

Table 1. Production Segment Emission Sources

Emission Source	GHGRP Reference
Vented Emission Sources	
Gas Well Completions and Work overs with Hydraulic Fracturing	98.232(c)(6), 98.232(c)(8)
Gas Well Completions and Work overs without Hydraulic Fracturing	98.232(c)(5), 98.232(c)(7)
Well Venting for Liquids Unloading	98.232(c)(5)
Pneumatic Controller Vents	98.232(c)(1)
Chemical Injection Pump Vents	98.232(c)(3)
Dehydrator Vents	98.232(c)(14)
Storage Tanks Vents	98.232(c)(10)
Tank Vent Malfunctions	98.232(c)(10)
Well Testing Venting	98.232(c)(12)
Associated Gas Venting	98.232(c)(13)
Acid Gas Removal	98.232(c)(17)
Well Drilling	Not included
Vessel Blowdowns	Not included
Pipeline Blowdowns	Not included
Compressor Blowdowns	Not included
Compressor Starts	Not included
Pressure Relief Valves	Not included
Mishaps	Not included
Fugitive Emission Sources	
Reciprocating Compressors	98.232(c)(11)
Centrifugal Compressors	98.232(c)(19)
Well site Fugitive Emissions	98.232(c)(21)
Combustion Emission Sources	
Internal Combustion Units	98.232(c)(22)
External Combustion Units	98.232(c)(22)
Flare Stacks	98.232(c)(9)
Well Testing Flaring	98.232(c)(12)
Associated Gas Flaring	98.232(c)(13)

1.1 Subpart W Sources and Methods

For production operations, the GHGRP requires reporting emissions for the sources shown in Table 1.2. The estimation method(s) required by the GHGRP is also summarized in the table. ONE Future proposes to report emissions based on metric tons of CH_4 emissions for the sources listed below.

Table 1.2. GHGRP CH_4 Emission Sources for Production Operations

CH4 Emission Source	GHGRP Subpart	CH4 Estimation Method
Vented Emission Sources		
Gas well venting during completions and workovers without hydraulic fracturing	989.233(h)	Default emission factor
Gas well venting during completions and workovers with hydraulic fracturing	98.233(g)	Measured flowback gas volume vented or flared
Well venting for liquids unloading	98.233(f)	Engineering estimation or direct measurement
Pneumatic Controllers	98.233(a)	Default emission factors based on type of pneumatic controller
Pneumatic Pumps	98.233(c)	Default emission factor
Dehydrator Vents **Kimray Vents**	98.233(e)	Dehydrators >0.4 MMscf use modeling. Dehydrators <0.4 MMscf use default emission factor. Desiccant dehydrators use an engineering equation.
Storage Tanks	98.233(j)	For throughput > 10 barrels/day: Process simulator or engineering estimate based on liquid composition. For throughput <10 barrels/day: default emission factor.
Separator liquid dump valves	98.233(j)	Based on tank emissions and time the dump valve is not closing properly
Well Testing Venting and Flaring	98.233(l)	Engineering estimate based on gas to oil ratio or gas production rate
Associated Gas Venting and Flaring	89.233(m)	Engineering estimate based on gas to oil ratio
AGR Vents	98.233(d)	No CH4 emissions are required to be reported for AGR vents
Fugitive Emission Sources		
Reciprocating Compressors – Fugitive	98.233(p)	Default emission factor
Centrifugal Compressors - Fugitive	98.233(o)	Default emission factor
Well Site - Fugitive	98.233(q)	Default component counts and default emission factors
Combustion Emissions Sources		
External combustion sources > 5 MMBTU/hr	98.233(z)	Fuel combustion rates and gas composition
Internal combustion sources >1 MMBTU/hr	98.233(z)	Fuel combustion rates and gas composition
Flare Stacks	98.233(n)	Flow measuring device on the flare or use of engineering calculations based on process knowledge, company records, and best available data

1.2 Non Subpart W Sources and Methods

We propose that for emissions for facilities that are under the reporting threshold of 25,000 tonnes/year and/or are not subject to the GHGRP will be based on the participant's emissions data from the facilities that do report to the GHGRP. Where a participant does not have specific emissions data to apply to these facilities, default GHGRP emission factors will be applied, or average GHGRP emission factors will be developed from the publicly available GHGRP data. This approach applies to this category of 'below-threshold' emission sources for all segments.

1.3 Emissions for Sources Not Included in the GHGRP

Table 1.3 indicates emission sources that are not currently included in the GHGRP. An example of sources intentionally not included in GHGRP would be blowdown emissions in Production. Table 1.3 provides recommended emission factors for sources not currently included in the GHGRP for onshore production operations. ONE Future proposes that the emission factors for this category of sources be revised to align with future changes to the GHGI and/or GHGRP, as appropriate.

Table 1.3. Recommended CH4 Emission Factors for Missing Emission Sources in Onshore Production Operations

CH_4 Emission Source	Recommended CH_4 Emission Factor	Units	Data Source
Well Drilling	2,698	scfy CH_4/well	GHGI 2012
Vessel Blowdowns	82.6	scfy CH_4/vessel	GHGI 2012
Pipeline Blowdowns	327.1	scfy CH_4/mile	GHGI 2012
Compressor Blowdowns	3,967	scfy CH_4/compressor	GHGI 2012
Compressor Starts	8,149	scfy CH_4/compressor	GHGI 2012
Pressure Relief Valves	36.1	scfy CH_4/PRV	GHGI 2012
Mishaps	708.1	scfy CH_4/mile	GHGI 2012

At present date, the GHGRP does not currently require reporting for gas gathering pipelines and central gas handling facilities that exist between natural gas production operations and gas processing plants (emissions from these operations are expected to be added to the GHGRP in 2016, with reporting due in 2017). Table 1.4 provides recommended emission factors to account for the missing emission sources for Gathering operations. The emission factors shown are primarily default factors for gathering equipment as outlined in the proposed rule from December 2015[22], or emission factors derived from GHGRP data for similar equipment in production operations.

Table 1.5 outlines recommended emission factors for gathering sources which do not have similar emissions data from production operations in the GHGRP. GHGI emission factors are applied for these sources. We recommend that both Tables 1.4 and 1.5 be updated as reporting requirements under the GHGRP expand to include gathering operations and emissions data are available publicly.

[22] FR Vol. 79, 73148, December 9, 2014, Proposed Rules

Table 1.4. Recommended CH4 Emission Factors for Gathering Operations

CH_4 Emission Source	Recommended CH_4 Emission Factor	Units
Vented Sources		
Pneumatic Controllers	Low-bleed: 1.39 High bleed: 37.3 Intermittent bleed: 15.3	scfh gas/controller
Chemical Injection Pumps	13.3	scfh gas/pump
AGR Vents	6,083	scfd CH_4/AGR
Kimray Vents	1,297	Scf CH_4/MMscf throughput
Dehydrator Vents		
Storage Tank Vents	50,639 for throughput > 10 bbl/day	scf CH_4/sep-yr
	4,200 for crude throughput <10 bbl/day	scf CH_4/sep-yr
	17,600 for condensate throughput <10 bbl/day	scf CH_4/sep-yr
Tank Vent Malfunctions	To be developed from GHGRP data released in 2015	
Fugitive Emission Sources		
Reciprocating Compressors	9.48×10^3	scfy CH_4/compressor
Centrifugal Compressors	1.2×10^7	scfy CH_4/compressor
Gathering Pipeline	2.81	scf gas/hour/mile of pipeline
Heaters	Apply default component counts per equipment and default component emission factors from GHGRP	scfh gas/equipment
Separators		
Dehydrators		
Meters/Piping		
Combustion Emission Sources		
External combustion sources > 5 MMBTU/hr	55,652	scf CH_4/unit-yr
Internal combustion sources >1 MMBTU/hr	Not available until September 2015	scf CH_4/unit-yr
Flare Stacks	4,396	Mscf CH_4/flare-yr

Table 1.5. Recommended CH4 Emission Factors for Missing Emission Sources in Onshore Gathering Operations

CH4 Emission Source	Recommended CH4 Emission Factor	Units	Data Source
Vessel Blowdowns	82.6	scfy CH4/vessel	GHGI 2012
Pipeline Blowdowns	327.1	scfy CH4/mile	GHGI 2012
Compressor Blowdowns	3,967	scfy CH4/compressor	GHGI 2012
Compressor Starts	8,149	scfy CH4/compressor	GHGI 2012
Pressure Relief Valves	36.1	scfy CH4/PRV	GHGI 2012
Mishaps	708.1	scfy CH4/mile	GHGI 2012

2. Processing Segment

Table 2.1 outlines the CH_4 emission sources applicable to natural gas processing operations. For gas processing, all emission sources from the national GHGI are included in the GHGRP except pneumatic controllers.

Table 2.1. Processing Segment Emission Sources

Emission Source	GHGRP Reference
Vented Emission Sources	
Blowdown Vent Stacks	98.232(d)(3)
Dehydrator Vents	98.232(d)(4)
Acid Gas Removal Vents	98.232(d)(5)
Pneumatic Controllers	Not included
Fugitive Emission Sources	
Reciprocating Compressors	98.232(d)(1)
Centrifugal Compressors	98.232(d)(2)
Plant Fugitive Emissions	98.232(d)(7)
Combustion Emission Sources	
Internal Combustion Units	Subpart C
External Combustion Units	Subpart C
Flare Stacks	98.232(d)(6)

2.1 Subpart W Sources and Methods

For gas processing operations, the GHGRP requires reporting emissions for the emission sources shown in Table 2.2. The estimation method(s) required by the GHGRP is also summarized in the table.

Table 2.2. GHGRP CH4 Emission Sources for Gas Processing Facilities

CH_4 Emission Source	GHGRP Subpart	CH_4 Estimation Method
Vented Emission Sources		
Blowdown Vent Stacks	98.233(i)	Engineering estimation
Kimray Vents	98.233(e)	Dehydrators >0.4 MMscf use modeling. Dehydrators <0.4 MMscf use default emission factor. Desiccant dehydrators use an engineering equation.
Dehydrator Vents		
AGR Vents	98.233(d)	No CH_4 emissions are required to be reported for AGR vents
Pneumatic Controllers	Not included	Not included for gas processing
Fugitive Emission Sources		
Reciprocating Compressors – Fugitive	98.233(p)	Emissions are based on annual measurement of compressors in the mode found for reciprocating rod packing vents, unit isolation valve vents, and blowdown valve vents
Centrifugal Comp. (wet seals) – Fugitive	98.233(o)	Emissions are based on annual measurement of compressors in the mode found for all vents, including wet seal oil degassing vents, unit isolation valve vents, and blowdown valve vents
Centrifugal Comp (dry seals) – Fugitive		
Plants - Fugitive	98.233(q)	Equipment leaks from valves, connectors, open ended lines, pressure relief valves, and meters are calculated based on a leak detection survey and default leaker emission factors
Combustion Emission Sources		
Gas Engines	Subpart C	Fuel combustion rates and measured or default HHV or carbon content
Gas Turbines		
Flare Stacks	98.233(n)	Flow measuring device on the flare or use of engineering calculations based on process knowledge, company records, and best available data

2.2. Non Subpart W Sources and Methods

Refer to Section 1.2

2.3. Emissions for Sources Not Included in the GHGRP

For gas processing, emissions from pneumatic controllers are included in the GHGI, but are not included in Subpart W of the GHGRP. Exhaust emissions from gas engines and turbines are reported under Subpart C which does not currently enable emission factor development. In addition, although Acid Gas Removal units are reported in the GHGRP, only CO_2 emissions are required to be reported. Table 3.8

provides recommended emissions factors for these sources based on emission factors from the GHGI. ONE Future proposes that the emission factors for this category of sources be revised to align with future changes to the GHGI and/or GHGRP, as appropriate.

Table 2.3. Recommended CH4 Emission Factors for Missing Emission Sources in Gas Processing Operations

CH_4 Emission Source	Recommended CH_4 Emission Factor	Units	Data Source
Acid Gas Removal Units	5,376.4	Scfd CH_4/AGR	GHGI 2012
Pneumatic Controllers	145,524	scfy CH_4/plant	GHGI 2012
Exhaust from Gas Engines and Turbines	306.8	tonnes CH_4/plant-yr	Derived from GHGI 2012 data

3. Transmission and Storage Segment

Table 3.1 and 3.2 outline the emission sources applicable to natural gas transmission and storage operations, respectively. The tables indicate which sources are included in the GHGRP and those that are not.

Table 3.1. Transmission Segment Emission Sources

Emission Source	GHGRP Reference
Vented Emission Sources	
Transmission Storage Tanks and compressor scrubber dump valve leakage	98.232(e)(3)
Blowdown Vent Stacks	98.232(e)(4)
Pneumatic Controllers	98.232(e)(5)
Dehydrator Vents	Not included
Pipeline Venting	Not included
Fugitive Emission Sources	
Reciprocating Compressors	98.232(e)(1)
Centrifugal Compressors	98.232(e)(2)
Station Fugitive Emissions	98.232(e)(7)
Pipeline Leaks	Not included
Combustion Emission Sources	
Internal Combustion Units	Subpart C
External Combustion Units	Subpart C
Flare Stacks	98.232(e)(6)

Table 3.2. Storage Segment CH4 Emission Sources

Emission Source	GHGRP Reference
Vented Emission Sources	
Pneumatic Controllers	98.232(f)(3)
Dehydrator Vents	Not included
Storage Station Venting	Not included
Fugitive Emission Sources	
Reciprocating Compressors	98.232(f)(1)
Centrifugal Compressors	98.232(f)(2)
Station Fugitive Emissions	98.232(f)(5)
Storage Wells	98.232(f)(5)
Combustion Emission Sources	
Internal Combustion Units	Subpart C
External Combustion Units	Subpart C
Flare Stacks	98.232(f)(4)

3.1 Subpart W Sources and Methods

For transmission operations, the GHGRP requires reporting CH_4 emissions for the emission sources shown in Table 3.3. Emission sources reported under the GHGRP for Storage operations are shown in Table 3.4. The estimation method(s) required by the GHGRP is also summarized in the tables.

Table 3.3. GHGRP CH4 Emission Sources for Transmission Facilities

CH_4 Emission Source	GHGRP Subpart	CH_4 Estimation Method
Vented Emission Sources		
Transmission Storage Tanks - compressor scrubber dump valve leakage	98.233(k)	Annual monitoring and measurement where the tank vapors from the vent stack are continuous for 5 minutes
Blowdown Vent Stacks	98.233(i)	Engineering estimation or flow meters
Pneumatic Controllers	98.233(a)	Default emission factors based on type of pneumatic controller
Fugitive Emission Sources		
Reciprocating Compressors – Fugitive	98.233(p)	Emissions are based on annual measurement of compressors in the mode found for reciprocating rod packing vents, unit isolation valve vents, and blowdown valve vents
Centrifugal Compressors – Fugitive	98.233(o)	Emissions are based on annual measurement of compressors in the mode found for all vents, including wet seal oil degassing vents, unit isolation valve vents, and blowdown valve vents

Plants - Fugitive	98.233(q)	Equipment leaks from valves, connectors, open ended lines, pressure relief valves, and meters are calculated based on a leak detection survey and default leaker emission factors
Combustion Emission Sources		
Gas Engines	Subpart C	Fuel combustion rates and measured or default HHV or carbon content
Gas Turbines		
Flare Stacks	98.233(n)	Flow measuring device on the flare or use of engineering calculations based on process knowledge, company records, and best available data

Table 3.4. GHGRP CH4 Emission Sources for Storage Facilities

CH_4 Emission Source	GHGRP Subpart	CH_4 Estimation Method
Vented Emission Sources		
Pneumatic Controllers	98.233(a)	Default emission factors based on type of pneumatic controller
Fugitive Emission Sources		
Reciprocating Compressors – Fugitive	98.233(p)	Emissions are based on annual measurement of compressors in the mode found for reciprocating rod packing vents, unit isolation valve vents, and blowdown valve vents
Centrifugal Compressors – Fugitive	98.233(o)	Emissions are based on annual measurement of compressors in the mode found for all vents, including wet seal oil degassing vents, unit isolation valve vents, and blowdown valve vents
Stations - Fugitive	98.233(q)	Equipment leaks from valves, connectors, open ended lines, pressure relief valves, and meters are calculated based on a leak detection survey and default leaker emission factors
Storage Wellheads - Fugitive	98.233(q)	Equipment leaks from valves, connectors, open ended lines, and pressure relief valves are calculated based on a leak detection survey and default leaker emission factors
Combustion Emission Sources		
Gas Engines	Subpart C	Fuel combustion rates and measured or default HHV or carbon content
Gas Turbines		
Flare Stacks	98.233(n)	Flow measuring device on the flare or use of engineering calculations based on process knowledge, company records, and best available data

3.2 Non Subpart W Sources and Methods

Refer to Section 1.2.

3.3 Emissions for Sources Not Included in the GHGRP

Table 3.5 lists CH_4 emission sources that are not currently included in the GHGRP for the transmission and storage segments and provides suggested emission factors to account for the missing emission sources. ONE Future proposes that the emission factors for this category of sources be revised to align with future changes to the GHGI and/or GHGRP, as appropriate.

Table 3.5. Recommended CH_4 Emission Factors for Missing Emission Sources in Transmission and Storage Operations

CH_4 Emission Source	Suggested CH_4 Emission Factor	Units	Data Source
Transmission			
Dehydrator Vents	93.72	Scf CH_4/MMscf	GHGI 2012
Pipeline Venting	31.65	Mscfy CH_4/mile	GHGI 2012
Pipeline Leaks	1.55	Scfd CH_4/mile	GHGI 2012
Storage			
Dehydrator Vents	117.18	scf CH_4/MMscf	GHGI 2012
Storage Station Venting	4,359	Mscfy CH_4/station	GHGI 2012
Transmission and Storage Combustion			
Engine Exhaust	10,525	scf CH_4/station	GHGI 2012
Turbine Exhaust	100	scf CH_4/station	GHGI 2012

4. Distribution Segment

Table 4.1, 4.2 and 4.3 outline the emission sources applicable to LNG storage, LNG import and export terminals, and natural gas distribution operations, respectively. The tables indicate sources that are included in the GHGRP and those that are not.

Table 4.1. LNG Storage Segment CH_4 Emission Sources

Emission Source	GHGRP Reference
Vented Emission Sources	
Storage Station Venting	Not included
Fugitive Emission Sources	
Reciprocating Compressors	98.232(g)(1)
Centrifugal Compressors	98.232(g)(2)
Station Fugitive Emissions	98.232(g)(3)
Combustion Emission Sources	
Internal Combustion Units	Subpart C
External Combustion Units	Subpart C
Flare Stacks	98.232(g)(4)

Table 4.2. LNG Import/Export Segment CH4 Emission Sources

Emission Source	GHGRP Reference
Vented Emission Sources	
Blowdown Vent Stacks	98.232(h)(3)
Fugitive Emission Sources	
Reciprocating Compressors	98.232(h)(1)
Centrifugal Compressors	98.232(h)(2)
Station Fugitive Emissions	98.232(h)(4)
Combustion Emission Sources	
Internal Combustion Units	Subpart C
External Combustion Units	Subpart C
Flare Stacks	98.232(h)(5)

Table 4.3. Distribution Segment CH4 Emission Sources

Emission Source	GHGRP Reference
Vented Emission Sources	
Pneumatic Controllers	Not included
PVR Releases	Not included
Pipeline Blowdowns	Not included
Dig-ins	Not included
Fugitive Emission Sources	
Station Fugitive Emissions	98.232(i)(1)
Below Grade Transmission-Distribution Transfer Stations	98.232(i)(2)
Above Grade Metering-Regulating Stations	98.232(i)(3)
Below Grade Metering-Regulating Stations	98.232(i)(4)
Distribution Mains	98.232(i)(5)
Distribution Services	98.232(i)(6)
Residential Meters	Not included
Commercial Meters	Not included
Industrial Meters	Not included
Combustion Emission Sources	
Internal Combustion Units	98.232(i)(7)
External Combustion Units	98.232(i)(7)

4.1 Subpart W Sources and Methods

Emission source reported under the GHGRP for LNG Storage operations are shown in Table 4.4 and Table 4.5 for LNG import/export operations. For distribution operations, the GHGRP requires reporting emissions for the emission sources shown in Table 4.6.

Table 4.4. GHGRP CH4 Emission Sources for LNG Storage Facilities

CH_4 Emission Source	GHGRP Subpart	CH_4 Estimation Method
Fugitive Emission Sources		
Reciprocating Compressors – Fugitive	98.233(p)	Emissions are based on annual measurement of compressors in the mode found for reciprocating rod packing vents, unit isolation valve vents, and blowdown valve vents
Centrifugal Comp. (wet seals) – Fugitive	98.233(o)	Emissions are based on annual measurement of compressors in the mode found for all vents, including wet seal oil degassing vents, unit isolation valve vents, and blowdown valve vents
Centrifugal Comp (dry seals) – Fugitive		
Storage Station Fugitive Emissions	98.233(q)	Equipment leaks from valves, pump seals, connectors, and “other” are calculated based on a leak detection survey and default leaker emission factors. .
	98.233(r)	Default emission factor is provided for vapor recovery compressors
Combustion Emission Sources		
Gas Engines	Subpart C	Fuel combustion rates and measured or default HHV or carbon content
Gas Turbines		
Flare Stacks	98.233(n)	Flow measuring device on the flare or use of engineering calculations based on process knowledge, company records, and best available data

Table 4.5. GHGRP CH_4 Emission Sources for LNG Import/Export Facilities

CH_4 Emission Source	GHGRP Subpart	CH_4 Estimation Method
Vented Emission Sources		
Blowdown Vent Stacks	98.233(i)	Engineering estimation
Fugitive Emission Sources		
Reciprocating Compressors – Fugitive	98.233(p)	Emissions are based on annual measurement of compressors in the mode found for reciprocating rod packing vents, unit isolation valve vents, and blowdown valve vents
Centrifugal Comp. (wet seals) – Fugitive	98.233(o)	Emissions are based on annual measurement of compressors in the mode found for all vents, including wet seal oil degassing vents, unit isolation valve vents, and blowdown valve vents
Centrifugal Comp (dry seals) – Fugitive		
Station Fugitive Emissions	98.233(q)	Equipment leaks from valves, pump seals, connectors, and “other” are calculated based on a leak detection survey and default leaker emission factors.
	98.233(r)	A default emission factor is provided for vapor recovery compressors.
Combustion Emission Sources		
Gas Engines	Subpart C	Fuel combustion rates and measured or default HHV or carbon content
Gas Turbines		
Flare Stacks	98.233(n)	Flow measuring device on the flare or use of engineering calculations based on process knowledge, company records, and best available data

Table 4.6. GHGRP CH4 Emission Sources for Distribution Operations

CH4 Emission Source	GHGRP Subpart	CH4 Estimation Method
Fugitive Emission Sources		
Equipment leaks from above grade transmission-distribution transfer stations	98.233(q)	Equipment leaks from connectors, block valves, control valves, pressure relief valves, orifice meters, regulators, and open ended lines are calculated based on a leak detection survey and default leaker emission factors.
Equipment leaks from below grade transmission-distribution transfer stations	98.233(r)	Emission factors are calculated based on all surveyed above grade transmission-distribution transfer stations
Equipment leaks from above grade metering-regulating stations	98.233(r)	Emission factors are calculated based on all surveyed above grade transmission-distribution transfer stations
Equipment leaks from below grade metering-regulating stations	98.233(r)	Default emission factors are provided for below grade M&R stations
Distribution main equipment leaks	98.233(r)	Default emission factors are provided by pipeline material type.
Distribution services equipment leaks	98.233(r)	Default emission factors are provided by pipeline material type.
Combustion Emission Sources		
External combustion sources > 5 MMBTU/hr	98.233(z)	Fuel combustion rates and gas composition
Internal combustion sources >1 MMBTU/hr	98.233(z)	Fuel combustion rates and gas composition

4.2 Non Subpart W Sources and Methods

Because all natural gas distribution companies are required to report under Subpart NN of the GHGRP, all companies also have to report under Subpart W. Therefore, Subpart W reporting includes emissions from all natural gas distribution companies.

4.3 Emissions for Sources Not Included in the GHGRP

For LNG Storage and Import/Export operations, exhaust emissions from gas engines and turbines are reported under Subpart C which does not currently enable emission factor development. Table 4.7 provides recommended CH_4 emission factors for these sources.

Table 4.7. Recommended CH_4 Emission Factors for Missing Emission Sources Associated with LNG Operations

CH_4 Emission Source	Suggested Emission CH_4 Factor	Units	Data Source
Combustion Emission Sources			
LNG Engines	0.24	scf CH_4/HP-hr	GHGI 2012
LNG Turbines	0.0056	scf CH_4/HP-hr	GHGI 2012

Table 4.8 provides recommended CH_4 emission factors for emission sources that are included in the GHGI but are not currently reported under Subpart W for distribution operations. ONE Future proposes

that the emission factors for this category of sources be revised to align with future changes to the GHGI and/or GHGRP, as appropriate.

Table 4.8. Recommended CH_4 Emission Factors for Missing Emission Sources in the Distribution Segment

CH_4 Emission Source	Suggested Emission Factor	Units	Data Source
Vented Emission Sources			
PVR Releases	0.0502	Mscf CH_4/mile	GHGI 2012
Pipeline Blowdowns	0.1023	Mscf CH_4/mile	GHGI 2012
Dig-ins	1.595	Mscf CH_4/mile	GHGI 2012
Fugitive Emission Sources			
Residential Meters	143.3	scfy CH_4/meter	GHGI
Commercial Meters	47.9	scfy CH_4/meter	GHGI
Industrial Meters	47.9	scfy CH_4/meter	GHGI

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December 11, 2015

Carey Bylin
U.S. Environmental Protection Agency
1200 Pennsylvania Ave., NW (6207-J)
Washington, DC 20460

Via e-mail: methanechallenge@tetratech.com

RE: The U.S. Environmental Protection Agency's Proposed Natural Gas STAR Methane Challenge Program: Supplementary Technical Information for ONE Future Commitment Option.

Dear Ms. Bylin:

Our Nation's Energy Future Coalition, Inc. (ONE Future) appreciates the opportunity to comment on the U.S. Environmental Protection Agency's (EPA) Proposed Natural Gas STAR Methane Challenge Program's Supplementary Technical Information for ONE Future Commitment Option (STI) released on November 24, 2015.

ONE Future is a unique coalition of leading companies with operations in one or more of the following four principal segments of the natural gas industry: (1) oil and natural gas production and gathering; (2) natural gas processing; (3) natural gas transmission and storage; and (4) natural gas distribution. ONE Future is a non-profit 501(c)(6) trade group that is focused exclusively on improving the management of methane emissions from the wellhead to the burner tip. By bringing together companies from every segment of the natural gas value chain, we aim to deploy innovative solutions to operational and policy challenges that will deliver better results to our customers, increase value to our shareholders, and improve the environment.

We have reviewed the Agency's draft STI, and in general, find the direction of the proposal to be a substantial deviation from the ONE Future framework as it has been discussed with EPA. Moreover, the proposal appears to require the gathering of significant volumes of superfluous data that does nothing to contribute to improved emissions performance, with an associated expense that would serve as a deterrent to participation in the ONE Future framework. Our more substantive comments follow, but given the elements of EPA's proposal that conflict with the ONE Future framework, we believe that it would be beneficial for the Agency to hold a stakeholder workshop, in an attempt to arrive at a better common understanding of how the Methane Challenge can accommodate both the Best Management Practices approach and the ONE Future approach.

ONE Future has recently provided detailed comments to the EPA on its Proposed Framework for the Natural Gas STAR Methane Challenge Program (Proposed Framework) issued on July 23, 2015, as well as the Supplementary Technical Information released on October 19, 2015, and the Draft Partnership Agreement and Draft Implementation Plan Guidelines released on November 10, 2015. We have elected to re-submit those comments to the Proposed Framework in their entirety, as our recommendations were not incorporated into the STI.

As we stated in our recent comments to the EPA's Proposed Framework for the Natural Gas STAR Methane Challenge Program, ONE Future appreciates EPA's proposal to establish an official linkage between ONE Future and the Methane Challenge program. We strongly believe that in supporting ONE Future as a Methane Challenge commitment option, EPA facilitate an approach that can achieve significant methane reductions at the lowest cost to industry and consumers. EPA's support could ensure that emission performance will be uniformly tracked and reported in public to assure transparency and credibility, while facilitating performance benchmarking.

However, insofar as the EPA proposes in the STI that participants will report extensive data and information extraneous to EPA's program mission, we believe that such a reporting effort will detract from that mission and deter industry participation in the Methane Challenge program. For that reason, ONE Future strongly opposes certain elements of the EPA's draft STI which we believe will run counter to the mission of the ONE Future Coalition and the Methane Challenge program.

Specifically, ONE Future urges the EPA to consider the following changes to the draft STI:

1. **Eliminate any requests to report supplemental data and information below the facility level.** Such requests would include component-level emissions or the specific equipment changes or work practices that were deployed at a given facility. As we stated in our comments to the Proposed Framework, ONE Future member companies will report their emissions to EPA via the Methane Challenge reporting platform in order to demonstrate progress toward our emission intensity commitments. Under the ONE Future program, net emissions and emission intensities will be computed from emissions estimated and aggregated at the levels indicated in the table at left

Industry Segment	Reporting Facility
Production & Gathering	Consistent with Subpart W
Processing	Consistent with proposed Subpart W
Transmission & Storage	Reported at each Pipeline level[1]
Distribution	Consistent with Subpart W[2]

[1] The reporting level for ONE Future's Transmission and Storage industry segment would be at the Business Unit level, or alternately would include the aggregate of the covered emission sources included in the following facility definitions listed in Appendix C of the Methane Challenge Supplementary Technical Information: "Natural Gas Transmission Compression & Underground Natural Gas Storage" and "Onshore Natural Gas Transmission Pipeline".
[2] ONE Future is supportive of the clarifying changes to this reporting classification requested by the American Gas Association in its comments to the Proposed OOOOa Rule.

for all covered emission sources. This reporting structure is consistent with the EPA's Greenhouse Gas Reporting Program, and will enable both the EPA and the public to track progress toward our commitments on a year-over-year basis.

2. **Eliminate any requests that program partners classify emission abatement actions as "voluntary" or "mandatory".** Once again, ONE Future is a goal-oriented program that has specified an ambitious, specific and measurable performance target. Whether a company achieves its target by means of deploying voluntary or mandatory measures is immaterial. Likewise, it is immaterial whether a company was already operating at or near its targeted level of performance upon entering the Methane Challenge program. Upon entering Methane Challenge and choosing the ONE Future Commitment Option, all companies will report their emissions in exhaustive detail far above and beyond what is required of companies under existing law or under the Methane Challenge BMP Commitment Option. As noted throughout our comments on EPA's Proposed Framework, the ONE Future approach was built around identifying a robust, scientifically-determined performance target that is consistent with optimal performance. Even in the unlikely event that a company was to achieve and sustain such a level of performance exclusively by adhering to state and federal mandates, the outcome is what is important: optimal performance.

   Further, it should be noted that although the Administration has always communicated that a combination of mandatory and voluntary measures would contribute toward achieving its stated goal of 40-45% reduction in methane emissions from 2012 levels, neither the Administration nor the EPA has chosen to delineate specific targets to the voluntary and mandatory components of their plans. In light of this, we are at a loss to see why it would be incumbent upon industry to differentiate between the two.

   Therefore ONE Future opposes those elements of EPA's proposal that would require companies to classify actions taken as being compliance-related or wholly voluntary, as gathering this information is extraneous, and will lead to unnecessary expenditures that are neither reasonable nor practical.

3. **As stated in our comments to the Proposed Framework, ONE Future urges the EPA to issue Methane Challenge program guidance that recognizes and accounts for the reduction potential of fugitive emissions abatement practices such as Leak Detection and Repair (LDAR) and Directed Inspection and Maintenance (DI&M).** These programs have been demonstrated to be effective in reducing equipment leaks and fugitive methane emissions, however the GHGRP does not account for any reductions achieved via the application of these work practice standards. EPA has indicated that they will recognize reductions related to these programs but has proposed to await finalization of EPA's proposed standards of performance for emissions of methane and volatile organic compounds (VOCs) from new, modified and reconstructed sources

in the oil and gas sector[3] *before* specifying abatement options (or defining emission factors for such options) for fugitive emissions and equipment leaks.

ONE Future opposes such a delay as we believe that there is no reason to link pending regulatory requirements governing fugitives from new sources with voluntary actions on both new and existing sources. To the contrary, one of the key features of a voluntary program is the fact that it can accommodate and encourage the deployment of innovative and customized approaches to emissions abatement. We encourage the EPA not to wait for finalization of the proposed OOOOa to arrive at appropriate reduction estimates for companies utilizing these work practice standards; rather we urge EPA to provide a clear methodology that allows companies to quantify their reductions by implementation of these voluntary practices.

4. **Finally, we urge EPA to revise the data elements requested under the heading of "Emission Sources" in the STI to be consistent with those delineated in the Emissions Reporting Appendix of ONE Future's Comments to the Proposed Framework.**

Thank you for your consideration of these comments. Should you have any questions, please contact me directly.

Tom Michels
Executive Director,
ONE Future Coalition

[3] Oil and Natural Gas Sector: Emission Standards for New and Modified Sources, 80 Fed. Reg. 56,593 (Sep. 18, 2015) ("Proposed OOOOa Rule" or "Proposed Rule").

COMMENTER:

Southern California Gas Company (SoCalGas) & San Diego Gas & Electric (SDGE)

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November 13, 2015

Ms. Carey Bylin
Methane Challenge Program Leader
United States Environmental Protection Agency
William Jefferson Clinton Building
1200 Pennsylvania Avenue, N. W.
Mail Code: 6207A
Washington, DC 20460

Sent via Electronic Mail

Subject: EPA Methane Challenge Proposal – SoCalGas/SDGE Comments

Dear Ms. Bylin,

Southern California Gas Company (SoCalGas) and San Diego Gas & Electric (SDGE) appreciate the opportunity to provide comments on the Environmental Protection Agency's (EPA) proposed Methane Challenge Program. We have been working closely with Pam Lacey of the American Gas Association (AGA) and Brian Jones of the Down Stream Initiative (DSI) group in recent months to help develop relevant industry comments on the enhanced methane reduction program. We support comments they will be providing to you on this program. We also appreciate EPA staff efforts to facilitate open dialogue with industry partners that have resulted in reframing the proposed Gas STAR Gold program into the Methane Challenge Program. We believe the proposed program framework allows companies to balance critical operational, cost and safety demands with practical methane reduction strategies.

In addition to our support of AGA and DSI comments, we believe it is important to note that utilities located in California are faced with additional regulatory challenges. As such, the potential for implementing additional or new methane reduction strategies may vary based on state or regional factors. Our comments primarily address select proposed Best Management Practice (BMP) options as they relate to proposed California-based methane reduction programs and our operations.

Impacts of Proposed Regulatory Activity in California

The Methane Challenge is being proposed at a time when California-based utilities are also being subjected to pending regulations that target methane reductions. Regulatory efforts initiated by the California Air Resources Board (CARB) and the California Public Utilities Commission (CPUC) in the past year will impose mandatory requirements that affect transmission and storage facilities and local distribution systems. Briefly, the proposed regulatory activities are as follows:

CARB Efforts Include:
- Establishing greenhouse gas emission standards for crude oil and natural gas facilities;
- Measuring impacts to new and existing onshore natural gas transmission compressor stations and underground storage fields;

CPUC Efforts Include:
- Issuing the Order Instituting Rulemaking (OIR) 15-01-008, which seeks to implement Natural Gas Leakage Abatement Senate Bill 1371 (Leno, 2014);
- OIR 15-01-008 will require the adoption of rules and procedures to minimize natural gas leakage from CPUC-regulated natural gas pipeline facilities
- OIR 15-01-008 will also require gas corporations to file an annual report about their natural gas leaks and leak management practices
- OIR 15-01-008 will seek to reduce methane emissions from leaks in the gas transmission, distribution and storage utilities in California;
- OIR 15-01-008 will also seek to establish and require the use of best practices for leak surveys, patrols, leak survey technology, leak prevention, and leak reduction

Local Air Districts' Efforts:
- As a direct result of the CARB standards, local Air Districts will eventually update or modify existing regulations or draft new regulations to incorporate methane emission standards or control measures. It is not yet known if local Districts will elect to adopt the state standards or choose to impose more rigorous methane reduction standards for sources within their jurisdiction.

These pending regulatory actions present California utilities with the unique challenge of educating state lawmakers and agencies to better understand the impacts of potentially overlapping or duplicative regulations. Since both the CARB and CPUC actions will become mandatory, they will be the primary drivers for any methane reduction strategies that are implemented by SoCalGas and SDGE. Aside from seeking to avoid duplicative requirements, California utilities also do not want to be inadvertently "penalized" for implementing mandatory requirements that might be similar to Methane Challenge BMPs. We, therefore, suggest that EPA include language in the proposals and subsequent Memoranda of Understanding (MOUs) that would allow affected California utilities to meet Methane Challenge BMP requirements by implementing mandatory control/reduction requirements that may be required by a CPUC or CARB-driven regulation. The same flexibility would apply where other states may have similar regulatory actions or those affected by proposed updates to the EPA Oil & Gas Methane New Source Performance Standards (NSPS) and draft Control Techniques Guidelines. The mandatory requirement would ensure that a particular reduction standard or objective is met, which could also serve as a BMP for the Methane Challenge program.

Currently, the Methane Challenge is scheduled to be finalized and launched well in advance of any of the California regulations. The implementation plan submission will also likely be submitted in advance of those regulations. We, therefore, suggest that program flexibility be provided for companies to modify BMP selections and implementation strategies contingent upon the final release of any local or state-mandated regulations.

Comments on Selected Emission Sources and BMP Strategies

Natural Gas Continuous Bleed Pneumatic Controllers

Mitigation Options:
Utilize natural gas-actuated pneumatic controllers with a continuous bleed rate less than or equal to 6 scf of gas per hour, or
Utilize zero emitting controllers (e.g. instrument air, solar, electric, or mechanical controllers), or
Remove natural gas pneumatics controllers from service with no replacement.

Comment:
In addition to the proposed BMPs for this source category, we suggest EPA also consider that some companies may need to conduct a study to properly characterize their regulator/controller inventory and actual bleed rates. In many instances the actual bleed rates may vary from rates in manufactures literature. In this way they can properly categorize the highest methane emission equipment, implement plans to systematically replace that equipment and strategically specify low-bleed controllers for future equipment purchases within a specified timeframe.

Centrifugal Compressors-venting

Mitigation Options:
Route wet seal degassing to a capture system for beneficial use to achieve at least a 95% reduction in methane emissions, or
Route wet seal degassing to flare or control device24 to achieve at least a 95% reduction in methane emissions, or
Use centrifugal compressors with dry seals.

Comment:
In addition to the proposed BMP, replacement of wet seals with dry seals should take place where feasible. Note that a small population of wet seals may limit cost-effective reduction opportunities.

Reciprocating Compressors- Rod Packing Vent

Mitigation Options:
Replace the reciprocating compressor rod packing every 26,000 hours of operation, or
Replace the reciprocating compressor rod packing prior to every 36 months, or
Route rod packing vent to a capture system for beneficial use to achieve at least a 95% reduction in methane emissions, or
Route rod packing vent to flare or control device to achieve at least a 95% reduction in methane emissions.

Comment: Venting compressor rod packing fugitive emissions to a flare or other control device, though possible, is often impractical due to the cost associated with permitting and installing additional control equipment. We suggest adding a packing repair/replacement option that is "condition-based" rather than time based. This allows the operator to make a decision and investment based on specific known information on a case by case basis related to his particular compressor. Further, a time-based replacement does not necessarily guarantee a specified emission reduction. The proposed CARB Oil and Gas regulation requires measurement of fugitives from the packing and then requires repairs if the leaking exceeds a specific threshold. For others who would prefer to not add a new monitoring and measurement scheme to their operations, the time-based replacement may indeed be a viable option.

Transmission Pipeline Blowdowns between Compressor Stations
Distribution Pipeline Blowdowns

Mitigation Options:
Route gas to a compressor or capture system for beneficial use, or
Route gas to a flare, or
Route gas to a low-pressure system by taking advantage of existing piping connections between high- and low-pressure systems, temporarily resetting or bypassing pressure regulators to reduce system pressure prior to maintenance, or installing temporary connections between high and low pressure systems, or
Utilize hot tapping, a procedure that makes a new pipeline connection while the pipeline remains in service, flowing natural gas under pressure, to avoid the need to blow down gas

Comment:
Individual utilities will need to determine on their own the cost-effectiveness and feasibility of this proposed BMP, since it is often not feasible to route gas from a high-pressure transmission pipeline to an emission control device. Also the costs associated with mobilizing portable emissions control equipment, as well as the impact of releasing criteria pollutants into the atmosphere in exchange for methane reductions should be rigorously evaluated in advance.

Excavation Damages

Mitigation Options:
Shorten average time to shut-in for all damages, or
Reduce the number of damages per thousand locate calls; etc.

Comment:

We acknowledge the efforts by EPA to reduce methane emissions from excavation damages with the proposed mitigation options. However, reducing emissions from actions that are out of the utilities control remain both varied and challenging depending on geographical area, territory size and available company resources. We believe the area of reducing excavation damages is a clear example where system safety has a direct impact on emissions reductions where those reductions cannot be readily quantified. Strengthening customer and contractor education strategies and increasing work with agencies to enforce penalties on offenders (or repeat offenders) is critical. Further, improving locate and mark programs and increasing standby monitoring for high risk areas or repeat offenders are practices that will also improve chances for reduced incidents. As such each utility should have the ability to craft a company-specific plan that serves their purpose and also allows them to demonstrate progress.

Appendix A: Proposed Sources for BMP Commitment Option

In addition to the proposed sources in Appendix A, we suggest that Residential/Commercial and Industrial Meter Set Assembly (MSA) be added. Data collected by SoCalGas in support of the SB1371 submission to the CPUC indicates that a large amount of fugitive methane leakage may come from Residential, Commercial and Industrial MSAs. Utilities may want to evaluate the potential for cost-effective leak reductions in this area.

Additional Best Management Practices

The following scenarios may be suitable for individual utilities to use as BMPs on a case by case basis:

- The option to modify the utility's implementation plan with "equivalent" or more effective BMPs due to business need or emerging technologies that achieve or exceed proposed reductions;
- The option to include equipment repairs/replacements with less or non-emitting processes or equipment as a site or facility specific BMP.
- The option to include equipment, process or facility redesign that reduces methane, or a "shutdown" (equipment decommissioning) that entirely removes a methane source

Thank you once again for the opportunity to provide our comments. If you have any questions regarding this submittal, please contact Charles Humphrey at (213) 244-5476 or Darrell Johnson at (213) 244-2142.

Sincerely,

Charles Humphrey

Charles Humphrey

cc: Darrell Johnson, SoCalGas
Jill Tracy, SoCalGas

COMMENTER:

Texas Pipeline Association (TPA)

Texas Pipeline Association

Thure Cannon
President

November 13, 2015

Submitted via e-mail to methanechallenge@tetratech.com
Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, DC 20004

Re: Natural Gas STAR Methane Challenge Program: Proposed Framework

Dear Sir or Madam:

The Texas Pipeline Association ("TPA") submits the following comments on the proposed Natural Gas STAR Methane Challenge Program ("Methane Challenge Program") framework published by EPA on July 23, 2015. TPA is an organization composed of 50 members who gather, process, treat, and transport natural gas and hazardous liquids materials through intrastate pipelines in Texas. TPA members have the opportunity to participate in EPA's proposed Methane Challenge Program and therefore have an interest in the manner in which EPA structures the program. While individual TPA members may file comments directly responding to EPA's company-specific inquiries, TPA as an industry association files these comments addressing the general issues raised by EPA regarding the program and industry as a whole.

As a general matter, TPA believes that voluntary measures to achieve goals or outcomes are preferable to mandatory regulations. Voluntary measures allow individual companies to select projects based on economic and technical outcomes rather than on compliance with mandatory regulatory requirements that may or may not accurately assess cost-effectiveness or technical feasibility. However, TPA would urge EPA to include real, concrete and meaningful incentives in its voluntary program. Some examples of those incentives are discussed below.

Accordingly, TPA offers these comments in an effort to help EPA develop a meaningful voluntary methane reduction initiative as a whole.

1. Responses to EPA inquiries related to industry-wide issues.

EPA inquiry 2: In addition to recognition through the Program, what are the key incentives for companies to participate in this Program? Should EPA offer some partners extra recognition, such as awards?

TPA response: The key incentives for companies to participate in this program will include the types of recognition and economic savings that can be generated through it. While

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symbolic awards may be somewhat valuable, TPA believes that symbolic awards should not be the only recognition offered by EPA to companies participating in the Methane Challenge Program. Instead, we urge EPA to focus on developing concrete, substantive incentives and advantages to participants. Mere recognition via an award, such as a "gold star" performer or similar is not enough. Meaningful incentives would incentivize companies to participate in the Methane Challenge Program.

OSHA's Voluntary Protections Program ("VPP"), where participating companies are provided an exemption from programmed inspections, is such an example of a voluntary program that provides real concrete benefits to participants. In exchange for this favorable treatment on inspections, companies agree to develop and implement systems to effectively identify, evaluate, prevent, and control occupational hazards to prevent employee injuries and illnesses. They submit an application to OSHA and undergo an onsite evaluation by a team of safety and health professionals. These participants are re-evaluated every three to five years to remain in the program. This program has real results, as demonstrated by OSHA's publication, which states "the average VPP worksite has a lost workday incidence rate at least 50 percent below the average of its industry."[1]

Similarly, EPA could provide tangible benefits for program participants in the form of expedited treatment of air permit applications, in assessing a non-compliance penalty, or in establishing the frequency of or notice for site inspections. These benefits could be linked to percentage reductions or mass-based reductions of methane emissions from identified sources. Recognizing that in many instances state permitting authorities will be conducting the permit application review or enforcement action, EPA could recommend in the final Methane Challenge Program framework that state permitting authorities have the flexibility to develop and implement the type of measures recommended here. For example, the Texas Commission on Environmental Quality ("TCEQ") already has an expedited permitting program, which could be revised to include participation in the Methane Challenge Program. In addition, the TCEQ has a penalty calculation framework in which a reduction factor for participation in the Methane Challenge Program could easily be taken into account. The TCEQ penalty calculation methodology already takes into account penalty reductions for positive factors, such as, engaging in voluntary audits, implementing environmental management systems and participation in a voluntary pollution-reduction program. EPA should indicate that participating in the Methane Challenge Program would be participation in a "voluntary pollution-reduction program" and would represent a tangible benefit that could be provided to participating companies.

TPA also supports American Petroleum Institute's ("API") proposal to incentivize industry participation in the Methane Challenge Program by providing benefits to participants in the form of exemptions from certain requirements under the oil and gas NSPS rules and the (draft) Control Techniques Guidelines, and by developing guidance to account for the voluntary reduction measure in calculating the source's reduced potential to emit.

Finally, EPA should make clear that the implementation of a voluntary measure under the Methane Challenge Program will not impair a source's ability to generate emission reduction

[1] OSHA Fact Sheet at 1, *available at* https://www.osha.gov/OshDoc/data_General_Facts/factsheet-vpp.pdf.

credits ("ERCs") in an emissions banking and trading program. To be a creditable reduction available for certification, an ERC must *inter alia* be generated from voluntary reductions and be surplus beyond applicable local, state, and federal requirements. All reductions in methane achieved through participation in the Methane Challenge Program would and/or should meet this voluntariness standard, even if the company making the reductions received a benefit (*e.g.*, exemptions, expedited permitting, or penalty reductions) as a result of its participation. TPA urges EPA to clarify this outcome in its final framework for the Methane Challenge Program.

EPA inquiry 4: For the BMP option, how can EPA encourage companies to make commitments for sources for which they have not made significant progress in implementing mitigation options? In other words, how can companies be encouraged to participate beyond the sources for which they have already made significant progress?

TPA response: Enhanced company participation could be achieved if EPA allowed companies choosing the BMP Commitment option to address leaks and fugitive emissions through a Directed Inspection and Maintenance ("DI&M") program, as an alternative to the more formal leak detection and repair ("LDAR") approach. We note that EPA states[2] that it is already considering a proposal to structure BMP coverage of transmission and storage compressor stations as a DI&M Program. We urge EPA to follow through with this approach and to allow DI&M as a BMP option for leaks and fugitive emissions in all segments of the natural gas value chain.

Accordingly, we urge EPA to revise Appendix 2 to provide that an available BMP option for "Equipment Leaks / Fugitive Emissions" for both the Onshore Production and Gathering and Boosting sector and the Natural Gas Transmission and Underground Storage sector is a DI&M program, whereby the owner / operator conducts a baseline survey to identify leaks and makes repairs that are cost-effective. The BMP should provide that the survey / repair activities occur on an annual basis.

EPA inquiry 5: Please provide comments on the sources and corresponding BMPs that are provided in Appendix 2, including any recommended additions, deletions, or revisions.

TPA response: As previously stated, TPA believes that an available BMP option for addressing leaks and fugitive emissions should be use of the DI&M approach, as an alternative to LDAR, both for the onshore production and gathering and boosting sector and for the transmission and storage sector.

With respect to the BMPs proposed for reciprocating compressors, listed in Appendix 2, TPA is concerned that the BMP requiring "routing rod packing vent to capture/use" presents safety concerns. Routing rod packing vent emissions to a collection system can raise safety issues as entrained air may enter into low pressure gas steams thus creating hazardous conditions. Accordingly, we question whether routing packing vent emissions to a capture device should be retained as a BMP alternative. EPA should at a minimum ensure that

[2] *See* Natural Gas STAR Methane Challenge Program: Proposed Framework at 17 n. 17.

alternative BMP methods for reciprocating compressor venting are retained in the final program framework.

EPA inquiry 6: Please comment on the proposed definitions of the companies or entities that will make BMP commitments, per Appendix 3.

TPA response: Consistent with our view that the Methane Challenge Program should provide maximum flexibility for participating companies, TPA believes that companies should be able to choose the appropriate operational level for participation in the BMP Commitment option. For example, one company in the natural gas transmission segment might decide to participate at the pipeline operating entity level, while another company might choose to participate at the parent company level. In either instance, the goals of the Methane Challenge Program – methane reductions achieved through voluntary corporate efforts – could be achieved. EPA should not dictate the organizational level at which a participating company would make its commitment, as this might impede participation by companies whose operations did not fit a pre-determined reporting structure selected by EPA.

If EPA does choose to adopt definitions in this area, then TPA would support allowing companies to make BMP Commitments at the pipeline operating entity level, not the overall parent company level. This would allow participating companies to target specific parts of the company where reduction of methane emissions could provide the largest economic benefit, e.g. operating segments with relatively older equipment where substantial emission reductions might be possible.

EPA inquiry 7: Is a 5-year time limit to achieve BMP commitments appropriate? If not, please provide alternate proposals. Would a shorter time limit encourage greater reductions earlier?

TPA response: Setting a fixed five-year limit to achieve commitments under the BMP Commitment option would limit flexibility and possibly reduce program participants. To achieve maximum participation, TPA urges EPA not to establish a policy that would prevent a company from participating in the program simply because the company cannot achieve its commitment within five years and needs a longer period to reach those goals. Rather, EPA should allow companies to establish a reasonable timeframe for achieving their goals upfront. Perhaps EPA could establish a range of time to achieve the company's reduction goals, for example a period of five to ten years. The company could then commit to a timeframe upfront or make adjustments along the way, provided sufficient demonstrations were made to support the additional time. If EPA were to establish a hard timeframe, TPA believes that a period up to 10 years is reasonable. Increased flexibility regarding commitment time limits is especially important in the current environment, because the economic incentive to employ BMPs to reduce methane emissions may be relatively reduced at the present time due to recent decreases in natural gas prices. Those conditions may repeat themselves in the future. The program needs to be flexible to take these market swings into account.

EPA inquiry 9: To what extent is differentiating voluntary actions from regulatory actions important to stakeholders? What are the potential mechanisms through which the

Program could distinguish actions driven by state or federal regulation from those undertaken voluntarily or that go beyond regulatory requirements?

TPA response: Differentiating voluntary actions from regulatory actions is important to companies in the natural gas industry because allowing reductions to be made through voluntary actions allows companies to make decisions based on whether the action makes economic sense, rather than simply acting to fulfill the mandatory requirements of a regulatory program that may or may not achieve its stated goals. In addition, it is important to differentiate voluntary actions from regulatory actions because emission reductions that are generated through voluntary actions can potentially qualify as creditable ERCs in an emissions banking and trading program, while reductions that are required by a regulatory program cannot. Given the importance of ERC availability in light of the new 70 ppb ozone standard to continued industry growth and economic development, EPA should avoid imposing requirements that would transform reductions that otherwise would be voluntary under the program into mandatory reductions, which would have the effect of reducing the pool of potential ERCs in the future.

Moreover, the breadth of regulatory methane controls that will be in place once Subpart OOOOa and revisions to Subpart OOOO are finally adopted will address and control a large volume of methane emissions from the oil and gas value chain. Any additional regulatory controls for methane from these sources may not be justifiable based on a cost-benefit analysis. Hence voluntary, company-selected, methane emission reduction projects may be the only and best way to proceed within this industry.

More broadly, TPA believes that recognition of voluntary efforts to reduce emissions is important and is one of the main points of the proposed Methane Challenge Program. Historically, voluntary efforts by companies in the natural gas industry have been successful at reducing emissions, even as production has been increasing. For example, natural gas system methane emissions have decreased almost 17 percent from 1990 to 2012, even as natural gas production, processing, and transmission activities have significantly increased during the same time period.[3] Based on EPA's own estimates, the natural gas industry's participation in voluntary emission reduction programs has led to methane emission reductions of over one trillion cubic feet (over 400 MMTCO2e) through 2013.[4] An example of voluntary efforts to reduce emissions is the midstream pipeline industry's replacement of high-bleed equipment with lower-emitting components as part of ongoing maintenance activities, an effort that has achieved substantial emission reductions in the past. In Texas, find-and-fix initiatives have been used in the past by the Texas Commission on Environmental Quality ("TCEQ") to effectively reduce emissions through cooperative efforts between government and private industry. For example, when TCEQ fly-overs detected high emissions levels in a given area, TCEQ contacted the operators that could be responsible for the emissions so that the operators could make any necessary corrections to stop the emissions. In one instance, such an effort in the Houston Ship Channel resulted in reductions of VOC emissions of 7,000 tons per year.

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[3] *See* "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012," EPA 430-R-14-003 (April 15, 2014), Executive Summary at ES-13-14, *available at* http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[4] EPA, "Natural Gas STAR Methane Challenge Program: Proposed Framework," at 4.

Companies in the natural gas industry have both an economic and a safety incentive to reduce losses of natural gas in the processing, transmission, and delivery sectors. For this reason it is unnecessary to institute a new regulatory program that would prescribe methods to curb leaks or other losses; operators are already implementing voluntary methods to reduce leaks and emissions, and these efforts have been successful because operators are free to implement whatever methods are best suited to their own particular facilities. Given the plethora of regulatory programs designed to reduce emissions from this industry, any additional controls should be achieved through a voluntary program.

EPA inquiry 10: EPA plans to leverage existing reported data through the GHGRP (Subpart W) in addition to supplemental data that partners would submit to EPA. Would the e-GGRT system be an appropriate mechanism to collect the voluntary supplemental data?

TPA response: TPA's urges that whatever reporting system used as part of the Methane Challenge Program is user-friendly and employs the same terms, forms, and interfaces that are familiar to companies reporting under Subpart W. We have concerns about the expansion of the Greenhouse Gas Reporting Program ("GHGRP") e-GGRT system to incorporate additional reporting requirements. Most importantly, there would appear to be a disconnect between reporting under Subpart W of the GHGRP and reporting under the Methane Challenge Program. Subpart W reporting is done on a facility-by-facility basis, while the Methane Challenge Program envisions commitments that are broader and that may include entire divisions or broad business units. For this reason, we do not support use of the facility-based e-GGRT system by Methane Challenge Program participants due to the lack of parallel or similar reporting levels.

EPA inquiry 12: EPA seeks feedback on potential mechanisms for encouraging continued, active participation in the Program once a company's initial goals have been achieved.

TPA response: Companies will be more likely to participate in the Methane Challenge Program, now and continuing in the future, if it is structured so that it is easy to participate in (*e.g.*, use of user-friendly reporting mechanisms) and if EPA recognizes the achievements made by participating companies through the provision of concrete, tangible, and meaningful benefits such as those referenced in our response to inquiry 2 above. In addition, EPA could develop additional BMPs to address methane emissions in additional industry segments, which participants could add to their BMP commitment program in the future.

2. Conclusion.

TPA appreciates EPA's recognition that industry participants can achieve methane reductions through voluntary means. As noted above, companies employing voluntary measures have made substantial reductions in methane emissions in the past, and the proposed Methane Challenge Program would further the progress that has already been made. We urge EPA to refrain from finalizing program guidelines that would be overly restrictive, as this might discourage participation. Maximum flexibility for participants will increase the likelihood of participation, which in turn will increase the likelihood that the Methane Challenge Program will produce meaningful reductions in future methane emissions.

We appreciate the opportunity to provide these responses. Please let me know if you have any questions.

Yours truly,

Thure Cannon
President

COMMENTER:

Vectren Corporation (Vectren)

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November 12, 2015

Via: Electronic Mail
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Ms. Carey Bylin
Natural Gas STAR Program
U.S. EPA
1201 Constitution Way
Washington DC 2004

RE: Comments from Vectren Corporation on EPA's Proposed Methane Challenge Program

Dear Ms. Bylin,

Vectren Corporation (Vectren) hereby submits comments in response to the U.S. Environmental Protection Agency's (EPA) proposed voluntary Methane Challenge Program as published on the EPA Natural Gas Methane Challenge Program website.

Vectren is headquartered in Evansville, Indiana and through its natural gas utility subsidiaries Indiana Gas Company (IGC), Southern Indiana Gas and Electric Company (SIGECO), and Vectren Energy Delivery of Ohio (VEDO) is the owner operator of three natural gas distribution, transmission and storage systems that serve customers in Indiana and Ohio. More specifically, the IGC service territory covers 6742 square miles and provides natural gas to approximately 570,000 customers in central and southeast Indiana through 12,529 miles of distribution pipeline, 639 miles of transmission lines, 1343 regulator stations, and 4 natural gas storage fields. SIGECO gas operations covers 2750 square miles and serves 110,000 customers in southwest Indiana through 3095 miles of distribution lines, 148 miles of transmission lines, 620 regulator stations and 3 natural gas storage fields. VEDO provides natural gas to roughly 312,000 customers in west central Ohio with a gas territory that covers 2549 square miles through 5284 miles of distribution pipelines, 217 miles of transmission lines, and 2309 regulator stations.

Vectren appreciates the opportunity to provide comment on the proposed Methane Challenge Program and Supplementary Technical Information Document. We feel direct involvement from those affected by the proposal is the best way to create a program that not only meets EPA's stated goal for reducing methane emissions from the Oil and Gas energy sectors, but is also workable in real life operational situations.

General Comments

Vectren supports the goal identified by EPA for the Methane Challenge Program to recognize leading companies that make voluntary commitments to increased action to reduce methane emissions from their operations. Public recognition through the Methane Challenge Program will help support the efforts of local distribution companies (LDCs) to communicate the value of operational excellence and methane reductions to regulators, consumer advocates, customers, and environmental organizations.

BMP Commitment Option

Vectren supports EPA's proposed BMP commitment option. One of the main benefits of this option is the flexibility it provides potential program partners to choose which sources they will address.

Vectren supports the approach outlined by EPA to become a Methane Challenge Program partner by entering into a memorandum of understanding (MOU) with EPA documenting commitments and reporting. We also support the development of an Implementation Plan to detail anticipated rate of progress, key milestones, and context for partner implementation plans.

If an LDC selects the distribution main pipeline replacement BMP for its commitment, the MOU should make it clear that the tier and associated percentage reduction commitment for the entirety of the MOU term will be based on the inventory of cast iron and unprotected steel distribution pipelines in service in the LDC's distribution system as of January 1, 2015.

Sector Definitions

EPA has proposed definitions for the different industry segments and facilities in Appendix C of the Supplementary Technical Information Document. Vectren supports the proposed level at which LDCs would make commitments under the Methane Challenge Program BMP Option - a LDC as regulated by a single state public utility commission. This proposed level is consistent with the Subpart W facility definition and the manner by which companies manage their infrastructure assets.

Vectren appreciates the clarification that a "natural gas transmission pipeline" for purposes of Methane Challenge Program includes interstate, intrastate, and Hinshaw transmission pipelines. Thus, as we understand it, a LDC could opt to participate in Methane Challenge for its distribution system, but not its intrastate transmission pipelines or for its transmission compression.

Vectren also understands the definition of Underground Natural Gas Storage to mean that a LDC that operates underground storage facilities could participate in Methane Challenge for distribution, but not for its underground storage. Please confirm that our understanding is correct.

Data Reporting and Emission Factors

Vectren agrees that the current eGRRT system should provide a generally acceptable and efficient reporting platform, if EPA makes the necessary modifications in a "user-friendly" format and keeps the Mandatory Reporting Rule (MRR) restricted-access data separate from the more visible data that will be posted under the voluntary Methane Challenge program. If possible the Methane Challenge Program data entry and reporting should be a separate reporting section from the mandatory Subpart W data reporting platform. Access and use of the eGRRT system is difficult for casual users. Vectren suggests a lightweight "user-friendly" reporting application built outside of the eGRRT application interface to input and report the data in the eGRRT databases.

There are limitations in the current Subpart W formulas and outdated emission factors that prevent them from reflecting the true levels of natural gas emissions. For example, systems that replace cast iron or unprotected steel mains with modern polyethylene (PE) plastic or protected steel pipe do not get credit for the full value of their emission reductions because EPA is still using emission factors that are based on the 20 year old limited data collected in the GRI-EPA study. This could be remedied if EPA would revise its emission factors to reflect the far more robust and recent data provided in the Washington State University (WSU) distribution methane measurement study published March 31, 2015.

An additional improvement would be to allow an emission factor based on the number of reported non-hazardous leaks rather than simply number of pipe miles. This would help demonstrate improvements in reducing leaks that do not show up when using just miles of pipe times an emission factor. Otherwise, using the existing formulas in the Subpart W eGRRT system will mean that even if an LDC makes significant investments and improvements by implementing BMPs in the Methane Challenge Program, the true levels of methane reduction will not be fully reflected in the reported Subpart W values. Vectren urges EPA to update its emission factors on an expedited schedule. This will help support all of EPA's methane programs as well as provide a more accurate assessment of total emissions in the annual GHG Inventory.

To avoid unnecessary burdens on EPA and participants, the Methane Challenge Program reporting deadline should be 60 days after the MRR reporting deadline.

M&R Station City Gates

Vectren already performs annual leak surveys on M&R Stations. EPA's Technology Support Document released on October 19 acknowledges that Subpart W reporting data "indicates a low level of emissions from this source relative to other distribution sources." At this time Vectren is neutral on the inclusion of this BMP as part of the Methane Challenge Program.

Distribution Mains – Cast Iron, Unprotected Steel

Vectren generally supports the approach EPA has proposed with this BMP option: replace cast iron mains with plastic or cathodically protected steel and replace or cathodically protect unprotected steel mains, or rehabilitate cast iron and unprotected steel pipes with plastic pipe inserts, also referred to as slip-lining or u-liners, or cured-in-place liners. This approach provides LDCs with flexibility to implement the strategies most appropriate for their given infrastructure make up, cost effectiveness and other factors.

LDCs that achieve a higher replacement rate should receive additional recognition from EPA. LDCs that currently replace mains at a faster rate than the minimum proposed by EPA should also receive EPA recognition and could commit to maintaining that rate or increasing it in the future.

Vectren supports replacement rates as proposed by the American Gas Association. These suggested adjustments to the tiers and goals to avoid unintended and unachievable "cliffs." In addition, since companies report their mileage on an annual basis to the U.S. Department of Transportation (DOT), we urge EPA to set the baseline inventory as of January 1 of the year in which a participant adds the pipeline replacement BMP to their commitment under Methane Challenge. Vectren asks EPA to revise the pipe replacement BMP as follows:

Tier	Inventory as of Jan. 1, 2015* of Cast Iron and Unprotected Steel Mains	% Annual Mileage to Replace, Line, Seal, or Protect
1	<500 miles	5%
2	500 – 1,000 miles	4%
3	1,001-1,500 miles	3%
4	1,500 miles-3,000 miles	2%
5	>3,000 miles	1.5%

***Or January 1 of the year in which a participant adds this BMP to their commitment.**

Vectren requests clarification that the BMP % Annual Mileage Goal is not a moving target and remains the same throughout the MOU timeframe.

For DOT reporting, wrought iron and ductile iron are included in the "cast iron" category. The Methane Challenge pipe replacement BMP should clearly use the same definition of cast iron to align with the DOT reporting category, which is also used in the EPA Greenhouse Gas Inventory.

Distribution Services

Vectren agrees that replacement and rehabilitation of services should be part of the overall Methane Challenge Program approach. While LDCs typically replace or rehabilitate services as part of main replacement programs, some LDCs may have dedicated replacement/repair programs for services.

This BMP should be based on the number of services by material rather than their length. This would better align with the way that gas utilities and the Energy Information Administration (EIA) account for services.

Vectren supports the approach EPA has proposed with this BMP option: replace unprotected steel and cast iron services with copper, plastic, or protected steel, or rehabilitate cast iron and unprotected steel services with plastic pipe inserts.

High Pressure Pipe Blowdown

Vectren agrees that 60 psi or more is an acceptable category of higher pressure distribution main for deploying methods for reducing planned, non-emergency blowdowns. It is helpful to have a clear cutoff level to know what types of distribution mains are eligible for credit under this voluntary blowdown reduction BMP. From a cost effectiveness perspective, operational releases from high pressure mains are the most appropriate to focus on mitigating in the near term. Vectren also agrees with EPA that this BMP should not be applicable to emergency situations.

EPA requested feedback on the proposal of 50% as the minimum reduction percentage commitment, and whether the minimum commitment should be adjusted to serve as an appropriate stretch goal for partner companies. A 50% reduction commitment may be hard to achieve for LDCs already implementing those mitigation activities by minimizing lost gas by taking gas into a lower pressure system, installing temporary by-passes, and/or flaring-off gas through the blowdown process. Vectren requests clarification on whether the 50% reduction is based on the amount that could have been released in total annually by an LDC.

EPA assumes a full evacuation of the pipeline to atmospheric pressure in the methodology for calculating total potential emissions for blowdowns and requested feedback from companies on the validity of this assumption. Vectren has observed situations where line pressure cannot be drawn down to atmospheric pressure prior to venting due to system constraints. However, the occurrence of this situation would be hard to model since the draw down pressure would be on a case by case basis.

Excavation Damage Prevention
Vectren supports the EPA proposed method for company-specific goal setting. LDCs should be allowed to set their own target and likely would use the damage rate as set by the Common Ground Alliance of the number of damages per thousand locates. Many LDCs already participate in damages metric tracking through their DIRT program.

Vectren does not believe that quantifying methane emissions associated with excavation damages or setting emission reduction targets is appropriate for this BMP source. Setting an emission reduction target for this BMP would be challenging due to the fact that emissions quantification is difficult because of the varying levels of damages to mains and services. While LDCs do estimate the quantity of gas lost from significant excavation damages for billing purposes, quantifying methane emissions reliably from all damages would be a challenge. Quantifying emissions associated with damages would require the development of a standardized methodology and would likely involve considerable uncertainty.

BMPs – Areas of Future Focus

Mains and Services - Vintage and Century Plastic
Vectren agree with EPA's decision not to include vintage or Century plastic in the mains or services BMP at this time. Plastic is not differentiated between plastic types with the current emission factors. Therefore, when LDCs replace vintage or Century plastic mains and services, this is not currently reflected in Subpart W reporting.

Vectren proposes that EPA work with LDCs and other stakeholders to add vintage and Century plastic as a BMP option in the future. This will require improved understanding of the main and services inventory as well as methane emissions from leaks and cracks in this material. As part of the Methane Challenge Program, EPA should establish a group of LDCs and other interested stakeholders to address these issues. We suggest that EPA engage stakeholders in AGA's Plastic Pipe Data Collection Initiative. The goal of the Initiative is to create a national database of information related to the in-service performance of plastic piping materials. Members include AGA, the American Public Gas Association, the Plastics Pipe Institute, NARUC, the National Association of Pipeline Safety Representatives, and PHMSA.

Customer Meters
As LDCs replace and rehabilitate leak prone pipe and modernize facilities, EPA should consider adding other BMP sources to the Methane Challenge Program. For example, for some LDCs, customer meters are estimated to be one of the most significant sources of methane emissions. As such, EPA should work with LDCs and other stakeholders to evaluate the development of a BMP focused on customer meters. The mitigation options for this BMP could include the repair or replacement of a specified percentage of customer meters annually.

Leak Backlogs
In addition to leaks found through routine LDC surveys, many LDCs have a backlog of nonhazardous leaks on their systems. These leaks are typically classified as Grade 3 leaks and reported to PHMSA. EPA should work with LDCs and other stakeholders to evaluate the development of a BMP focused on reduction of leak backlogs and the repair of leaks. The mitigation options for this BMP could include the repair of a specified percentage of leaks annually based on the size of the leak backlog. In addition, this BMP could also include increased surveys, emissions quantification of leaks found and repaired.

Recognizing Historic Action
The Methane Challenge Program should recognize previous actions by program partners for one or more BMP sources. Background data and information on a partner's prior mitigation efforts and recognition by EPA would improve transparency and inform stakeholders as the program is launched. EPA could acknowledge these actions within the implementation plan of the LDC along with fact sheets and other materials prepared for the launch of the program in early 2016.

To award program partners that have already shown a commitment to methane reductions by early adoption of best management practices for leak reductions, Vectren suggests that EPA determine an acceptable metric of overall achievement by a program partner versus quantifying past annual emission reductions. EPA should avoid making the data required a burden to Methane Challenge Program partners which could result in LDCs forgoing this opportunity.

In addition to the above comments which are specific to Vectren's facilities, we are also members of and support comments submitted by the American Gas Association (AGA). Thank you for the opportunity to provide this feedback and we look forward to continued engagement in the development of this important program. If you have any questions, please contact the undersigned at 812-491-4029 or ebeck@vectren.com

Sincerely,

Elizabeth Beck
Manager, Energy Policy & Strategy

COMMENTER:

Western Energy Alliance/Independent Petroleum Association of America/American Exploration and Production Council (WEI/IPAA/AXPC)

Via e-mail: methanechallenge@tetratech.com

November 13, 2015

The Honorable Gina McCarthy
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D. C. 20460

Re: Natural Gas STAR Methane Challenge Program Proposal

Dear Administrator McCarthy:

The following comments to the proposed Methane Challenge program released by the Environmental Protection Agency (EPA) on July 23, 2015, are submitted on behalf of the Independent Petroleum Association of America, the American Exploration and Production Council, and Western Energy Alliance. We appreciate the opportunity to provide EPA with comments on its proposed Methane Challenge program and collectively, we support using a voluntary program to achieve emission reductions. A flexible, voluntary program that offers tangible benefits to participants and provides regulatory certainty is the most efficient and quickly-implemented path to achieving EPA's emissions goals. Voluntary programs allow companies to focus resources in areas where the greatest gains can be achieved, while reducing the administrative burden when compared to a regulatory program. Tangible benefits will attract broader participation, thus creating a more successful program.

Western Energy Alliance represents over 450 companies engaged in all aspects of environmentally responsible exploration and production of oil and natural gas in the West. The Alliance represents independents, the majority of which are small businesses with an average of fifteen employees.

The Independent Petroleum Association (IPAA) represents the thousands of independent oil and natural gas explorers and producers, as well as the service and supply industries that support their efforts, that will most directly be impacted by the proposed actions. Independent producers develop 90 percent of American oil and natural gas wells, produce 54 percent of American oil and produce 85 percent of American natural gas. IPAA is dedicated to ensuring a strong, viable American oil and natural gas industry, recognizing that an adequate and secure supply of energy is essential to the national economy.

The American Exploration & Production Council (AXPC), is a national trade association that represents 31 of the largest US independent natural gas and crude oil exploration and production companies - Leaders in finding and developing secure energy supplies throughout North America. Members are "independent" in the sense that that they do not have petroleum refining or retail marketing operations and therefore are not "fully-integrated". The AXPC mission is to work constructively for sound energy, environmental and related public policies that encourage responsible exploration, development and production of natural gas and crude oil to meet consumer needs and fuel our economy.

In addition to the comments submitted herein, Western Energy Alliance, IPAA, and AXPC also endorse the comments submitted by the American Petroleum Institute.

As EPA is well aware, the proposed Methane Challenge enters a regulatory environment in which there are numerous existing and forthcoming regulations. Many of these regulations address new source emissions standards, and therefore these new sources would not be eligible for a voluntary program due to regulatory requirements. However, there are many modified and existing sources that could potentially fit into a voluntary program.

Efficiently regulating existing sources in the upstream oil and natural gas industry is a complex undertaking due to the natural decline of production over time from those existing sources. A realistic existing source regulatory strategy needs to recognize that there is little value in regulating marginal oil and natural gas wells. While these wells make up the preponderance of American wells, their individual low production rates means that their emissions will be correspondingly small. The methane emissions inventory is demonstrating that the application of the 2012 New Source Performance Standards (NSPS) Subpart OOOO that targets the larger emissions source in the upstream oil and natural gas industry is reducing methane emissions. As these new wells become the majority of non-marginal US wells, the benefit of an existing source regulatory program rapidly diminishes. A voluntary program offers the benefit of a faster implementation time than a regulatory program, which means those existing sources can be controlled more quickly. Additionally, the reduced cost burden of a voluntary program allows companies to focus their resources on taking steps to reduce emissions, rather than on added compliance and reporting steps that offer minimal environmental benefit. However, a voluntary program, like an existing source regulatory program, should be directed toward facilities with an emissions profile that makes the controls cost effective and should not apply to marginal wells. As an industry, we support these voluntary programs when they are properly structured and incentivized.

Program Incentives

A voluntary approach to emission control is a logical starting point. It is also critical to determine what tangible incentives exist to encourage participation. In its program proposal, EPA solicited comments on incentives and we appreciate EPA's request for input. In order to get widespread participation in the Methane Challenge program, we recommend several approaches for incentives:

1. **Regulatory relief from existing rules and forthcoming rulemaking:** In order to make decisions about participation, companies need to have some degree of certainty on the regulatory process. EPA should consider ways of offering companies that enroll in the Methane Challenge exemptions from

current and future regulatory programs including: Control Technique Guidelines (CTGs) in existing or future Non-Attainment Areas (NAAs), exemption from Clean Air Act (CAA) rules targeting existing sources of methane emissions, forthcoming BLM Venting and Flaring rules for new and existing sources, and individual state programs such as Colorado's Regulation 7 or Wyoming's Minor Source program.

2. **Voluntary reductions should be made available as offsets for future projects:** By allowing offsets to be credited and banked for projects in NAAs, EPA would incentivize aggressive early action by industry. If companies either do not receive credit for early action taken or are expected to do even more because of their decision to be proactive, there is limited incentive for participation in a voluntary program.

3. **Streamlined reporting requirements and protection from voluntary reporting data being used for enforcement actions:** Some of the most costly elements of any regulatory program are the reporting and recordkeeping requirements. Using data already available through Subpart W reporting is appropriate and using supplemental data from e-GGRT is also appropriate, however there have been numerous technical issues with the e-GGRT database.

4. **An off-ramp for declining sources:** EPA solicited feedback on the five year implementation window for Best Management Practices (BMP) commitments. In most instances, a five year window would be appropriate and we generally support this approach. However, if there is a phase-in period we also recommend including a phase-out period. As was raised earlier in our letter, many sources of emissions in upstream oil and gas decline over time. In order to keep funds available to target the most high-impact sources, we recommend EPA also include a production level-based off-ramp for declining emission sources. If a source is kept in the program in perpetuity, it would not offer any environmental or financial benefit. If anything, it would have a negative overall impact by keeping capital tied up in an ineffective program, rather than allowing it to be redirected to areas where companies can deliver larger methane emissions reductions. EPA begins to address the issue of the scope of regulation in its Subpart OOOOa and CTG proposals by identifying the exclusion of marginal wells. EPA should, at a minimum, provide that as wells in the voluntary program become marginal, they should be removed from the program, but a higher level might be appropriate and should be considered.

This is an even greater concern in the current commodity price environment. EPA should maximize flexibility for industry so that it can deploy its resources as efficiently as possible. A program that hampers companies by forcing emission control programs on sources that offer minimal benefit could potentially deter participation. Instead, companies must be free to allocate their capital to cost-effective control strategies. Companies currently face many difficult choices regarding capital expenditures across the industry. EPA must recognize the conditions within industry as it is proposing this program and maintain realistic expectations about how companies will be able to participate. In order to best engage with industry under current commodity prices, we recommend EPA pursue a stakeholder process to determine benefits. Should EPA consider adopting all, any, or none of these suggestions, we would recommend it engage directly with operators through a collaborative process to determine the final incentive structure.

Proposed Commitment Options

In EPA's proposed program, it identified three options for participants to make commitments. We support EPA offering options for participants, as greater flexibility will lead to a more successful voluntary program. The first option identified by EPA, known as the BMP Commitment Option allows companies to commit to emission source-based mitigation practices, while the One Future option allows companies to commit to an intensity target that it reaches through a mix of mitigation options. We support the inclusion of both of these strategies. The third strategy identified but not favored by EPA is the Emission Reduction (ER) commitment option. We support the inclusion of this third commitment option in the program.

1. BMP Commitment Option

EPA identified seven sources that would be eligible for the BMP commitment option. These sources are very similar to those subject to regulation under the NSPS Subpart OOOO and potentially under Subpart OOOOa proposed by EPA, with the exception of liquids unloading. Liquids unloading was held out of NSPS OOOOa because of uncertainty, variability and monitoring difficulty associated with this source. These same issues will all hold true for liquids unloading under a voluntary program, therefore we do not believe this is a viable BMP option.

Leak Detection and Repair (LDAR) is similarly problematic, as LDAR programs do not offer quantifiable emission reductions under the proposed reporting methods, making it impossible to evaluate the benefit of an LDAR program. We request that EPA clarify how it intends to demonstrate that any LDAR program included in the Methane Challenge can be evaluated for cost-effectiveness.

The large overlap between NSPS Subpart OOOO and proposed Subpart OOOOa and the Methane Challenge gives us concern because so many of these BMP-eligible sources are already or potentially regulated. That means that many incentives to enroll in the Methane Challenge will be taken away through regulatory obligations. Although existing facilities will be eligible, in many cases these will offer limited benefit due to production and associated emission declines.

2. One Future Commitment Option

As indicated, the Associations support EPA providing different voluntary options to further reduce methane emissions from the oil and natural gas sector. Some Association members are part of the Our Nation's Energy Future Coalition, Inc. (ONE Future). ONE Future seeks to achieve an average annual rate of methane emissions across the collective ONE Future operations equivalent to one percent or less of gross US natural gas production by 2025. The Associations support the inclusion of ONE Future as one of the voluntary program options available in the Methane Challenge.

3. ER Commitment Option

We support including ER as a possible option in the Methane Challenge. Although this would require some additional baseline data, BMP options would require similar baseline data and therefore we do not believe this would be a significantly greater burden. ER has the benefit of being another option that increases flexibility to participants. Although it might not work for all companies, we support including it as greater choice to make the Methane Challenge more attractive to potential participants.

Conflicts with Other Regulations

We support the framework of commitment options laid out by EPA, with the inclusion of the incentives discussed above. However we do have reservations about the Methane Challenge that particularly affect companies operating on tribal and federal lands. As EPA is undoubtedly aware, there are numerous regulations in place or under development that could potentially limit the voluntary options for these operations. Among those that could potentially overlap are:

- BLM Venting and Flaring
- Indian Country Minor NSR
- A Lowered Ozone National Ambient Air Quality Standard
- Control Technique Guidelines (CTGs) in NAAs
- State regulations like Colorado's Regulation 7
- New Source Performance Standards Subpart OOOO and proposed Subpart OOOOa

We strongly encourage EPA, in coordination with its state and federal agency partners, to consider offering regulatory relief from these regulations to incentivize participation in the Methane Challenge. Without such relief, companies may not have compliance options available to them, as these regulations will in effect require any voluntary action companies might otherwise take.

Areas Needing Clarification

There are several areas in the proposal that require additional clarification and we request feedback from EPA on these points.

- **Business Unit definition:** EPA asked for comments on the definition of companies or entities. EPA defines a business unit as "a separately managed division or unit of an enterprise with strategic and/or operational objectives that may be distinct from the parent unit and other divisions or business units." However, it is unclear how this would apply across companies that divide their businesses differently. For example, some companies may have a Colorado or Rocky Mountain business region but cost-effective control strategies might look different in Colorado versus Wyoming or across basins within the same state. We encourage EPA to provide additional information on what they envision as a business unit.

- **Consequences for not meeting goals:** In EPA's webinar, it was asked what the possible consequences or penalties would be for companies that are unable to meet their goals under the Methane Challenge. EPA's response was that it was unsure of what the consequences would be, which we find troubling. Since this is a voluntary program, there should be no penalties for companies that are unable to fulfill their commitments under the program. We request that EPA clarify this point.

We appreciate the opportunity to comment on EPA's proposed program. We are strong supporters of a voluntary program with the proper incentive structure. We appreciate EPA's willingness to consider our concerns and provide clarification on the topics we have identified. We would welcome the opportunity to discuss the program further.

Sincerely,

Kathleen M. Sgamma
VP, Public & Gov't Affairs
Western Energy Alliance

Lee O. Fuller
Executive Vice President
IPAA

V. Bruce Thompson
President
AXPC