United States Environmental Protection Agency

Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act:

EPA's Response to Public Comments

Volume 3: Attribution of Observed Climate Change

Attribution of Observed Climate Change

U. S. Environmental Protection Agency
Office of Atmospheric Programs
Climate Change Division
Washington, D.C.

FOREWORD

This document provides responses to public comments on the U.S. Environmental Protection Agency's (EPA's) Proposed Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act, published at 74 FR 18886 (April 24, 2009). EPA received comments on these Proposed Findings via mail, e-mail, and facsimile, and at two public hearings held in Arlington, Virginia, and Seattle, Washington, in May 2009. Copies of all comment letters submitted and transcripts of the public hearings are available at the EPA Docket Center Public Reading Room, or electronically through http://www.regulations.gov by searching Docket ID *EPA-HQ-OAR-2009-0171*.

This document accompanies the Administrator's final Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act (Findings) and the Technical Support Document (TSD), which contains the underlying science and greenhouse gas emissions data.

EPA prepared this document in multiple volumes, with each volume focusing on a different broad category of comments on the Proposed Findings. This volume of the document provides responses to public comments regarding the attribution of observed climate change.

In light of the very large number of comments received and the significant overlap between many comments, this document does not respond to each comment individually. Rather, EPA summarized and provided a single response to each significant argument, assertion, and question contained within the totality of comments. Within each comment summary, EPA provides in parentheses one or more lists of Docket ID numbers for commenters who raised particular issues; however, these lists are not meant to be exhaustive and EPA does not individually identify each and every commenter who made a certain point in all instances, particularly in cases where multiple commenters expressed essentially identical arguments.

Several commenters provided additional scientific literature to support their arguments. EPA's general approach for taking such literature into consideration is described in Volume 1, Section 1.1, of this Response to Comments document. As with the comments, there was overlap in the literature received. EPA identified the relevant literature related to the significant comments, and responded to the significant issues raised in the literature. EPA does not individually identify each and every piece of literature (submitted or incorporated by reference) that made a certain point in all instances.

Throughout this document, we provide a list of references at the end of each volume for additional literature cited by EPA in our responses; however, we do not repeat the full citations of literature cited in the TSD.

EPA's responses to comments are generally provided immediately following each comment summary. In some cases, EPA has discussed responses to specific comments or groups of similar comments in the Findings. In such cases, EPA references the Findings rather than repeating those responses in this document.

Comments were assigned to specific volumes of this Response to Comments document based on an assessment of the principal subject of the comment; however, some comments inevitably overlap multiple subject areas. For this reason, EPA encourages the public to read the other volumes of this document relevant to their interests.

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Acronyms and Abbreviations

ACRIM	Active Cavity Radiometer Irradiance Monitor
AMO	Atlantic Multi-decadal Oscillation
BC	black carbon
CCSP	U.S. Climate Change Science Program
CH_3I	methyl iodide
CH_4	methane
cm	centimeter
CO_2	carbon dioxide
dms	dimethyl sulfide
ENSO	El Niño-Southern Oscillation
EPA	U.S. Environmental Protection Agency
GCM	general circulation model
GHG	greenhouse gases
HITRAN	High-Resolution Transmission Molecular Absorption
hPa	hectopascal
IPCC	Intergovernmental Panel on Climate Change
IR	infrared radiation
K	degrees Kelvin
Ka	kiloannum
Km	kilometer
LLGHG	long-lived greenhouse gases
LOSU	Level of Scientific Understanding
mm	millimeter
MPI	maximum potential intensity
N_2O	nitrous oxide
NAM	Northern annular mode
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Protection
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration
PDO	Pacific Decadal Oscillation
PMOD	Physikalisch-Meteorologisches Observatorium Davos
ppm	parts per million
RF	radiative forcing
SRES	IPCC Special Report on Emissions Scenarios
TSD	Technical Support Document
TSI	total solar irradiance
USGCRP	U.S. Global Change Research Program
W/m^2	watts per meter squared
WMO	World Meteorological Organization

3.0 Attribution of Observed Climate Change to Increase in Greenhouse Gas (GHG) Concentrations

Comment (3-1):
A commenter (3747.1) argues that the information EPA used as basis for the Proposed Findings does not meet EPA's information quality requirements because the Technical Support Document (TSD) does not differentiate between anthropogenic and non-anthropogenic climate forcing variables.

Response (3-1):
Please see Volume 1 of this Response to Comments document for EPA's general response to the information quality concerns submitted during the public comment process. In addition, please see previous responses in this section regarding EPA's consideration of the science on the attribution of observed climate change to increases in GHG concentrations and other substances with radiative forcing effects.

EPA appreciates the complexities of the issues raised by the commenter, however, we disagree with the comment that the TSD does not establish a reasonable baseline by differentiating between anthropogenic and non-anthropogenic climate forcing variables. Please see the Introduction and Sections 4 and 5 of the TSD for our discussion of this topic. Our treatment of this attribution issue is consistent with EPA's *Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility and Integrity of Information Disseminated by the Environmental Protection Agency*. We note that the *Guidelines* encourage risk assessments to analyze and consider 'real world situations.' EPA's approach to and description of anthropogenic and non-anthropogenic climate forcing variables is therefore consistent with the *Guidelines* because the TSD describes the radiative forcing effects of both variables and includes an entire section on the attribution of observed climate change to anthropogenic greenhouse gas emissions at the global and continental scale. Furthermore, the Introduction of the TSD describes this approach, therefore ensuring transparency of methods employed.

Comment (3-2):
Several commenters state that specific aspects of the attribution evidence summarized in the TSD do not support the Administrator's endangerment finding.

Response (3-2):
The specific issues that underlie these comments are addressed in the responses throughout this volume, and other volumes of the Response to Comments document. With regard to the commenters' conclusion that the current science does not support an endangerment finding with respect to attribution, we disagree based on the scientific evidence before the Administrator. See the Findings, Section IV.B, "The Air Pollution is Reasonably Anticipated to Endanger Both Public Health and Welfare," for details on how the Administrator weighed the scientific evidence underlying her endangerment determination in general, and with regard to the evidence of attribution in particular.

3.1 Degree of Anthropogenic Climate Influence

Comment (3-3):
Numerous commenters (e.g., 0214, 0247, 0286, 0434, 0525, 0534, 0546, 0583, 0714.1, 1312, 2895, 3427.1, 3497.1, 3722R85, 4092, 7037) argue that anthropogenic greenhouse emissions have no effect on the climate. A second large group of commenters (e.g., 0400, 0499, 0736, 2210.4, 2818, 2933, 4003, 3427.1, 3440.1, 3450.1, 3553.1, 3596.1. 3915) do not explicitly rule out the possibility of an

anthropogenic influence on climate but state that it is likely to be minimal or insignificant, or that the current level of scientific understanding about climate and the carbon cycle involves too many uncertainties for the observed changes to be attributed to anthropogenic emissions with any degree of confidence.

Response (3-3):

We reviewed the arguments by the commenters that anthropogenic GHG emissions have minimal or no influence on the climate. While uncertainties exist, we disagree that anthropogenic GHG emissions have little to no effect on climate or that scientific understanding is inadequate for attributing climate change to human causes. We find these comments to be inconsistent with the assessment literature, which is summarized in Section III of the TSD. Studies to detect climate change and attribute its causes using patterns of observed temperature change show clear evidence of anthropogenic influence. On the basis of these studies, the Intergovernmental Panel on Climate Change (IPCC), the U.S. Climate Change Science Program (CCSP) and the U.S. Global Change Research Program (UGSCRP) reports have reached high-confidence conclusions that anthropogenic GHG emissions and warming of the climate system are causally linked. The 2007 IPCC Fourth Assessment Report concluded the following about the linkage between anthropogenic GHG emissions and the observed warming: "Most of the observed increase in global average temperatures since the mid-20th century is very likely [where very likely signifies a 90-99% probability the statement is true] due to the observed increase in anthropogenic GHG concentrations." In 2009, the USGCRP reached an even stronger conclusion, unequivocally stating: "The global warming of the past 50 years is due primarily to human-induced increases in heat-trapping gases." Both of these findings are included in the TSD.

The IPCC, CCSP and USGCRP have also concluded that there is evidence of anthropogenic influence in other parts of the climate system, including ocean heat content, precipitation, and wind patterns. Comments pertaining to the degree to which changes in these parts of the climate system can be attributed to the observed increase in the atmospheric GHG concentration are covered in other responses within this section of the Response to Comments document.

As the TSD describes, the attribution of observed climate change to anthropogenic activities is based on multiple lines of evidence. The first line of evidence arises from our basic physical understanding of the effects of changing concentrations of GHGs, natural factors, and other human impacts on the climate system. The second line of evidence arises from indirect, historical estimates of past climate changes that suggest that the changes in global surface temperature over the last several decades are unusual (Karl et al., 2009). The third line of evidence arises from the use of computer-based climate models to simulate the likely patterns of response of the climate system to different forcing mechanisms (both natural and anthropogenic). We received many comments on each of these lines of evidence. See our responses regarding how GHGs trap heat in Section 3.2.2; our responses related to indirect estimates of climate change over the last 2,000 years in Volume 2; our response related to the carbon cycle in response 3-21 and Volume 2; and our responses related to the consistency between observed changes in climate and computer model simulations in both this Volume and Volume 4.

Comment (3-4):

Numerous commenters (e.g., 2253, 3205.1, 3330, 3432.1, 3569.1, 10394, 10499) posit the lack of correlation between global surface and satellite-derived temperature trends and GHG changes calls into question any cause and effect relationship. Specifically, they note global GHG emissions have dramatically risen since 2000 and yet there has not been a concomitant increase in global temperature. Some commenters point to other (prior) short periods of no temperature change or cooling to demonstrate this lack of direct correlation. Another commenter (3722) states that CO_2 concentrations do not correlate causatively with temperature records, presenting a quote by Professor Philander (Philander, 1998) that "in contrast to the steady rise in the atmospheric concentration of carbon dioxide…temperatures have fluctuated erratically."

Response (3-4):

We reviewed the arguments by the commenters that there is no correlation, and no cause–and-effect relationship, between GHG concentrations and global temperature trends. Climate science research and assessments have clearly established the relationship between warming and anthropogenic GHG emissions. However, the relationship is complex and non-linear. As discussed in the IPCC, CCSP, and USGCRP assessment reports, and summarized in the TSD, elevated atmospheric levels of GHGs are not the only determinant of changes in temperature at the surface and in the troposphere; they act in addition to aerosols, land albedo changes, volcanoes, solar changes, and internal variability As such, examination of the relationship of shorter intervals (e.g., five to 10 years) can provide limited insight, and drawing conclusions from short time-scales is of limited value. Directly comparing global GHG emissions with global temperatures on decadal or shorter time-scales must consider all plausible variations and other existing non-linear inter-relationships. Both the IPCC and the TSD note that "difficulties remain in attributing temperature changes on smaller than continental scales and over time scales of less than 50 years," and that with limited exceptions attribution at these scales has not yet been established. Hegerl et al. (2007) state:

> Averaging over smaller regions reduces the natural variability less than does averaging over large regions, making it more difficult to distinguish between changes expected from different external forcings, or between external forcing and variability. In addition, temperature changes associated with some modes of variability are poorly simulated by models in some regions and seasons. Furthermore, the small-scale details of external forcing, and the response simulated by models are less credible than large-scale features.

From a recent study cited by the USGCRP, it is true (for some datasets) if a linear trend is fitted to annual global surface temperature data for the period 1998 to 2008, there is no real trend, even though temperatures remain well above the long-term average (Easterling and Wehner, 2009). Climate over the 21^{st} century can and likely will produce periods of a decade or two where the globally averaged surface air temperature shows no trend or even slight cooling in the presence of longer-term warming. We note there are other 10-year periods in the temperature record that when extracted show no trend even though these periods are embedded within a longer period showing substantial overall warming (Easterling and Wehner, 2009). Therefore, it is clear that temperatures do not rise monotonically despite the continuing increase of GHG concentrations. Observations over such short periods examined in isolation may be misleading in the interpretation of the longer-term trend in temperatures.

Over longer time periods and larger geographic scales, the attribution of recent change in part to CO_2 and other GHGs is clear. See Hegerl et al. (2007) and Karl et al. (2009) and the summaries of those two assessment reports in Section 5 of the TSD for discussions of the specific observed changes that have been attributed to increased GHG concentrations, and the evidence for and confidence in those attributions.

Therefore, we disagree with the commenters' assertion that there is not a cause-and-effect relationship between GHG concentrations and global temperature trends.

Comment (3-5):

Several commenters (e.g., 0169, 3432.1) argue that because the observed warming has occurred in Northern Hemisphere and not the Southern Hemisphere, the warming is not global and inconsistent with anthropogenic attribution.

Response (3-5):
While the Northern Hemisphere has warmed more and at a faster rate than the Southern Hemisphere, the commenter's statement that the Southern Hemisphere has not warmed is inaccurate. Warming trends in both hemispheres are clearly documented by the IPCC (Trenberth et al., 2007), and the most current data from satellite and surface-based records) indicate some warming in the Southern Hemisphere. Differences in Northern and Southern Hemisphere temperature trends are related to the different evolution of aerosol forcing and the greater thermal inertia of the large ocean surfaces in the Southern Hemisphere (Hegerl et al., 2007). The Northern Hemisphere has significantly more land mass than the Southern Hemisphere and because oceans tend to warm and cool more slowly than land areas, continental temperatures have risen more quickly than have ocean temperatures. Therefore, the data show that warming is indeed global, and that the hemispheric pattern is consistent with scientific understanding.

Comment (3-6):
A number of commenters (e.g., 3446.3, 3596.1, 3722) note that temperatures rose significantly from 1910 to 1940 before significant increases in GHGs, and just when GHG emissions began ramping up, the temperature cooled from the 1940s to 1970s. They suggest the lack of temporal correlation between GHG trends and temperature trends calls into question GHG attribution for the observed warming.

One commenter (3136.1) argues that natural variability should receive greater consideration in the TSD and questioned whether the changes that occurred prior to the past 30 to 50 years are attributable to anthropogenic climate change. The commenter argued that the behavior of the climate system from 1901 to the mid-1970s shows that predominantly natural variability can be quite large over the United States and stated that: "The TSD needs to be modified to discriminate between natural and anthropogenic warming." The commenter further argued the TSD represents all changes that have occurred since 1901 as a result of anthropogenic climate change and suggests that the TSD should present the trends for 30 year-periods between 1900 and 1975 as representing predominantly natural variability.

Response (3-6):
As stated in an earlier response, elevated GHGs are not the only determinant of changes in temperature at the surface and in the troposphere, though most of the observed increase in global temperatures since the mid-20th century has been attributed to the observed increase in GHG concentrations. Elevated GHGs act in addition to aerosols, land albedo changes, volcanoes, solar changes, and internal variability. A review of the literature shows that there are scientifically compelling explanations for the pattern of global temperature change over the past century. The information on attribution assessed by the IPCC, USGCRP, and CCSP, as summarized in the TSD, is consistent with the observed temperature record and therefore does not call into question the evidence supporting attribution of most of the observed warming since 1950 to increased GHG concentrations.

As the TSD notes, "[t]he IPCC (Hegerl et al., 2007) finds that anthropogenic GHG emissions were one of the influences contributing to temperature rise during the early part of the 20th century along with increasing solar output and a relative lack of volcanic activity. During the 1950s and 1960s, when temperature leveled off, increases in aerosols from fossil fuels and other sources are thought to have cooled the planet. For example, the eruption of Mt. Agung in 1963 put large quantities of reflective dust into the atmosphere. The rapid warming since the 1970s has occurred in a period when the increase in GHGs has dominated over all other factors (Hegerl et al., 2007)."

We have also added a paragraph to the TSD in order to better describe the key conclusions of the assessment literature with respect to the relative role of internal variability for observed and projected climate change on multi-decadal time scales:

> Changes arising from internally generated variations in the climate system can influence surface and surface and atmospheric temperatures substantially; however, climate models indicate that global-mean unforced variations on multidecadal timescales are likely to be smaller than the 20th century global-mean increase in surface temperature (Karl et al., 2006). The IPCC reports that global mean and hemispheric scale-temperatures on multi-decadal time scales are largely controlled by external forcing (Hegerl et al., 2007). Hegerl et al. (2007) note that, "many observed changes in surface and free atmospheric temperature, ocean temperature, and sea ice extent, and some large-scale changes in the atmospheric circulation over the 20th century are distinct from internal variability and consistent with the expected response to anthropogenic forcing."

As stated, on multi-decadal scales global and hemispheric temperatures are largely controlled by external forcings, which means that over the long term, large changes in GHG concentrations will dominate any unforced temperature changes from natural variability.

Comment (3-7):

Many commenters (e.g., 3215.1, 3330, 3446.1, 3596.2, 4003) indicate an anthropogenic warming is missing in the vertical and horizontal profile of the atmosphere in the tropics. They argue that the distinct human fingerprint of warming concentrated in the tropics between 30 degrees N and 30 degrees S and increasing with altitude to 10 kilometers (km) is the mechanism for amplified warming but that this fingerprint exists only in the models and not in the empirical science. They state that models predict significantly increasing warming with altitude up to 10 km and warming continuing beyond 15 km. Yet, they find except for surface temperatures, observations show limited warming that is statistically significantly less than the warming projected by the models. They indicate observations show a cooling with altitude beyond 13 km while the models still project a warming.

Response (3-7):

EPA is aware of the emerging literature on this issue and the challenges in identifying the anthropogenic fingerprint in the tropics. The TSD's characterization of this issue is consistent with the assessment literature as well as the most recent studies, which find that when uncertainties in models and observations are properly accounted for, newer observational data sets are in agreement with climate model results.

In light of this comment, EPA reviewed the assessment reports and newer literature on this topic. As one commenter notes, Christy et al. (2007) find discrepancies between surface and tropospheric temperature data in the tropics, and Douglass et al. (2007) report model results that are in disagreement with the observed trends. However, Haimberger et al. (2008) analyze weather balloon (radiosonde) records of tropospheric temperature data and find "….we note that the temperature trends from RICH–RAOBCORE version 1.4 [a homogenized radiosonde record] are more consistent with trends from recent climate model runs than earlier radiosonde datasets. In the tropical upper troposphere, where the predicted amplification of surface trends is largest, there is no significant discrepancy between trends from RICH–RAOBCORE version 1.4 and the range of temperature trends from climate models. This result directly contradicts the conclusions of a recent paper by Douglass et al. (2007)." They further note: "A robust warming maximum of 0.2–0.3K (10 yr)−1 for the 1979–2006 period in the tropical upper troposphere could be found in both homogenized radiosonde datasets."

Another paper by Allen and Sherwood (2008) reports: "Climate models and theoretical expectations have predicted that the upper troposphere should be warming faster than the surface. Surprisingly, direct temperature observations from radiosonde and satellite data have often not shown this expected trend.

However, non-climatic biases have been found in such measurements. Here we apply the thermal-wind equation to wind measurements from radiosonde data, which seem to be more stable than the temperature data.…Warming patterns are consistent with model predictions except for small discrepancies close to the tropopause."

Finally, Santer et al. (2008) analyze differences in trends between observed surface and tropospheric temperature records, and also compare the observational trends with the models. They conclude: "There is no longer a serious and fundamental discrepancy between modeled and observed trends in tropical lapse rates, despite [the Douglass et al., 2007] incorrect claim to the contrary."

The TSD summarizes this issue and cites the conclusions of the latest major assessments. It states: "…an important inconsistency may have been identified in the tropics. In the tropics, most observational data sets show more warming at the surface than in the troposphere, while almost all model simulations have larger warming aloft than at the surface (Karl et al., 2006). Karl et al. (2009) claim that when uncertainties in models and observations are properly accounted for, newer observational data sets are in agreement with climate model results." EPA concludes that the TSD's summary of the current state of the science on tropical tropospheric warming as reflected in the underlying assessment literature is accurate.

Comment (3-8):
Several commenters (3187.4, 7031, 9877) argue that the recent plateau in ocean heat content (from 2003 to 2008) suggests anthropogenic warming is not occurring because it indicates that the climate system is not accumulating heat. The lack of heat accumulation, they state, demonstrates a failure of the anthropogenic global warming hypothesis to account for natural climate variability, especially as it relates to ocean cycles. They claim that the recent trends in ocean heat content suggest the Earth's energy budget is not out of balance owing to GHGs, in contrast to the findings of Hansen et al. (2005).

Response (3-8):
We have reviewed the assessment literature in light of these comments and disagree with the assertions made by commenters. Just as temperature will not necessarily increase monotonically with increases in GHGs (per response 3-6) neither will ocean heat content on short time scales. Many of the same factors that influence global surface temperature in addition to GHG forcing will also result in short-term variability in ocean heat content such as aerosol emissions (anthropogenic and/or volcanic), solar forcing, and internal variability in the climate system. EPA does not suggest that GHGs are the only factors that would influence the global energy budget, and hence ocean heat content. EPA agrees that internal variability likely plays an important role in the interannual and interdecadal variability of ocean heat content, as indicated by IPCC (Bindoff et al., 2007). But as noted in Volume 2 of the Response to Comments document, the long-term trend in ocean heat content is indisputably upward, which is what we would expect given the anthropogenic heating from GHGs. The IPCC notes that ocean heat content is a critical variable for detecting the effects of the observed increase in GHGs in the Earth's atmosphere and for resolving the Earth's overall energy balance (Bindoff et al., 2007)

Though the commenters refer to a recent plateau in ocean heat content, there are published papers which find the opposite, as mentioned in Volume 2 of the Response to Comments document. In fact, this work (von Schuckmann et al., 2009) indicates the global ocean accumulated (between the surface and 2,000 meter depth) 0.77 (plus or minus 0.11) watts per square meter of heat between 2003 and 2008, which is roughly consistent with the 0.86 (plus or minus 0.12) watts per square meter of heat (between the surface and 750 meter depth) accumulated between 1993 and 2003 as documented in Willis et al. (2004); and Hansen et al. (2005). These studies suggest the ocean has and continues to accumulate heat, contributing to an overall imbalance in the Earth's energy budget, as further documented in two other recent studies by

Trenberth et al. (2009) analyzing the period March 2000 to May 2004 and Murphy et al. (2009) (analyzing the period 1950–2004).

We have added the following text on this topic to Section 4(f) of the final TSD on this topic:

> The thermal expansion of sea water is an indicator of increasing ocean heat content. Ocean heat content is also a critical variable for detecting the effects of the observed increase in GHGs in the Earth's atmosphere and for resolving the Earth's overall energy balance (Bindoff et al., 2007). For the period 1955 to 2005, Bindoff et al. (2007) analyze multiple time series of ocean heat content and find an overall increase, while noting interannual and inter-decadal variations. NOAA's report *State of the Climate in 2008* (Peterson and Baringer, 2009), which incorporates data through 2008, finds "large" increases in global ocean heat content since the 1950s and notes that over the last several years, ocean heat content has reached consistently higher values than for all prior times in the record.

Thus, the TSD's summary of the current state of the science on ocean heat content as reflected in the underlying assessment literature is reasonable and sound.

Comment (3-9):
Commenters (e.g., 3596.2, 7031) indicate trends in global precipitation cannot be attributed to anthropogenic forcing and an enhancement of the hydrological cycle. Several (3596.2, 5058R8) refer to a study by Gerten et al. (2008) who find precipitation over the global land area has been highly variable over the 20th century, characterized by a large degree of interdecadal fluctuation.

Response (3-9):
We have reviewed these comments and the referenced study, and we agree that a human influence has not been detected in global precipitation trends. We also agree that there has been significant interdecadal fluctuation in global precipitation as documented in Gerten et al. (2008). Our review of Gerten et al. (2008) reveals they were not able to confirm an enhancement of the hydrological cycle in their analysis of precipitation in recent decades. Note that the IPCC (Hegerl et al., 2007), consistent with this finding, concludes a human influence has not been detected in global-scale precipitation trend, and that this conclusion is reported in the final TSD.

However, the IPCC does find that the latitudinal pattern of change in land precipitation and observed increases in heavy precipitation over the 20th century appear to be consistent with the anticipated response to anthropogenic forcing (Hegerl et al., 2007), as is noted in the TSD.

A recent study by Zhang et al. (2007) supports and builds on IPCC's assessment. The study finds:

> Overall, we find that anthropogenic forcing has had a detectable and attributable influence on the latitudinal pattern of large-scale precipitation change over the part of the twentieth century that we were able to analyse. Our best estimate of the response to anthropogenic forcing suggests that anthropogenic forcing has contributed approximately 50–85% (5–95% uncertainty) of the observed 1925–1999 trend in annual total land precipitation between 40° N and 70° N (62 mm [millimeters] per century), 20–40% of the observed drying trend in the northern subtropics and tropics (0° to 30°N; a decrease of 98 mm per century) and most (75–120%) of the moistening trend in the southern tropics and subtropics (0° to 30° S; 82 mm per century).

Gerten et al. (2008), in fact, cite this study and conclude "…the human impact on the global water cycle is both intensifying and diversifying."

Therefore, EPA concludes that the TSD provides an accurate and sound summary of the state of the science by stating that latitudinal patterns in land precipitation, observed increases in heavy precipitation events, and increased extremes of summer dryness and winter wetness are consistent with anticipated response to anthropogenic forcing.

Comment (3-10):
Comments (e.g., 3161.1, 3394.1, 3596.2) assert there is absolutely no indication that U.S. GHG emissions have produced an unusual situation when it comes to U.S. annual precipitation totals and/or trends. They also assert the TSD does not adequately review the topic of precipitation variability and its causes across the United States.

Response (3-10):
While attribution of precipitation trends at the regional scale (e.g., within the United States) is challenging, the TSD includes appropriate caveats discussing the links between anthropogenic forcing and U.S. precipitation trend. In response to this comment, we added the following language to the final TSD, which explains why attributing trends in precipitation is difficult at the regional scale:

> As with temperature, attributing changes in precipitation and other climate variables to anthropogenic forcing at continental or smaller scales is more challenging. One reason is that as spatial scales considered become smaller, the uncertainty becomes larger because internal climate variability is typically larger than the expected responses to forcing on these scales (Gutowski et al., 2008). For example, there is considerable evidence that modes of internal variability (such as ENSO [El Niño-Southern Oscillation], PDO [Pacific Decadal Oscillation], and NAM [Northern Annual Mode]) substantially affect the likelihood of extreme temperature, droughts, and short-term precipitation extremes over North America (Gutowski et al., 2008).

Although, for the most part, we agree with commenters that a human influence on North American (and therefore the United States) precipitation amounts has not been formally attributed in the assessment literature (e.g., Clark et al., 2008), and this has been further reflected in the TSD (see Section 5[a]), certain characteristics of the observed changes in precipitation over the United States have been linked to anthropogenic forcing in the assessment literature. As the TSD now notes, Karl et al. (2009) find that heavy precipitation events averaged over North America have increased over the past 50 years at a rate higher than total precipitation increased, consistent with the observed increases in atmospheric water vapor, which have been associated with human-induced increases in GHGs. In addition, Clark et al. (2008) indicate the recent trend toward increased aridity in the Southwest is consistent with model projections for that region under increased GHG forcing, though the TSD cites the cautions by Clark et al. that there is considerable natural variability in the hydroclimate of the Southwest and that there is no clear evidence to date of human-induced global climate change effects on North American precipitation amounts. While the assessment literature has not formally attributed North American precipitation changes to human-induced climate change, Clark (2008a) did find that "both models and observations show a pattern of increasing precipitation north of 50°N and decreasing precipitation between 0-30°N" and conclude that anthropogenic influence on the spatial distribution of global land precipitation has been detected.

The TSD adequately reviews the topic of precipitation variability and its trends across the United States and that its summary of the current state of the science as reflected in the underlying assessment literature is reasonable and sound.

Comment (3-11):

Commenters (e.g., 3136.1) posit that drought that has occurred in the United States has been mostly a result of the long-term variability in atmospheric/ocean cycle rather than anthropogenic forcing. They and another commenter (5058R29) reference a study by McCabe et al. (2004), who specifically examined the trends in the variability of drought frequency (as captured by the Palmer Drought Severity Index) across the United States and found that the majority of the long-term variability is explained by atmospheric/ocean cycles over the Pacific and Atlantic oceans (specifically, the Pacific Decadal Oscillation and the Atlantic Multi-decadal Oscillation). They, along with another commenter (3394.1), also reference a recent study by Seager et al. (2009) who find recent droughts in the southeastern United States do not show any indication of anthropogenic influences. A commenter (3394.1) contends that the discussion on drought suggests that water shortages are a problem in certain regions of North America because of causes unrelated to climate change.

Response (3-11):

For most of the United States, we do not make any statements that link observed drought to anthropogenic forcing. The exception to this, as stated in response 3-10, is that the TSD does summarize the findings in the assessment literature that the recent trend toward increased aridity in the Southwest is consistent with model projections for that region under increased GHG forcing (Clark et al., 2008).

We reviewed the studies by McCabe et al. (2004) and Seager et al. (2009) and agree that they do not document evidence of anthropogenic influence on drought in the regions studied; however, Karl et al. (2009) indicate that increasing temperatures—which have been linked to anthropogenic forcing over North America—have made existing droughts more severe and widespread than they otherwise would have been. Also note that even in cases where we cannot yet attribute current trends to changes in GHG concentrations, the signals of these changes are projected to become much larger as GHG concentrations continue to increase.

Karl et al. (2009) find that drought, “related to reduced precipitation, increased evaporation, and increased water loss from plants, is an important issue in many regions, especially in the West,” and notes that the Southwest, in particular, is expected to experience increasing drought.” Though water shortages are also related to natural variability and human usage patterns, by “changing the existing patterns of precipitation and runoff, climate change will add another stress to existing problems” (Karl et al., 2009).

Comment (3-12):

A commenter (3596.1) writes that EPA’s TSD suggests that trends in non-tropical (or extratropical) storms are a reflection of extreme weather events created by anthropogenic warming but that a literature review by Craig Idso (comment 3596.3) does not support EPA’s claim.

Response (3-12):

We have reviewed the comment and the referenced literature review, and we disagree with the commenter’s characterization of EPA’s assessment of this issue. The April 2009 TSD did not include a statement attributing trends in non-tropical storms to anthropogenic warming. Rather, we noted that “Karl et al. (2008) find that heavy precipitation events averaged over North America have increased over the past 50 years at a rate higher than total precipitation increased, consistent with the observed increases in atmospheric water vapor, which have been associated with human-induced increases in GHGs." A change in heavy precipitation events (and its attribution) is a different issue from changes in non-tropical storms, in general. We agree with the commenter that the literature does not link trends in non-tropical storms to anthropogenic warming. To provide further summary of the conclusions of the assessment literature on this topic, we have added a statement to the TSD from the IPCC, which states: "An anthropogenic influence has not yet been detected in extra-tropical cyclones owing to large internal variability and problems due to changes in observing systems (Hegerl et al., 2007)."

Comment (3-13):
A number of commenters (e.g., 0591, 3432.1, 3596.2, 3679.1, 7031) suggest that trends in glaciers in certain regions/locations are inconsistent with and/or unrelated to anthropogenic warming. Some commenters link glacier loss to a recovery from cold conditions prior to 1900 and/or to internal variability (changing atmospheric and oceanic cycles) within the climate system.

Response (3-13):
EPA's summary is consistent with the assessment literature. The TSD notes that the IPCC (Hegerl et al., 2007) finds that anthropogenic warming has *likely* (where likely signifies a 66-90% probability the statement is true) "contributed" to the "widespread" retreat of glaciers. This wording implies other factors besides anthropogenic forcing impact glacier trends and it is referring to glaciers collectively, rather than individually. As noted in responses in Volume 2 about glaciers trends, although most observed glaciers are retreating, there are exceptions, which are noted in the TSD.

The IPCC (Hegerl et al., 2007) found that widespread shrinkage in glaciers implied widespread warming as the probable cause, although in the tropics changes in atmospheric moisture might be contributing. Hegerl et al. also found that the correlation between temperature and net glacier balance indicates the primary role of temperature in forcing glacier fluctuations. In addition, the IPCC cites the study by Reichert et al. (2002), which finds recent glacier retreat cannot be explained by internal variability, while the glacier advance during the "Little Ice Age" could be explained by internal variability.

While noting the primary role of temperature in causing glacier fluctuation (i.e., warming causing glacial retreat; Hegerl et al., 2007) and the large-scale correlation between tropical sea surface temperature anomalies and tropical glacier mass balance (Lemke et al., 2007), the IPCC (Lemke et al., 2007) finds the evidence suggests changes in atmospheric moisture have been the primary driver of the observed retreat of tropical glaciers. For example, studies (some cited by IPCC, some cited by commenters, and some new; e.g., Kaser et al., 2004; Cullen et al., 2006; Molg et al., 2008, 2009; Duane et al., 2008) attribute most of the retreat of slope glaciers on Mt. Kilamanjaro to a transition to a drier regime since the late 1800s. Shrinkage of the ice area on Kilimanjaro's plateau has been largely linked to solar radiation (Cullen et al., 2006).

In other words, at regional to local scales, particularly in the tropics, we acknowledge (based on our review of the assessment literature and the latest studies) that the evidence indicates other variables besides temperature are important for glacier mass balance trends; however, at global scales the body of the literature remains consistent with the statement from the IPCC on the likely contribution of anthropogenic warming to glacial retreat, as summarized in the TSD.

Comment (3-14):
A commenter (3729.7) posits snowpack trends in the U.S. Pacific Northwest are not consistent with anthropogenic warming but rather natural atmospheric-oceanic cycles (e.g., the Pacific Decadal Oscillation).

Response (3-14):
We begin by noting that EPA did not assign a cause for the observed changes in U.S. western snowpack in the April 2009 TSD. Rather, we reported the overall declining trend in snowpack as stated in the assessment literature (Lettenmaier et al., 2008) while subsequently stating (also citing the assessment literature, IPCC, 2007b) that many observed changes in physical and biological systems are being affected by regional climate changes, particularly temperature increases (which are linked to anthropogenic forcing).

As we noted in our response in Volume 2, a number of very recent studies have also documented the trend towards declining snowpack in the West, though some highlight significant decadal variability especially over smaller regions such as the Pacific Northwest (in the Cascades). These studies also evaluate attribution, and all suggest that anthropogenic forcing is contributing to trends in western snowpack, but to varying degrees.

We reviewed a recent study by Barnett et al. (2008), which finds that in the Western United States "up to 60% of the climate-related trends of river flow, winter air temperature, and snow pack between 1950 and 1999 are human-induced." A study by Pierce et al. (2008) concludes about half of the snowpack reductions observed in the West from 1950 to 1999 are the result of climate changes forced by anthropogenic GHGs, ozone, and aerosols.

Two recent studies attempt to attribute changes in a region confined to the Cascades (in the Pacific Northwest). Casola et al. (2008), while cautioning "the science of modeling the regional impacts of global warming is still in its infancy," finds "global warming would have produced an 8%–16% decrease in the snowpack in the Cascades over the last 30 yr." They suggest most of that warming was caused by anthropogenic forcing but do not quantify the percentage. A study submitted to *Journal of Climate* (Stoelinga et al., 2009, submitted) finds a 16% decline in snowpack in the Cascades for the period 1930–2007 and conclude 80% is due to natural variability (including the Pacific Decadal Oscillation, referred to by the commenter) with some or all of the remaining loss attributable to anthropogenic warming.

Finally, we note that CCSP (Backlund et al., 2008b) finds: "There is a trend toward reduced mountain snowpack and earlier spring snowmelt runoff peaks across much of the western United States. This trend is very likely attributable at least in part to long-term warming, although some part may have been played by decadal-scale variability, including a shift in the phase of the Pacific Decadal Oscillation (PDO) in the late 1970s." Accordingly, while we agree with the commenter that the PDO may play a role in the decadal variability of western snowpack, we do not agree that the current science shows that anthropogenic warming is not a contributor. EPA has incorporated the findings from Backlund et al. into the TSD (Section 5), and note it is further supported by our review of the most recent literature.

Comment (3-15):
Numerous commenters (e.g., 2750, 3291.1, 3411.2, 3446.1, 3596.1, 3679.1, 3729.8, 7031) note Arctic ice has melted to a significant degree in the historic past in the absence of significant anthropogenic GHG emissions. They note that although there has been a considerable temperature increase during the last decade, a similar increase and at a faster rate occurred during the early part of the 20th century (1920 to 1930) when carbon dioxide or other GHGs could not be a cause. Many relate sea ice loss to multi-decadal ocean cycles. Some refer to a paper by Chylek et al. (2009) that documents the major role of regional

atmospheric/ocean circulation pattern changes on regional multi-decadal climate variability in the Arctic. One commenter suggests the possibility that sea ice loss has been recently accentuated by major undersea volcanism and the invasion of tundra shrubs and deposition of soot from Asia. A commenter (3722) also provides an analysis by Dr. Akasofu that notes high variability in Arctic temperatures, noting that it is unlikely that CO_2 caused major temperature fluctuations before 1940.

Response (3-15):

The commenters' claims are inconsistent with the assessment literature. The scientific assessment literature (notably the IPCC's Fourth Assessment Report and the CCSP Synthesis and Assessment Product [SAP], *Past Climate Variability and Change in the Arctic and at High Latitudes*)—as summarized in the TSD—concludes that the recent decline in Arctic sea ice is unusual and cannot be explained by natural variability alone.

The IPCC (Hegerl et al., 2007) states that the recent decline in Arctic sea ice is inconsistent with simulated internal climate variability and the response to natural forcings alone.

The CCSP (Polyak et al., 2009) further finds that:

> The current decline of the Arctic sea-ice cover is much larger than expected from decadal scale climatic and hydrographic [i.e., pertaining to the physical characteristics of water] variations (e.g., Polyakov et al., 2005; Steele et al., 2008). The recent warming and associated ice shrinkage are especially anomalous because orbitally driven insolation has been decreasing steadily since its maximum at 11 ka [11,000 years ago], and it is now near its minimum in the 21 k.y. [21,000 years] precession cycle (e.g., Berger and Loutre, 2004), which should lead to cool summers and extensive sea ice.

Based on the IPCC assessment, the TSD states that anthropogenic forcing has *likely* contributed to the recent decreases in Arctic sea ice extent while noting that Karl et al. (2009) add:

> The observed decline in Arctic sea ice has been more rapid than projected by climate models. Clear linkages between rising GHG concentrations and declines in Arctic sea ice have been identified.

Although rapid observed warming in the Arctic also occurred from approximately the late 1920s to the early 1950s (as described in Section 4(b) of the TSD and discussed further in Volume 2 of the Response to Comments document), we do not find this past warming suggests the warming in recent decades and related loss of Arctic ice is not significantly attributable to anthropogenic forcing. In fact, the CCSP (White et al., 2009) states the following with respect to attribution of Arctic temperature trends:

> In the instrumental data (Parker et al., 1994; also see Delworth and Knutson, 2000), the Arctic sections, particularly the North Atlantic sector, show warming of roughly 1°C in the first half of the 20^{th} century (and with peak warming rates of twice that average). The warming likely arose from some combination of volcanic, solar, and human (McConnell et al., 2007) forcing, and perhaps some oceanic forcing. The warming was followed by weak cooling and then a similar warming in the latter 20^{th} century (roughly 1°C per 30 years) primarily attributable to human forcing with little and perhaps opposing natural forcing (Hegerl et al., 2007).

We note that the McConnell et al. (2007) paper cited by the CCSP (White et al., 2009) finds anthropogenic black carbon emissions have substantially contributed to surface forcing over the Arctic during and after industrialization. They write: "Beginning about 1850, industrial emissions resulted in a sevenfold increase in ice-core BC [black carbon] concentrations, with most change occurring in winter. BC concentrations after about 1951 were lower but increasing." So we concur with the comment that soot deposition has probably influenced Arctic sea ice trends. Other recent studies draw similar conclusions (e.g., Flanner et al., 2007; Strack et al., 2007; Quinn et al., 2008a, 2008b; Hegg et al., 2009).

We also acknowledge natural variability plays an important role in year-to-year changes in sea ice extent (as stated in Hegerl et al., 2007 and Karl et al., 2009) and we note this in the TSD.

We are aware of the study by Chylek et al. (2009), which finds "Arctic temperature changes are highly correlated with the Atlantic Multi-decadal Oscillation (AMO)." While the study concludes the AMO is a potential "major" cause of Arctic temperature variation, it does not specifically quantify the anthropogenic contribution. This study is too new to have been assessed by the broader scientific community, but its finding that the AMO is an important factor in Arctic temperature trends is not inconsistent with IPCC's assessment of the role of multi-decadal oscillation on regional climate, as we note in the following TSD statements:

> "The IPCC (Hegerl et al., 2007) cautions that difficulties remain in attributing temperature changes on smaller than continental scales and over time scales of less than 50 years"
> "Changes arising from internally generated variations in the climate system can influence surface and atmospheric temperatures substantially."

One commenter (3729.8) suggests that the encroachment of tundra shrubs is also contributing to recent declines in sea ice. IPCC (Fischlin et al., 2007) indicates shrubs have been migrating poleward as the climate warms and are likely to decrease regional albedo (reflectivity) in the Arctic leading to a net warming effect in the future. We are aware of a modeling study by Strack et al. (2007) that finds a complete invasion of the tundra by shrubs would lead to a 2.2°C warming of 3 meter air temperatures. Rather than being a forcing of Arctic warming and sea ice loss, our review of the literature (e.g., Strum et al., 2005) indicates the encroachment of tundra shrubs into the Arctic acts as a positive feedback enhancing the warming initiated by GHGs, aerosols, and/or natural variability.

Regarding the potential effects of underwater volcanism on Arctic sea ice trends, we are not aware of any recent peer-review studies documenting such an effect or any discussion of such an effect in the assessment literature. We note that *New York Times* writer Andrew Revkin queried a number of Arctic oceanographers and climate and ice experts on this issue and he reported that: "They uniformly reject the idea that heat from the bottom—either from the general geothermal activity beneath the seabed or the occasional outbursts of lava or vents—could have a significant impact on the veneer of floating, drifting ice on the surface." For more information, see http://dotearth.blogs.nytimes.com/2008/07/01/whats-up-with-volcanoes-under-arctic-sea-ice/. Also see the responses in Volume 4 on the relatively small magnitude of total geothermal heat compared to the radiative forcing imposed by changes in GHG concentrations.

Comment (3-16):
Numerous commenters (e.g., 0498, 3291.1, 3477, 3596.1, 4509) find that the observed trends in Antarctic temperatures and sea ice cast doubt on anthropogenic warming. They refer to research and datasets that indicate Antarctica is cooling and gaining ice.

Another comment (3596.2) indicates the TSD's statement that models explain the observed warming over the Antarctic Peninsula is false and based on Figure 3 in a study by Gillett and Thompson (2003). The comment argues that models underestimate the observed warming over the Antarctic Peninsula by a factor of three. This comment, in addition to a second comment (3136.1), also references Karpechko et al. (2008), stating that Karpechko et al. claimed that the Southern Annular Mode is far more influenced by ozone depletion than by global warming.

<u>Response (3-16):</u>
Regarding the observed trends in temperatures and sea ice extent over the Antarctic, we refer readers to Volume 2 of the Response to Comments document. While the IPCC found that "The substantial anthropogenic contribution to surface temperature increases likely applies to every continent except Antarctica (which has insufficient observational coverage to make an assessment) since the middle of the 20th century (Hegerl et al., 2007)," the more recent USGCRP assessment found that there were human fingerprints in the pattern of changes in Antarctic surface temperatures, based on a study by Gillett et al. (2008). The Gillett et al. study, *The Attribution of Polar Warming to Human Influence*, stated quite clearly that updated land-surface temperature sets and modeling results led to the finding that "the observed changes in Arctic and Antarctic temperatures are not consistent with internal climate variability or natural climate drivers alone, and are directly attributable to human influence. Our results demonstrate that human activities have already caused significant warming in both polar regions…"

Additionally, Baldwin et al. (2007) also found that the literature showed that combined effects of stratospheric ozone depletion and GHG increases could explain the pattern of warming and cooling found in Antarctica:

> The observed trend toward the positive phase of the SAM [Southern Hemisphere Annular Mode] in December to May has been associated with a surface cooling of the Antarctic interior of ~1 K [degrees Kelvin], and a warming of the Antarctic Peninsula, the Scotia Sea, and the southern tip of South America (Thompson and Solomon, 2002) (Figure 5-8). A similar pattern of warming and cooling has been simulated in response to stratospheric ozone depletion (Gillett and Thompson, 2003) and combined stratospheric ozone depletion and GHG increases (Shindell and Schmidt, 2004; Arblaster and Meehl, 2006)

Regarding the comment (3596.2) that models underestimate the observed warming based on the results shown in Gillett and Thompson (2003) in Figure 3, which is also Figure 5-8 in Baldwin et al., we find that the commenters have misinterpreted this information. The legend in the figure notes that the observed temperature trends are 32-year linear trends for the period December to May, whereas the modeled temperatures in that figure are perturbed minus control runs, averaged for the period December to February. Therefore, the trends are not comparable in the way in which the comment suggested. Further, Gillett, and Thompson explicitly stated that "The discrepancy between the simulated and observed trends during the months of April and May implies that the observed trends during this season are not attributable to the prescribed ozone depletion." This discrepancy was addressed by Shindell and Schmidt (2004), which was also included in the Baldwin assessment that the TSD relies on, who state:

> Indeed, previous simulations driven by ozone depletion alone showed a strong DJF [December, January, February] response but could not reproduce observed MAM [March, April, May] trends in the lower troposphere [Gillett and Thompson, 2003]. Conversely, previous simulations driven by greenhouse gases alone showed a weaker DJF response than the observations suggest [Fyfe et al., 1999; Kushner et al., 2001]. Observations thus suggest, and previous modeling allows, a sizeable role for both ozone and greenhouse gases in the lower atmosphere.

Finally, Arblaster, and Meehl (2006), the third study cited by Baldwin et al., included solar and volcanic forcings and updated observational trends, and stated:

> The observational trends are calculated from the SAM [Southern Hemisphere Annular Mode] index of Marshall (2003) (updated online at http://www.nerc-bas.ac.uk/icd/gjma/sam.html) and show positive trends in all seasons and for the annual value, with the summer season and annual values having a large significant positive trend, and DJF and March–May (MAM) having the largest relative positive seasonal trends, consistent with Thompson and Solomon (2002). The model all-forcing ensemble reproduces this seasonality, obtaining significant trends of a similar magnitude to the observations in both DJF and MAM seasons as well as annually.

Therefore, it is inappropriate to conclude that models "underestimate warming by a factor of three" based on comparing a December to February result to a December to May result, from a figure from a 2003 paper that only looked at ozone changes without concurrent GHG or other forcing changes and which has been superseded by later papers included in the assessment. While, as stated in the IPCC and summarized by the TSD, attribution at smaller than continental scales is difficult, and the observational coverage in Antarctica is limited, we find that Baldwin et al. appropriately assessed the underlying literature in regards to model agreement with observations of patterns of warming and cooling, and the TSD appropriately reflects those conclusions. The Karpechko et al. (2008) paper cited by one commenter is reasonably consistent with these results, stating that "[o]ur results demonstrate that both ozone depletion and GHG increases have played a role in the observed decrease of tropospheric geopotential height over the Antarctic. At the surface, their contributions are comparable while in the upper troposphere the ozone contribution dominates," and Karpechko is also a co-author of the 2008 Gillett study cited by the USGCRP.

<u>Comment (3-17):</u>

A number of commenters (e.g., 0509, 0700.1, 1309.1, 1616.1, 1961, 3136.1, 3394.1, 3596.2, 3722, 10562, and 11000) argue that there is no relation between sea level and carbon dioxide (CO_2) emissions, or that it is highly uncertain. One commenter (3722) states that "there is no consistent rate of sea level rise in the last century, much less is there any correlation with the increase in human-caused CO_2 emissions." Many of these commenters (e.g., 0509, 0700.1, 1309.1, 1616.1, 1961, 3136.1, 3394.1, 3596.2, 3722, and 11000) argue that sea levels are rising not because of greenhouse-induced warming but due to other factors, including seabed shifting, land subsidence, atmospheric circulation patterns, and solar-driven temperature effects of this past century.

<u>Response (3-17):</u>

These comments are inconsistent with the assessment literature. Regarding the primary causes of sea level rise, IPCC states (as discussed in Section 4(f) of the TSD):

> "On decadal and longer time scales, global mean sea level change results from two major processes, mostly related to recent climate change, that alter the volume of water in the global ocean: i) thermal expansion (Section 5.5.3), and ii) the exchange of water between oceans and other reservoirs (glaciers and ice caps, ice sheets, other land water reservoirs - including through anthropogenic change in land hydrology, and the atmosphere). All these processes cause geographically nonuniform sea level change (Section 5.5.4) as well as changes in the global mean; some oceanographic factors (e.g., changes in ocean circulation or atmospheric pressure) also affect sea level at the regional scale, while contributing negligibly to changes in the global mean. Vertical land movements such as resulting from glacial isostatic adjustment (GIA), tectonics, subsidence and sedimentation influence local sea level measurements but do not alter ocean water volume; nonetheless, they affect global mean sea level through their alteration of the shape and hence the volume of the ocean basins containing the water (Bindoff et al., 2007)."

The IPCC concludes that "it is very likely that the response to anthropogenic forcing contributed to sea level rise during the latter half of the 20th century. Models including anthropogenic and natural forcing simulate the observed thermal expansion since 1961 reasonably well. Anthropogenic forcing dominates the surface temperature change simulated by models and has likely contributed to the observed warming of the upper ocean and widespread glacier retreat (Hegerl et al., 2007)." Furthermore, IPCC finds that "Anthropogenic forcing is also expected to produce an accelerating rate of sea level rise (IPCC, 2007d)." Section 5 of the TSD on Attribution of Observed Climate Change to Anthropogenic Greenhouse Gas Emissions at the Global and Continental Scale further discusses this issue, and the statement above from Hegerl et al. (2007) has been added to that section.

We agree that non-climate factors, such as subsidence and seabed shifting, can have a substantial effect on locally observed sea level rise, and we discuss this point in the TSD. For example, Section 4(g) of the TSD describes that sea level changes in the United States vary from about 0.36 inches per year of rise (10 mm per year) along the Louisiana Coast (due to land sinking), to a drop of a few inches per decade in parts of Alaska (because land is rising) (Field et al., 2007). The TSD describes that the sea levels are rising along the Louisiana Coast by about 10 mm per year, which is greater than other rates in the United States because of the additional affects associated with subsidence. Furthermore, new studies (Hu et al., 2009; Yin et al., 2009) that have not yet been reviewed by the assessment literature, and thus not included in the TSD, suggest that warmer water temperatures and increased melting of Greenland ice sheets could shift ocean currents in a way that would raise sea levels off the Northeast by about 12 to 20 inches more than the average global sea level rise. However, the IPCC has concluded that non-climate factors have negligible impact on global rates of sea level rise (Bindoff et al., 2007; Hegerl et al., 2007; Nicholls et al., 2007) and are most relevant for analyzing sea level changes at regional and local scales. Therefore, we disagree that sea levels are rising due solely to non-climate factors such as land subsidence. For reasons discussed in the following section of this volume (3.2), we have additionally concluded that the evidence does not support arguments that observed temperature change and related sea level rise are due solely or mostly to internal variability (e.g., changes in atmospheric circulation patterns) or solar-driven temperature effects

Given robust findings by the assessment literature that anthropogenic forcing contributes to sea level rise we have determined that the TSD's discussion of this issue is accurate and represents the best available scientific information.

Comment (3-18):

Numerous commenters (e.g., 3136.1, 3291.1, 3347.3, 3596.1, 3722) suggest observed trends in tropical cyclone activity (i.e., hurricanes and tropical storms) cannot be attributed to anthropogenic forcing. They refer to the Statement on Tropical Cyclones and Climate Change from the WMO [World Meteorological Organization] International Workshop on Tropical Cyclones, held November 2006 (WMO, 2006) and a number of very recent studies (e.g., Vecchi et al., 2008; Swanson, 2008; Knutson et al., 2008).

Response (3-18):

We base our statements about the attribution of tropical cyclone activity to anthropogenic GHG forcing on the latest assessment literature, namely IPCC's Fourth Assessment Report and the CCSP SAP "Weather and Climate Extremes in a Changing Climate" (CCSP, 2008i, as referenced in the TSD). As summarized in the TSD, the IPCC (Hegerl et al., 2007) finds *it is more likely than not* that the anthropogenic influence has contributed to increases in the frequency of the most intense tropical cyclones, where *more likely than not* conveys a greater than 50% assessed likelihood. For the Atlantic basin specifically, the TSD cites the CCSP (Gutowski et al., 2008) finding that the evidence suggests a human contribution to recent tropical cyclone activity.

We acknowledge the attribution of trends in tropical cyclone activity is challenging and have added cautionary language to this effect in the TSD. Specifically, we added the following text:

> …the IPCC (Hegerl et al., 2007) cautions that detection and attribution of observed changes in hurricane intensity or frequency due to external influences remains difficult because of deficiencies in theoretical understanding of tropical cyclones, their modeling, and their long-term monitoring.

This caveat is in addition to the following statement in the TSD (in the final version as well the April 2009 version):

> [Gutowski et al., 2008] caution that a confident assessment of human influence on hurricanes will require further studies using models and observations, with emphasis on distinguishing natural from human-induced changes in hurricane activity through their influence on factors such as historical sea surface temperatures, wind shear, and atmospheric vertical stability.

We are aware of the Statement on Tropical Cyclones and Climate Change (WMO, 2006) authored by participants of the WMO International Workshop on Tropical Cyclones, IWTC-6, and recognize that one of its conclusions was that “Though there is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone climate record to date, no firm conclusion can be made on this point.” We note another conclusion in the statement was that “Given the consistency between high resolution global models, regional hurricane models and maximum potential intensity (MPI) theories, it is likely that some increase in tropical cyclone intensity will occur if the climate continues to warm,” and the final conclusion in the statement was, “Despite the diversity of research opinions on this issue it is agreed that if there has been a recent increase in tropical cyclone activity that is largely anthropogenic in origin, then humanity is faced with a substantial and unanticipated threat.” However, we defer to the more recent statements in the IPCC and CCSP assessments for the discussion of this issue in the TSD.

Furthermore, the very recent assessment of Karl et al. (2009), which synthesizes some of the latest literature, draws conclusions consistent with the 2008 CCSP assessment (CCSP, 2008i). For example, it reports that an increase in the maximum wind speeds of the strongest Atlantic hurricanes has been documented and linked to increasing sea surface temperatures, citing Elsner et al. (2008).

Karl et al. (2009) also cite recent studies on the causes of variability in Atlantic tropical cyclones which highlight the complexity of this issue. These include the studies referenced by commenters such as Vecchi et al. (2008), Swanson (2008) and Knutson et al. (2008). These studies were cited in the context of the following discussion:

> New evidence has emerged recently for other temperature related linkages that can help explain the increase in Atlantic hurricane activity. This includes the contrast in sea surface temperature between the main hurricane development region and the broader tropical ocean [Knutson et al., 2008; Swanson, 2008; Vecchi et al., 2008]. Other causes beyond the rise in ocean temperature, such as atmospheric stability and circulation, can also influence hurricane power. For these and other reasons, a confident assessment requires further study. [Gutowski et al., 2008]

In summary, the latest assessment literature integrates key findings from the latest studies on this issue and is consistent with the very qualified discussion of the linkage between anthropogenic forcing and tropical cyclone activity in our TSD.

Comment (3-19):
Some commenters (e.g., 0400, 0583, 0736, 0796, 3307.1) point to the facts that Earth's climate has never been static and that over long time scales temperatures have dropped and later increased significantly without any anthropogenic GHG emissions as evidence that anthropogenic emissions has little to no influence on climate. Commenter 3307.1, for example, states: "The Earth's history demonstrates not only that there have been previous periods in our history that are equally warm (or even warmer), but also that such warming can occur at a rate that is even more rapid than the current 20th Century warming: All without any industrial emission of CO_2."

Response (3-19):
The fact that Earth's climate has never been static and that in the past the Earth has experienced significant temperature change without anthropogenic emissions of GHGs in no way contradicts the robust conclusion that the global average net effect of human activities since 1750 has been one of warming. The assessment literature takes natural climate variability and historical records of climate changes into account and still comes to conclusions such as "Average Northern Hemisphere temperatures during the second half of the 20th century were *very likely* higher than during any other 50-year period in the last 500 years and *likely* the highest in at least the past 1300 years," "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations," that the rate of increase in radiative forcing from the increase in anthropogenic GHGs is very likely unprecedented in more than 10,000 years, and finally that "Continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century."

For EPA's responses to comments on past periods of global warming and their relationship to GHG concentrations please see Section 3.2.4 of this volume.

Comment (3-20):
Some commenters (e.g., 0525, 0546) argue that the idea that human activity can change climate runs counter to established scientific principles. Commenter 0525, for example, states: "The hypothesis that human activity can create global warming is extraordinary because it is contrary to validated knowledge from solar physics, astronomy, history, archaeology and geology."

Response (3-20):
We disagree that "the hypothesis" that human activity can create global warming runs contrary to established scientific principles. The claim was not accompanied by any evidence and is inconsistent with both the assessment literature and fundamental physical understanding. As discussed throughout this document, there is extensive observational and theoretical evidence that human activity is exerting a warming influence on the global climate.

Comment (3-21):
A number of commenters (e.g., 0736, 0796, 3553.1) argues that we do not understand climate mechanisms well enough to establish GHGs as the primary driver of global warming with any degree of confidence. Some commenters (e.g., 0553) suggest that the carbon cycle, in particular, is poorly understood and that the anthropogenic contribution to climate change is therefore highly uncertain.

Response (3-21):
For a number of aspects of climate change, attribution to increased GHGs has become clearer over time. For example, Hegerl et al. (2007) found the attribution of most of the warming in the last 50 years to increases in GHG concentrations to be "very likely," compared to a judgment of "likely" in the Third Assessment Report (IPCC, 2001c). A number of other aspects of climate have also been attributed to human influences with some level of certainty, as summarized in Section 5 of the TSD. The attribution of the increase in CO_2 concentrations to human emissions, in specific, is not in doubt—see Volume 2 of this Response to Comments document. Some uncertainties inherent to climate change attribution remain, and these uncertainties are acknowledged and discussed in both the Finding and the TSD, as well as throughout this Response to Comment document. The precise rate and magnitude of future climate change, for example, remain uncertain, and we do not know exactly what fraction of the recent warming may be due to natural factors (although on the basis of the IPCC, CCSP, USGCRP, and NRC reports, we are confident it is less than half).

We also acknowledge that there are a number of uncertainties involved in fully understanding the carbon cycle. There exist, for example, uncertainties about the exact quantity of carbon contained in the ocean and terrestrial carbon reservoirs and the precise size of the fluxes between the various reservoirs. We disagree, however, that knowledge of the basic nature of the carbon cycle is lacking, or that the remaining uncertainties call into question our fundamental understanding of GHG forcing. The key mechanisms that drive the carbon cycle are well established in numerous scientific textbooks and reports (see, for example, CCSP, 2007), as are the mechanisms by which anthropogenic carbon emissions cause the amount of carbon contained in the atmosphere and ocean reservoirs to increase. The annual flux from fossil fuel combustion and cement manufacturing to the atmosphere is well constrained, and the amount of carbon dioxide contained in the atmosphere is known with a high degree of precision (Denman et al., 2007; CCSP, 2007).

Comments about the level of certainty with respect to the scientific basis for this action are comprehensively addressed in Volume 1: Section 1.2 of this Response to Comments document.

Comment (3-22):
A commenter (3291.1) objects that the IPCC underestimates uncertainty. In particular, he objects that the "Level of Scientific Understanding" (LOSU) for radiative forcings was raised since the Third Assessment Report without explanation. The commenter also notes that the LOSU for forcings from direct and indirect aerosol effects are still estimated to be medium-low and low. Because the understanding of these forcings are low, the commenter argues that it is not valid to add these poorly understood forcings together with the better understood forcings in order to come up with a total forcing estimate.

Response (3-22):
Page 199 to 200 of Forster et al. (2007) in the IPCC Fourth Assessment Report discusses in detail the changes in LOSU for radiative forcing (RF) since the Third Assessment Report. Forster et al. note that the Third Assessment process of assigning an LOSU was "a subjective judgment of the estimate's reliability." In contrast, for the Fourth Assessment Report, Forster provides this description of an approach:

> "Evidence" is assessed by an A to C grade, with an A grade implying strong evidence and C insufficient evidence. Strong evidence implies that observations have verified aspects of the RF [radiative forcing] mechanism and that there is a sound physical model to explain the RF. "Consensus" is assessed by assigning a number between 1 and 3, where 1 implies a good deal of consensus and 3 insufficient consensus. This ranks the number of studies, how well studies agree on quantifying the RF and especially how well

observation-based studies agree with models. The product of "Evidence" and "Consensus" factors give the LOSU rank. These ranks are high, medium, medium-low, low or very low. Ranks of very low are not evaluated.

Similarly, Forster et al. discusses in detail the rationale for summing multiple forcings together to develop a probability density function for a net effect of all forcings. The discussion notes that the procedure used followed the example of Boucher and Haywood (2001), giving individual RF mechanisms equal weighting "even though the level of scientific understanding differs between forcing mechanisms," along with several other issues that would introduce further uncertainties. However, the IPCC states (and EPA concurs) that "Despite these caveats … it remains extremely likely that the combined anthropogenic RF is both positive and substantial" (Forster et al., 2007).

3.2 Alternative Explanations of Observed Changes

Comment (3-23):
A very large number of commenters (e.g., 0230, 0245, 0315, 0368, 0400, 0435, 0521, 0630, 0639.1, 0657, 0659, 0700.1, 0716.1, 1217.1, 1309.1, 1309.1, 1468, 1519, 1544, 1613.1, 1924, 2888.1, 2929, 2992, 3136.1, 3160, 3160.1, 3205.1, 3281.1, 3281.1, 3440.1, 3446.1, 3446.2, 3535.1, 3535.2, 3596.3, 3602.1, 3627.2, 3707.1, 3722, 3722, 37222R13, 3722R24, 3722R49, 3722R51, 3722R55, 3722R85, 3729.1, 3769.1, 4003, 4206, 4244, 4395, 4632R22, 4632R48, 6712, 7025, 7026, 7037) argue that natural factors provide a sufficient explanation for most or all recent climate change. These commenters state that natural processes either are or could be the primary driver of the observed changes in climate discussed in the Proposed Findings and the April TSD, and they posit specific alternative drivers other than anthropogenic GHG emissions. Some commenters focus solely on natural external forcings (e.g., solar output), others solely on natural modes of internal variability (e.g., the El Niño-Southern Oscillation [ENSO]), and some suggest that climate change could be the result of interactions between the two.

Response (3-23):
The claim that natural internal variability or known natural external forcings can explain most (more than half) of the observed global warming of the past 50 years is inconsistent with the assessment literature and the vast body of science it represents. Based on analyses of widespread temperature increases throughout the climate system and changes in other climate variables, the IPCC has reached the following conclusions about external climate forcing: "It is *extremely unlikely* (<5%) that the global pattern of warming during the past half century can be explained without external forcing, and *very unlikely* that it is due to known natural external causes alone" (Hegerl et al., 2007). With respect to internal variability, the IPCC reports the following: "The simultaneous increase in energy content of all the major components of the climate system as well as the magnitude and pattern of warming within and across the different components supports the conclusion that the cause of the [20th century] warming is *extremely unlikely* (<5%) to be the result of internal processes" (Hegerl et al., 2007). As noted in the TSD, the observed warming can only be reproduced with models that contain both natural and anthropogenic forcings (IPCC, 2007d), and the warming of the past half century has taken place at a time when known natural forcing factors alone (solar activity and volcanoes) would likely have produced cooling, not warming (Hegerl et al., 2007). See also other responses in this volume for EPA's responses to comments on specific alternative warming mechanisms.

Comment (3-24):
Many commenters (e.g., 0245, 0400, 0435, 1309.1, 1519, 1544, 1924, 3205.1, 3627.2, 3729.1, 3769.1, 4003, 4632R48, 7025) argue that changes in solar activity are (or in a few cases that solar activity could be) the primary driver of both distant past and recent changes (and possibly future changes) in climate. Commenter 3627.2, for example, states: "It is the sun's influence that is responsible for the lion's share of climate change during the past century and beyond" and additionally argues that "[c]osmic rays could provide the mechanism by which changes in solar activity affect climate."

Response (3-24):
The claim that changes in solar activity are the principal cause of recent (1955 to present) climate change has received limited support from a small number of peer-reviewed articles, many of which have been assessed in the IPCC and/or CCSP/USGCRP reports (discussed in Section 3.2.2), but this claim is inconsistent with the vast body of the science and the assessment literature. As the TSD notes, the IPCC Fourth Assessment Report estimates that changes in solar irradiance since 1750 are estimated to cause a radiative forcing of +0.12 (+0.06 to +0.30) watts per square meter (W/m^2) The combined radiative forcing due to the cumulative (1750–2005) increase in atmospheric concentrations of CO_2, methane (CH_4), and nitrous oxide (N_2O), on the other hand, is 2.30 W/m^2 with an uncertainty range of +2.07 to +2.53 W/m^2. In addition, the IPCC (Solomon et al., 2007) reports that continuous monitoring of total solar irradiance now covers 28 years and that "[t]he data show a well-established 11-year cycle in irradiance that varies by 0.08% from solar cycle minima to maxima, with no significant long-term trend." As noted above, the sum of solar and volcanic forcing in the past half century would likely have produced cooling, not warming. In addition, direct satellite measurements of solar output show slight decreases during the recent period of warming (Karl et al., 2009).

The fact that the observed pattern of atmospheric temperature change is inconsistent with well established scientific understanding of how the climate should respond to solar forcing provides additional evidence that changes in solar output are not the principal cause of recent changes in climate. If an increase in solar output were responsible for the recent warming, both the troposphere and the stratosphere would have warmed. By contrast, the observed pattern of atmospheric temperatures change has been characterized by warming in the troposphere and cooling in the stratosphere, a result predicted by models and consistent with a GHG forcing. For our responses to additional comments on solar irradiance see response 3-35.

As noted previously, some commenters argue that cosmic rays could provide the mechanism by which changes in solar activity affect climate. However, the IPCC (Solomon et al., 2007) assessed the science on this issue and concluded the following:

> Empirical associations have been reported between solar-modulated cosmic ray ionization of the atmosphere and global average low-level cloud cover but evidence for a systematic indirect solar effect remains ambiguous. It has been suggested that galactic cosmic rays with sufficient energy to reach the troposphere could alter the population of cloud condensation nuclei and hence microphysical cloud properties (droplet number and concentration), inducing changes in cloud processes analogous to the indirect cloud albedo effect of tropospheric aerosols and thus causing an indirect solar forcing of climate. Studies have probed various correlations with clouds in particular regions or using limited cloud types or limited time periods; however, the cosmic ray time series does not appear to correspond to global total cloud cover after 1991 or to global low-level cloud cover after 1994. Together with the lack of a proven physical mechanism and the plausibility of other causal factors affecting changes in cloud cover, this makes the association between galactic cosmic ray-induced changes in aerosol and cloud formation controversial.

The TSD appropriately summarizes this information by stating that empirical associations have been reported between solar-modulated cosmic ray ionization of the atmosphere and global average low-level cloud cover, but evidence for a systematic indirect solar effect remains ambiguous, and by noting that the lack of a proven physical mechanism and the plausibility of other causal factors make the association between galactic cosmic ray-induced changes in aerosol and cloud formation controversial (Forster et al., 2007). For our responses to additional comments on cosmic rays, see response 3-36.

Thus, the TSD comprehensively reviews the topic of solar activity and its effects on climate and its summary of the current state of the science as reflected in the underlying assessment literature is accurate and sound.

Comment (3-25):
Some commenters (3136.1, 3411.2, 3627.2, 3729.1, 4003, 4632R31) argue that modes of interannual variation in oceanic temperature and circulation such as the Pacific Decadal Oscillation (PDO), the El Niño-Southern Oscillation (ENSO), and the Atlantic Multidecadal Oscillation (AMO) could be the proximate cause of most or all recent climate changes. Commenter 3729.1, for example, argues that the oceans "act as the flywheel of the climate system, providing the mechanisms to bring about the changes" and states: "with decadal scale smoothing the ocean multidecadal indices and U.S. temperatures correlate with an r-squared of 0.85." Commenter 4003 includes with their comment a document authored by Alan Carlin that states the following: "By far the best single explanation for global temperature fluctuations appears to be variations in the PDO/AMO/ENSO." A document included with comment 3411.2, a chapter by Joseph D'Aleo from the "Supplementary Analysis of the Independent Summary for Policymakers," published by the Fraser Institute, states: "When you combine the two indices [the PDO and AMO], you can explain much of the temperature variation of the past 110 years in US annual mean temperatures."

One commenter (4632) submitted a peer-reviewed study (Tsonis et al., 2007) that suggests that synchronous states between four climate indices (PDO, ENSO, the North Atlantic Oscillation, and the North Pacific Oscillation) grow in strength and then abruptly shift to a new climate state, and that interactions between these indices could explain much of the recent climate change. Commenter 3722 also submitted a peer-reviewed study pertinent to the relative influence of natural variability: Stott et al., (2001).

Response (3-25):
Claims that ENSO), PDO, AMO, and other known modes of internal climate variability can explain all or most of the changes in climate that have occurred over the past century are inconsistent with the assessment literature, and commenters did not provide compelling evidence that the assessment literature has reached fundamentally flawed conclusions.

Although ENSO and other teleconnections (a fixed spatial pattern with an associated index time series showing the evolution of its amplitude and change) influence climate over interannual and multi-decadal time scales, and fluctuations in these phenomena can account for much of the interannual variability in the circulation and surface climate (as supported by the assessment literature), these phenomena cannot, by themselves, explain most of the changes in climate that have occurred over the past half-century, including in particular the long-term warming trend clearly evident in the temperature record, as claimed by some commenters.

Karl et al. (2006) note that while changes arising from internally generated variations in the atmosphere-ocean-land-ice/snow climate system, such as equatorial sea-surface temperatures associated with ENSO, can influence surface and atmospheric temperature substantially, climate models indicate that global-mean unforced variations on multidecadal timescales are likely to be smaller than the 20th century global-mean increase in surface temperature. In addition, the IPCC reports that global mean and hemispheric-scale temperatures on multi-decadal are largely controlled by external forcing, noting that “many observed changes in surface and free atmospheric temperature, ocean temperature and sea ice extent, and some large-scale changes in the atmospheric circulation over the 20th century are distinct from internal variability and consistent with the expected response to anthropogenic forcing” (Hegerl et al., 2007).

With respect to projections of future change in relation to natural variability, the TSD (April 2009 and final) notes that some of the most challenging aspects of understanding and projecting regional climate changes relate to possible changes in the circulation of the atmosphere and the oceans, and their patterns of variability. However, the TSD also included the IPCC’s conclusions that recent advances in regional-scale modeling lead to higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation, and some aspects of extremes of ice. The IPCC has reported that changes in natural patterns such as ENSO themselves might be related to climate change (Bindoff et al., 2007) and that the question of whether observed changes in ENSO behavior are physically linked to global climate change is “a research question of great importance” (Trenberth et al., 2007).

We note that commenter 4632 provided a recent peer-reviewed reference paper (Swanson and Tsonis, 2009) of relevance to the interplay between internal variability and external forcing. One of the paper’s main arguments is that climate shifts due to couplings between modes of climate variability have not only played a key role in recent climate change but could lead global mean temperatures to remain near current levels for an extended period of several decades. In light of the magnitude of expected GHG forcing, we find it highly unlikely that temperatures will remain near current levels for decades—and it bears mentioning that Swanson and Tsonsis state: “[I]t is purely speculative to presume that the global mean temperature will remain near current levels for an extended period of time.”

It is important to note that Swanson and Tsonis (2009) do not interpret their findings in the same way the commenters have. In fact, they say:

> “Finally, it is vital to note that there is no comfort to be gained by having a climate with a significant degree of internal variability, even if it results in a near-term cessation of global warming. It is straightforward to argue that a climate with significant internal variability is a climate that is very sensitive to applied anthropogenic radiative anomalies [cf. Roe, 2009]. If the role of internal variability in the climate system is as large as this analysis would seem to suggest, warming over the 21st century may well be larger than that predicted by the current generation of models, given the propensity of these models to underestimate climate internal variability [Kravtsov and Spannagle, 2008].”

Thus, the conclusion they derive is that their findings could imply more, not less, severe climate effects in the future.

Tsonis et al., (2007) do not discuss the relative role of anthropogenic warming in as direct a manner as Swanson and Tsonsis but do state that the climate shift they find was trigged by synchronous states in the PDO, ENSO, the North Atlantic Oscillation, and the North Pacific Oscillation “may be superimposed on an anthropogenic warming trend.”

The principal conclusion of the Stott et al. (2001) paper submitted by commenter 3722 is highly consistent with the assessment literature conclusions on this topic. The authors state: “All the results presented here support the conclusions of T99 that anthropogenic factors are largely responsible for the warming in near-surface temperature observed since 1945.”

Comment (3-26):
Commenters submitted a number of works that claim that the recent warming is part of a cycle of temperature trends. One commenter (3722) submitted Klyashtorin and Lyubushin (2003), stating that the 60-year cycle found in the paper can be used to explain recent warming and extended to show that the Earth is entering a cooling phase. This commenter states that Loehle et al. (2004) support a similar conclusion of imminent near-term cooling, and also submitted Davis and Bohling (2001). The commenter states that these cycle analyses and near-term cooling predictions are consistent with a 1998 peak in global average mean temperature. Other commenters submitted *Unstoppable Global Warming Every 1500 Years* by Fred Singer and Dennis Avery, which claims that a cycle of warming has dominated the earth's temperature for the past 10,000 years, that there is evidence that this cycle has existed for a million years, and that this cycle explains most of the Earth's warming since 1850.

Response (3-26):
The predictions of imminent cooling based on cycle analysis are not consistent with the assessment literature. These studies do not present any evidence for any negative external radiative forcings that could be of the magnitude of the positive forcing from increases in GHG concentrations. IPCC has shown that it is possible to explain previous temperature trends based on reconstructions of historical solar, volcanic, GHG, and orbital forcings, but the methods used to explain the previous changes cannot explain recent warming without the contribution of changes in GHG concentrations due to anthropogenic emissions. Specifically, historical reconstructions of solar and volcanic forcing have been used as inputs to model simulations; these simulations explain much of the last 1,000 years of temperature change, but the recent warming cannot be explained by the same natural forces that explained previous temperature changes (Jansen et al., 2007). Similarly, when forced by changes in solar forcing due to orbital parameters, coupled climate models and Earth System Models of Intermediate Complexity were both able to capture reconstructructed regional temperature and precipitation changes (Jansen et al., 2007).

We note that the submitted references do not use rigorous attribution studies. Klyashtorin and Lyubushin (2003) compared correlations of trends in world fuel consumption to temperature, rather than the more appropriate comparison of some kind of reconstruction of radiative forcing based on actual greenhouse gas concentrations. The book by Singer and Avery, which has not been peer-reviewed, summarizes literature that looks at historical cycles, but relies on changes in solar irradiance or cosmic rays to explain how these cycles could be operating in the present. See response 3-24 and 3-36 in this volume for an analysis of the role of cosmic rays, and response 3-35 for an analysis of the role of solar irradiance in the past 50 years. Davis and Bohling put recent oxygen-18 isotope changes as recorded in Greenland ice cores in the context of past changes in the last 10,000 years, finding that recent changes have been unusually rapid but not unprecedented. However, without examining the causes of the previous changes, this does not present evidence that the recent changes are natural in origin, nor does it counter the evidence that large increases in GHG concentrations will lead to large increases in temperature in the future. Loehle (2004) tries to explain historical data using time-series models based on cosine functions, and shows that a large number of the time series models that fit the historical record both explain recent warming and project cooling over the next century. Again, as the models presented in the paper include no physical variables and are merely statistical fits, they are not credible alternatives to physics-based models.

With respect to the contention by the commenter that 1998 was the peak in global average surface temperature, please see responses on global average temperature records in Volume 2 of the Response to Comments document.

Thus, these theories are not appropriate for inclusion in the TSD, and the summary in the TSD of the current state of the science as reflected in the underlying assessment literature is accurate and sound.

<u>Comment (3-27):</u>
Commenters 3136.1 asserts that the primary cause of recent warming in Alaska is the PDO, not human GHG emissions. Commenter 3627.2 made a similar point with regard to glacial extent in Alaska. A reference document provided by commenter 5058 (Hartmann and Wendler, 2005) did not explicitly claim that all observed warming in Alaska can be attributed to the PDO but suggested that "a significant amount of the warming trend seen throughout Alaska during the last half of the twentieth century is largely a result of the sudden shift [in the PDO] in 1976," and also stated: "[t]he cooling trend throughout much of Alaska since 1977, though not statistically significant, is in contrast to some theories regarding the atmospheric warming in an increasing greenhouse gas environment."

<u>Response (3-27):</u>
The TSD does not specifically attribute recent temperature changes in Alaska to human GHG emissions, though the TSD summarizes the findings of the recent USGCRP assessment (Karl et al., 2009) on Alaska, stating that "Over the past 50 years, Alaska's annual average temperature has increased by 3.4°F (1.9 C) and winters have warmed by 6.3°F (3.5 C), which is more than twice the rate of the rest of the United States These observed changes are consistent with climate model projections of temperature increases in Alaska of 3.5 to 7°F (1.9 to 3.9 C) by mid-century." This does not eliminate a role for the PDO, as the assessment literature notes that attributing changes in temperature to anthropogenic forcing at continental or smaller scales is challenging. One reason is that as spatial scales considered become smaller, the uncertainty becomes larger because internal climate variability is typically larger than the expected responses to forcing on these scales (Gutowski et al., 2008). We also note that short-term, local regional variability occurs on top of long-term, global trends. For more on attribution of Alaska temperature trends to different causes by Hartmann and Wendler (2005), see Volume 4 of the Response to Comments document.

We specifically discuss Alaska temperature trends in Volume 2 of the Response to Comments document, and note that data are conflicting about Alaska temperature trends since 1977. For a response on glacial trends, see the response in Volume 2 of the Response to Comments document.

3.2.1 Other Substances With Radiative Forcing Effects

<u>Comment (3-28):</u>
A few commenters (3283.1, 3596.1, 3596.2) cite recent brown and black carbon (BC) research (e.g., the Ramanathan and Carmichael, 2008, estimate of 0.9 W/m^2, and work by Nagashima et al., 2006) as both a reason that GHG effects may have been overestimated and as a possible area for reduction rather than GHGs. Commenter 3596.1 estimates that this means that GHG impacts have been overestimated by 25% (based on an IPCC radiative forcing impact of BC of 0.2 W/m^2 in the IPCC). Similarly, a commenter (3316.1) questions the reliability of models, suggesting that they missed a major climate change factor.

Response (3-28):
First, we note that the effect of GHGs is in large part determined by the climate sensitivity and that climate sensitivity estimates are determined in a number of ways, only one of which is likely to be affected by changes in our understanding of black carbon. The one methodology from the IPCC Fourth Assessment Report, Ch. 9.6 (Hegerl et al., 2007) for determining climate sensitivity that might be sensitive to a changing estimate for black carbon would be the methodology that uses 20^{th} century historical temperature patterns to constrain climate sensitivity estimates. Estimates based on paleoclimate data, response to individual volcanic events, or theoretical approaches would be insensitive to new estimates of black carbon forcing. Even for the estimates based on 20^{th} century data, net aerosol forcing is often included as an uncertain input (e.g., Forest et al., 2008) and therefore the new Ramanathan and Carmichael estimates might only imply a different allocation of positive and negative contributions within the total net aerosol forcing estimate, rather than any change in allocation of warming attribution between aerosols and GHGs. Indeed, Ramanathan and Carmichael estimate a net aerosol forcing of -1.4 W/m^2, which is actually a larger cooling influence than the IPCC net estimate of -1.2 W/m^2 from direct and cloud albedo effects, so if anything, changing the estimates of the strength of the aerosol forcing effect used as an input to climate sensitivity studies to match the Ramanathan and Carmichael data might increase the estimates of climate sensitivity rather than decrease them, although this effect is likely to be small. In any case, our examination of the methods for estimating forcing for various substances concludes that the new literature on black carbon does not imply a reduced forcing for GHGs.

The change in the estimate of current BC forcing could also affect future projections, inasmuch as any change in BC emissions (either increasing or decreasing) would have a larger effect than previously estimated. However, given that the total GHG forcing in the reference projections from CCSP 2.1a (CCSP, 2007b) range from 6.4 W/m^2 to 8.6 W/m^2 by the end of the century, the uncertainty of less than 1 W/m^2 due to BC forcing will not fundamentally change the results. On a technical note, the IPCC estimate for radiative forcing from BC was 0.34 W/m^2 for the direct effect and 0.1 W/m^2 for the snow albedo effect, for a total of 0.44 W/m^2, not 0.2 W/m^2, as one commenter claimed (0.2 W/m^2 refers to the direct BC contribution from fossil fuels alone).

Regarding the comment that BC could be a possible area for emissions reductions, please see Volume 1: Section 3, Role of Adaptation and Emissions Mitigation Considerations, for EPA's response to comments regarding the relevance and implications of mitigation measures in the context of this action.

Comment (3-29):
One commenter (0373.1) proposed that stratospheric ozone depletion due to CFCs better explains the observed temperature pattern than does CO_2, referencing a study by Ashworth.

Response (3-29):
Many attribution studies already include stratospheric ozone depletion as a component of their analysis (e.g., Forest et al. 2008). The best explanations of historic temperature patterns arise from inclusion of stratospheric ozone depletion in addition to, not in replacement of, increasing GHG concentrations. Indeed, the science suggests that the global impact of destruction of stratospheric ozone is estimated to be a negative forcing (Forster et al., 2007). We note that the Ashworth study submitted by the commenter has not been peer-reviewed, and we have determined that the assertion regarding the role of stratospheric ozone depletion is not valid.

Comment (3-30):
A commenter (3476.6) notes that there are a number of "first-order" anthropogenic radiative forcings that are not GHGs, namely aerosols (direct, indirect, and snow-albedo effects), nitrogen deposition, land use change, albedo effects, and water evaporation from land use and irrigation. Additionally, CO_2 has an effect on plant growth changing water transpiration. The commenter claims that regional climate change will be dominated by regional forcings, not by global GHG forcings. Another commenter (3283.1) also objects that warming is the result of non-GHG anthropogenic factors as well as GHG factors but that the EPA's endangerment finding seems to place all of the focus on anthropogenic GHG emissions. Several other commenters (3295.1, 3722, 4395) argue that variations in the amount of water vapor in the atmosphere are a principal driver of climate change.

Response (3-30):
The assessment literature discusses all of these additional forcings, and they are summarized in the TSD. As stated in Forster et al. (2007):

> While most current GCMs [general circulation models] incorporate the trace gas RFs, aerosol direct effects, solar and volcanoes, a few have in addition incorporated land use change and cloud albedo effect. While LLGHGs [long-lived greenhouse gases] have increased rapidly over the past 20 years and contribute the most to the present RF (refer also to Figure 2.20 and FAQ 2.1, Figure 1), Figure 2.23 also indicates that the combined positive RF of the GHGs exceeds the contributions due to all other anthropogenic agents throughout the latter half of the 20th century.

Both the IPCC and CCSP agree that these effects can be locally important. CCSP (2008e) examines the effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States and concludes that global climate change effects will be superimposed on and modify those resulting from land use and land cover patterns in ways that are as of yet uncertain. Karl et al. (2009) find that the anthropogenic land use activities such as cutting and burning forests, replacement of natural vegetation with agriculture and cities, and large-scale irrigation can cause local (and even regional) warming or cooling, but that globally the net effect of these changes has probably been a slight cooling over the last 100 years. Karl et al. also discuss the possibility that the Dust Bowl of the 1930s was the result of an interaction between poor agricultural practices removing native vegetation that had maintained soil moisture, and variations in ocean temperatures that disrupted wind patterns and therefore rainfall. While these local and regional variations can lead to differing trends in the short term, in the long term the continued accumulation of GHGs will lead to a global forcing that will exceed the short-term, local variability.

The TSD has been updated to address water evaporation from land use. We have added the following statement to Section 4a: "Irrigation and deforestation both have small, poorly understood effects on humidity, in opposite directions, and the IPCC concluded that radiative forcing from these sources of tropospheric water vapor was smaller than their non-radiative effects (such as evaporative cooling)." On the other hand, water vapor changes resulting from changes in the global climate are significant, and are included in the models as a feedback (but not a forcing). For further detail on water vapor, see the responses on the percent contribution in the atmosphere in Volume 2, and on the contribution of emissions from irrigation and combustion in Volume 9, of this Response to Comments document.

Comment (3-31):
Commenter (3722) discusses the profound uncertainty involved in determining the interaction of water with the climate system (including clouds) and states that this needs to be properly acknowledged.

Response (3-31):
Randall et al. (2007) address the issue of uncertainties involved in the interaction of water with the climate system, stating that:

> Substantial progress has been made in understanding the inter-model differences in equilibrium climate sensitivity. Cloud feedbacks have been confirmed as a primary source of these differences, with low clouds making the largest contribution. New observational and modeling evidence strongly supports a combined water vapour-lapse rate feedback of a strength comparable to that found in General Circulation Models (approximately 1 W m^{-2} $°C^{-1}$, corresponding to around a 50% amplification of global mean warming).

Therefore, the assessment literature finds that observations ands models are consistent in terms of describing the interaction of water and climate feedbacks, though uncertainties remain. Uncertainties due to clouds are analyzed in the assessment literature and discussed in the TSD in the context of aerosols and contrails (Section 4a), and the determination of climate sensitivity and model projections (Section 6b). For example, Box 6.3 in the TSD summarizes the approach of the assessment literature in assessing cloud uncertainties in the process of determining the likely range of equilibrium climate sensitivity. We have reviewed the TSD in light of this comment and find that its summary of the issue accurately reflects the scientific literature.

Comment (3-32):
Commenter (3679.1) requests that the TSD address the natural heat vent over the tropics.

Response (3-32):
We have reviewed the literature on the natural heat vent over the tropics, a theory that increased warming will lead to changes in cloud cover in the tropics that will lead to cooling (e.g., a negative feedback). We found, however, that several recent papers have indicated that cloud feedback in the tropics may actually be positive (Clement et al., 2009, Su et al., 2008). A strong negative feedback is also inconsistent with historical variability. Climate sensitivity estimates and uncertainty in cloud feedbacks in general are addressed in more depth elsewhere in this volume and in Volume 4.

Comment (3-33):
A commenter (3679.1) requests that the TSD address cooling from plant emissions of carbonyl sulfide, iodine, and dms (dimethyl sulfide) emissions from marine organisms in the oceans and other natural aerosol emissions. The commenter also requests that the TSD address increased photosynthesis from diffuse light. Another commenter (3596.3) reviewed studies from 1990 to 2002 regarding dms and carbonyl sulfide, and cites Smythe-Wright et al. (2006) regarding methyl iodide feedbacks. The commenter also notes that natural aerosols should contribute significantly to radiative forcing uncertainty.

Response (3-33):
We have reviewed the literature on these aerosol types. We do find that there may be some feedbacks from climate change on natural aerosol emissions, as addressed in the Section 8 (Health) of the TSD, but the climate-relevant impacts of these feedbacks are expected to be small in comparison to direct anthropogenic forcing changes. For example, Denman et al. (2007) found that dimethyl sulfate feedbacks represent a “small negative climate feedback to global warming,” estimating the negative climate feedback due to natural production of dimethyl sulfate from marine organisms as resulting in –0.05 W/m^2,

two orders of magnitude smaller than the average projected forcing changes from the IPCC Special Report on Emissions Scenarios (SRES) and CCSP emissions scenarios (CCSP, 2008d).

The Smythe-Wright et al. (2006) paper concludes, based on extrapolations from laboratory experiments, that a shift away from microalgae towards the methyl iodide producing *Prochlorococcus* due to warming of the oceans might lead to an increase of 15% in global methyl iodide production, leading to cooling through indirect cloud effects. This would therefore be another small negative feedback. However, other papers indicate that the total ocean emissions of methyl iodide is smaller than the Smythe-Wright estimate of *Prochlorococcus* methyl iodide production alone (Sive et al., 2007), and while Wang et al. (2009) find a correlation between methyl iodide production and temperature they also note that "While the global ocean is an important source of atmospheric methyl iodide (CH_3I), the major producers of CH_3I within the ocean remain unclear." Denman et al. (2007) also stated: "Thus, a hitherto undiscovered remote ocean source of iodine atoms (such as molecular iodine) must be present if iodine-mediated particle formation is to be important in the remote marine boundary layer." The overall literature on methyl iodide does not make the case for a significant negative feedback.

The most recent paper submitted with regards to carbonyl sulfide was by Aydin et al. (2002), who found that preindustrial variations of carbonyl sulfide reconstructed from Antarctic ice core data were small in comparison to the anthropogenic increase in the last century. The only other paper more recent than 1994 that was submitted was by Kuhn and Kesselmeier (2000), who found that soils were actually more likely to be sinks for carbonyl sulfide than sources, in contrast to earlier research. Therefore, we find that the scientific literature in this area is still uncertain, and that these effects are likely to be small in comparison to changes in anthropogenic forcings.

With regard to increased photosynthesis from diffuse light, this phenomenon is related in large part to the "dimming" caused by aerosol particles. Trenberth et al. (2007) report that global "dimming" was not global nor had it continued after 1990. Denman et al. (2007) addressed this phenomenon and stated that "an increase in diffuse light at the expense of direct light may promote leaf carbon assimilation and transpiration." However, in our review of the assessment literature, we find no indication that this effect is large enough to materially change future projections of climate.

Comment (3-34):

Commenter (3701.1) requests that EPA analyze Miskolczi's theory (Miskolczi 2007) that water vapor balances out CO_2 forcing. Commenter 3535 submits a statement by Miskolczi that claims that the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Protection (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data show a slight decrease in global average absolute humidity in the past 61 years, which compensates for increases in GHGs. Another commenter submits Paltridge et al. (2009), which also found decreasing absolute humidity at high altitudes from the NCEP data. Some (0798, 2982) cite Miskolczi (2007), which theorizes that water vapor will condense or evaporate as needed to maintain a constant greenhouse effect, citing a finite atmosphere used in calculations and observed decline in upper atmosphere humidity as validating factors. A number of other commenters (3323.1, 4003, 4041.1, 4932.1, and 5158) state that the lack of observed constant humidity levels are contrary to anthropogenic global warming theory and the IPCC computer models.

Response (3-34):

The hypothesis that increased CO_2 forcing will lead to a counterbalancing decrease in water vapor is highly speculative, and is not supported by the vast body of scientific literature. Miskolczi claims that the greenhouse effect should maintain a balance, so that every increase in a GHG should lead to a corresponding decrease in water vapor (and vice versa), effectively implying a climate sensitivity of zero.

A climate sensitivity of zero is completely incompatible with historical temperature variations, as it would imply an unchanging climate in direct contrast to historically recorded temperatures changes on all timescales. Miskolczi also claims that "On global scale, however, there can not be any direct water vapor feedback mechanism, working against the total energy balance requirement of the system. Runaway greenhouse theories contradict to the energy balance equations and therefore, can not work." This demonstrates a lack of understanding of feedback mechanisms in the climate (see response in Volume 4 for a discussion of runaway climate).

Several commenters also cite evidence for decreasing absolute humidity, in contrast to the IPCC conclusions (cited in the TSD) that "[a]lthough surface specific humidity globally has generally increased after 1976 in close association with higher temperatures over both land and ocean, observations suggest that relative humidity has remained about the same overall, from the surface throughout the troposphere (Trenberth et al., 2007)." The data from the NOAA NCEP/NCAR reanalysis for humidity has been questioned in other papers (Soden et al., 2005) (especially for the pre-satellite period), and a Dessler et al. (2009) review also contradicts this data. Even Paltridge et al. (2009), which relied on the NCEP reanalysis data, recognized that "[i]t is accepted that radiosonde-derived humidity data must be treated with great caution, particularly at altitudes above the 500 hPa [hectopascal] pressure level." Falling absolute humidity during a period of warming is also difficult to reconcile with theoretical understanding, model results, and historical temperature trends. The analysis in the IPCC (Trenberth et al., 2007) stated: "Due to instrumental limitations, long-term changes in water vapour in the upper troposphere are difficult to assess," but nonetheless concluded: "To summarise, the available data do not indicate a detectable trend in upper-tropospheric relative humidity. However, there is now evidence for global increases in upper-tropospheric specific humidity over the past two decades, which is consistent with the observed increases in tropospheric temperatures and the absence of any change in relative humidity." No trend in upper-tropospheric relative humidity, and evidence for increases in specific humidity, are consistent with model predictions that relative humidity should stay fairly constant, implying increasing absolute humidity with increasing temperature, and therefore a positive feedback (see response on Volume 4 for more responses on relative humidity predictions in models).

3.2.2 Solar Irradiance

Comment (3-35):

A number of commenters (e.g., 0670) argue that the sun is the primary driver of global temperature changes. Several commenters (3323.1, 4003, 4041.1, 4932.1, and 5158) referred to a new 2009 paper by Scafetta and Willson suggesting that the IPCC used faulty solar data in dismissing the direct effect of solar variability on global temperatures. Commenters also cite other research by Scafetta and others that suggests that solar variability could account for up to 68% of the increase in Earth's global temperatures. One commenter (1616.1) attributes 0.14°C of the warming since 1950 to increased solar irradiance, and another 25% of warming since 1979, as in Scafetta and West (2006) (3596.1). Another commenter (7031) states that the correlation between solar variations such as sunspots and global climate has been pointed out by several scientists, such as Scafetta and West (2008). A number of specific climate-related regional phenomena have been related by commenters (e.g., 3596.1) to solar variability, such as sea surface temperature, floods, droughts, monsoons, and North Atlantic drift ice.

Response (3-35):

We have reviewed the comments and the literature submitted and have determined that changes in solar irradiance are not a sufficient explanation for recent climate change. The contention that direct solar variability can explain recent warming is not supported by the bulk of the scientific literature. As the TSD notes, the IPCC Fourth Assessment Report estimates that changes in solar irradiance since 1750 are estimated to cause a radiative forcing of +0.12 (+0.06 to +0.30) W/m^2, or approximately 5% of the combined radiative forcing due to the cumulative (1750–2005) increase in atmospheric concentrations of CO_2, CH_4, and N_2O (2.30 W/m^2 with an uncertainty range of +2.07 to +2.53 W/m^2). The natural 11-year cycle of solar irradiance has a magnitude of less than 2 W/m^2 at the distance of the Earth—which, once corrected for albedo and distribution over the surface area of the planet, is a magnitude of less than 0.35 W/m^2. In addition, Karl et al. (2009) state that "if most of the observed temperature change had been due to an increase in solar output rather than an increase in GHGs, Earth's atmosphere would have warmed throughout its full vertical extent, including the stratosphere. The observed pattern of atmospheric temperature changes, with its pronounced cooling in the stratosphere, is therefore inconsistent with the hypothesis that changes in the Sun can explain the warming of recent decades. Moreover, direct satellite measurements of solar output show slight decreases during the recent period of warming." A number of other recent studies also show results that contrast with the interpretation that solar variability is driving recent warming. Both Lockwood and Fröhlich (2008) and Lean and Rind (2009) show that the solar contribution to warming in recent decades has been small or negative, consistent with the IPCC attribution of most of the warming in recent decades to anthropogenic GHGs.

The attribution of components historical climate change to solar activity involves a number of issues. The first is the actual reconstruction of historical solar activity: even for the last three decades there is some controversy, as is evident in the differences between Scafetta and Willson (2009), which uses a total solar irradiance composite from the Active Cavity Radiometer Irradiance Monitor (ACRIM) analysis of satellite data, and Lockwood and Fröhlich (2008), which uses a composite based on the Physikalisch-Meteorologisches Observatorium Davos (PMOD) analysis of satellite data. These two composites don't even agree on the sign of the solar irradiance trend over this time period. Lockwood and Frolich analyze both datasets and find that the ACRIM dataset is inconsistent with methods of historical reconstructions that have shown correlations between historical solar activity and climate. Krivova, Solanki, and Wenzler (2009) also find no evidence of an increase in total solar irradiance (TSI) from 1986 and 1996 using an analysis based on magnetograms. Scafetta and Willson, on the other hand, claim that the PMOD approach requires a correction of the data from the earth radiation budget (ERB) system on the NIMBUS7 satellite, and this correction has been rejected by one of the scientists on the NIMBUS team (D.V. Hoyt, personal communication to Scafetta, 2008). Neither dataset shows an increase of solar irradiance between the minima of 1986 and 2008, which would be required in order to explain warming over that period. Therefore, reconstructions of recent solar variability do not agree, but in one case show no trend, and in the case of the Lockwood and Fröhlich reconstruction the solar contribution during this period would have been a cooling, not warming, influence.

The second issue is that in order for solar irradiance to be a major driver of recent warming, there must be an amplification effect that is active for solar irradiance that is not active for forcing due to GHGs. Studies such as Scafetta (2009) often rely on a significantly different factor for solar irradiance than is used for GHG climate sensitivity. Additionally, the Scafetta study relies on a "slow lag" solar response and the timescale chosen has itself been the subject of dispute. The climate sensitivity for this slow lag response used by Scafetta is 0.46° K/Wm^{-2}. Note that this is compared to the total solar irradiance: therefore, the effective sensitivity to the average solar irradiance according to Scafetta would be (4*0.46)/0.7 = 2.6° K/Wm^{-2}. This can be compared to a climate sensitivity range of 2 to 4.5, or about 0.5° K/Wm^{-2} to 1.2° K/Wm^{-2}. Additionally, Scafetta claims that solar variability accounts for most of the recent warming and that GHG sensitivity is on the low end of the range: this means that Scafetta is effectively claiming that sensitivity to solar variability is on the order of five times the sensitivity to forcing by GHGs, without a good mechanism to explain this extreme difference. Although it is not impossible that there are differences between solar and GHG induced changes, the evidence for an amplification of the magnitude needed to explain recent warming is weak. For example, while Meehl et al. (2009) find an amplification of the solar cycle variability is needed to explain certain patterns of tropical Pacific climate response, the authors note: "This response also cannot be used to explain recent global warming because the 11-year solar cycle has not shown a measurable trend over the past 30 years."

Moreover, the sensitivity needed is nowhere near as large as the Scafetta sensitivity, and the behavior explained is geographically localized, which is different from a global increase in sensitivity. Therefore, the evidence for an amplification of the magnitude needed to explain recent warming is weak.

Some other authors also show some correlations between solar variability and regional trends. Eichler et al. (2009) find a strong correlation between solar activity (as reconstructed by carbon-14 and beryllium-10 proxies) and temperatures in the Siberian Altai region. However, the authors note that "underlying physical processes are still not yet understood" in terms of amplifying a weak solar signal (in terms of radiative forcing) in order to see larger effects, and also that "[i]n large spatial scale hemispheric or global reconstructions the solar signal may therefore even vanish" because the "main effect of solar forcing is presumably on location, routes, and stability of atmospheric pressure systems, which all act on regional scales." The conclusion of the Eichler work is that while solar activity was a main driver for temperature variations in the Altai region preindustrially, during the industrial period they found that only CO_2 concentrations show a significant correlation with the temperature record. They did find agreement with the northern hemisphere (NH) temperature reconstruction of Scafetta and West (2007) in that they found that only up to approximately 50% of the observed global warming in the last 100 years can be explained by the sun. Note that this conclusion provides 50% as an upper limit to the explanatory power of solar variability, and this is for the full century. Therefore, for the last 50 years, this conclusion is still consistent with the IPCC (2007b) statement that "[m]ost of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."

Therefore, to summarize: attempting to attribute late-20th century temperature change mainly to solar variability requires choosing a specific solar dataset, assuming a simplified model with different "fast" and "slow lag" responses based on timescales from a controversial paper, and assuming that the climate system is several times more sensitive to changes in solar irradiance (or other, non-radiative changes in the sun) than it is to changes in GHG forcing. All three of these assumptions are counter to the conclusions of the IPCC and CCSP assessments and not viewed as established conclusions in the literature. While science in this area will continue to evolve, our review did not uncover any compelling alternatives to the science represented in the assessment literature, and summarized in the TSD.

Comment (3-36):

Many commenters (0153, 0245, 0509, 0591, 1017.1, 1187, 2953, 3722, 3729.1) claim that temperature is better correlated with solar activity patterns than with greenhouse forcing, some of whom reference researchers such as Svensmark or Shaviv that attribute the mechanism not to solar irradiance but rather solar wind or solar-magnetic flux (2917, 3205.1, 3324.1, 4632, 5058) and interactions with cosmic rays seeding low-lying clouds (0542, 0646, 0798, 1616.1), or length of solar cycles (0543) or sunspots (1219.1).

One commenter (7031) indicates that solar impacts on climate have received scant research attention and are minimized in the IPCC Fourth Assessment Report (2007a) and the climate model community, even though the IPCC authors rank the level of scientific understanding of solar-climate interactions as very low. The assumption is that variations in TSI are the only significant solar impact on global climate. The commenter also posits:

> Recent studies have shown strong correlations between solar-modulated cosmic ray fluxes and low-level cloud cover and its subsequent impact on global temperatures. Experimental verification of a cosmic-ray cloud seeding mechanism was recently completed by Svensmark et al. [1997], and the CLOUD (Cosmics Leaving OUtdoor

Droplets) experiments at CERN (the European Organization for Nuclear Research) over the next few years will provide definitive measurements of cloud seeding by cosmic rays.

The commenter concludes it is clear that solar variations have much larger impacts on global climate than what is estimated based solely on TSI variations.

One commenter (3446.2) requests that the TSD include a rigorous presentation of sunspot activity and temperature over the past century, and notes objection to the lack of sunspot discussion in Karl et al. (2009). Another (3397) requests more discussion of solar activity as a climate forcer.

Response (3-36):
The contention that cosmic rays could provide the mechanism by which changes in solar activity affect climate is not supported by the literature. Solomon et al. (2007) address this topic, noting that "the cosmic ray time series does not appear to correspond to global total cloud cover after 1991 or to global low-level cloud cover after 1994." More recent research continues to question the ability of this mechanism to play a significant role in climate change. Pierce and Adams (2009) use calculations to show that potential impacts on clouds from cosmic rays and "conclude that the hypothesized effect is too small to play a significant role in current climate change." Erlykin et al. (2009) found that the evidence showed that connections between solar variation and climate were more likely to be mediated by direct variation of insolation rather than cosmic rays, and concluded: "Hence within our assumptions, the effect of varying solar activity, either by direct solar irradiance or by varying cosmic ray rates, must be less than 0.07 ◦C since 1956, i.e. less than 14% of the observed global warming." Carslaw (2009) and Pittock (2009) review the recent and historical literature in this field and continue to find that the link between cosmic rays and climate is tenuous, though they encourage continued research.

The CLOUD experiments at CERN are interesting research but do not provide conclusive evidence that cosmic rays can serve as a major source of cloud seeding. Preliminary results from the experiment (Duplissy et al., 2009) suggest that though there was some evidence of ion mediated nucleation, for most of the nucleation events observed the contribution of ion processes appeared to be minor. These experiments also showed the difficulty in maintaining sufficiently clean conditions and stable temperatures to prevent spurious aerosol bursts. There is no indication that the earlier Svensmark experiments could even have matched the controlled conditions of the CERN experiment. We find that the Svensmark results on cloud seeding have not yet been shown to be robust or sufficient to materially alter the conclusions of the assessment literature, especially given the abundance of recent literature that is skeptical of the cosmic ray-climate linkage reviewed in the previous paragraph.

Therefore the TSD summary of the assessment literature on this issue is well founded: that the lack of a proven physical mechanism and the plausibility of other causal factors make the association between galactic cosmic ray-induced changes in aerosol and cloud formation controversial.

Comment (3-37):
Several commenters cite good sun-climate agreement over various timescales, such as during the past millennium, including the Maunder and Dalton minima (3411, 3729.1, and 4003), or over the past 500 million years (4003). One commenter attributed the "snowball earth" event 2.3 billion years ago to cosmic ray fluctuations resulting from passing through the arm of the Milky Way (3205.1).

Response (3-37):
With respect to the claim that cosmic rays can explain the "snowball earth" event, and other cosmoclimatology claims by Svensmark (2006) and Shaviv (2003), more recent research has indicated that there are no robust correlations between the solar system's passage through spiral arms and paleoclimate research (Overholt et al., 2009). We do not dispute that solar variability has likely had an influence on the millennial timescale, though Jansen et al. (2007) estimate that "the magnitude of the radiative forcing used in Chapter 9 for the Maunder Minimum period is relatively small (–0.2 W m^{-2} relative to today)" and in general that the "reconstructions of natural forcings (solar and volcanic) are uncertain for this period."

Comment (3-38):
A number of commenters (0219, 0425, 0468, 0591, 1579.1) mention the recent sunspot lull and concurrent low temperatures. Some (3159, 3265, 7026) worry that this lull is the first step towards a Maunder or Dalton minimum (3729.1) and cooling based on the projections of Landscheidt (0543), Archibald (0714.3), or Clilverd (3729.1). One commenter requests that the TSD discuss the possibility of imminent cooling (4003).

Response (3-38):
In response to commenters who noted the recent sunspot lull: while a lull in sunspots or solar irradiance may have a small cooling effect on climate, there is no evidence upon which to conclude that the sunspot lull will continue (as in a Maunder minimum). Even the radiative forcing from the Maunder minimum has been estimated to be only 0.2 W/m^2, which is significantly less than the projected increased forcing from elevated GHG levels. The possibility of orbitally induced reglaciation is also addressed by Jansen et al. (2007), which found that "It is virtually certain that global temperatures during coming centuries will not be significantly influenced by a natural orbitally induced cooling." In addition, the IPCC placed the rate of current and projected warming in the context of past changes and found that the present warming is occurring at an unprecedented rate on the global scale, exceeding even that of glacial to interglacial transitions—indeed, according to Jansen et al. (2007), it is possible that the rate of global change projected to occur in the next century would exceed "any comparable global temperature increase of the last 50 million years." Therefore, it is extremely unlikely that over the next couple of decades that there will occur reductions in solar forcing of sufficient magnitude to counteract the projected warming due to anthropogenic GHGs.

We find no evidence that historical variations in solar forcing, including the recent sunspot lull, are of comparable magnitude to the recent and continuing anthropogenic warming, and conclude that there is no expectation of large scale near-term cooling. Thus, there is no need for the TSD to address this issue.

Comment (3-39):
A few commenters (0717, 4003) noted that there is warming on other planets, mentioning Mars, Jupiter, and Pluto, and stated that this was evidence for the solar cause of global warming.

Response (3-39):
The commenters did not provide any peer-reviewed literature to support their argument. One indication that Mars is warming was a retreat of the South Polar Cap, but Colaprete et al. (2005) discuss the fact that the South Polar Cap is unstable, and that it is therefore difficult to extrapolate short-term changes in the cap to a long-term global trend. Martian climate is also influenced by non-solar mechanisms such as positive feedbacks between albedo changes and changes in dust storms (Fenton et al., 2007). Therefore, it is neither clear that Mars is warming nor that the warming is solar induced. The climate on Jupiter is

dominated by the dynamics of the massive standing vortices on the planet (Marcus, 2004), and solar energy is a less significant contribution to the temperature of Jupiter than it is for Earth. It is also unclear whether the warming of Jupiter is global or regional.

The changes in Pluto's atmosphere have been detailed in Elliot et al. (2007). The basic atmospheric expansion is well modeled by the frost migrations models of Hansen and Paige (1996), without requiring any solar effects beyond Pluto's seasonally changing sub-solar latitude. Because Pluto takes about 248 years to orbit the sun, Pluto's seasons can be measured in decades. Finally, Triton is the last commonly referenced "warming" planet. The last good measurements of Triton were in 1998 (Elliot et al., 1998), and the changes in Triton's pressure have been explained by the change in Triton's subsolar latitude uncovering polar icecaps to the sun as a result of Triton's obliquity.

Therefore, there is no indication that solar variability is the cause of recent warming on any solar system body. Additionally, the lack of recent observed trends in solar insolation (discussed in responses in this section of the Response to Comments document) makes it implausible that there would be such solar-induced warming trends on solar system bodies.

Comment (3-40):
One commenter (3722) submitted Kärner (2002) on analysis of the nonstationary climate system, emphasizing a dominant role for solar variability.

Response (3-40):
Kärner (2002) used satellite data records to show that solar variability was more dominant than elevated GHG concentrations. As Kärner relied on the University of Alabama–Huntsville (UAH) satellite dataset before the 2005 corrections which led to a significant change in temperature trends, we find that the conclusions of the paper are obsolete and do not affect the conclusions of the TSD.

Comment (3-41):
Several commenters (3250, 3283.1,) indicate that another phenomenon that complicates attribution is the fact that since the 1980s, the incident sunlight in North America and Europe has increased as solar dimming due to aerosols has abated, possibly causing the observed land temperature to increase. One of these commenters (3283.1) submitted Alpert et al. (2005), which studied global dimming over the period 1964-1989. According to the study, globally, there was considerable solar dimming in both rural and metropolitan areas. The study also finds:

> In urban locations the effect was 2.6 times larger.
> Since 1990, much of the Northern Hemisphere has brightened. This change may be reconciled with at least changes in cloudiness, and atmospheric transmission. This is yet another good reason to suggest that the global instrumental temperature record may be in error and in a way that has not been adequately appreciated.

The authors conclude the following: "[T]he absence of dimming since the mid-1980s may profoundly affect surface climate. Whereas the decline in solar energy could have counterbalanced the increase in down-welling long-wave energy from the enhanced greenhouse effect before the 1980s, this masking of the greenhouse effect and related impacts may no longer have been effective thereafter, enabling the greenhouse signals to become more evident during the 1990s." The commenter concludes these data demonstrate the complexity of processes of the lower atmosphere and also the importance of considering various sources of information to provide evidence of a warming climate.

Response (3-41):
Although global dimming is a recognized phenomenon, and since passage of the Clean Air Act in 1970 (and the successive amendments) aerosol concentrations have decreased—which has led to modest increases in incident sunlight—this phenomenon has been accounted for in the assessment literature already. The IPCC (Trenberth et. al., 2007) addressed the submitted studies (Alpert et al., 2005; Schwartz, 2005), finding that dimming varies geographically, with the greatest effect in large urban areas. The IPCC agrees that the trend of global dimming seems to have reversed in the early 1990s, possibly due to both direct and indirect (cloud interaction) effects of the reductions in anthropogenic aerosols. Dimming is discussed in Hegerl et al., Denman et al., Trenberth et al., and CCSP 2.3 (CCSP, 2009a). The changes in anthropogenic aerosol emissions and associated uncertainties are addressed in detail in the IPCC, CCSP, and UGSCRP attribution studies, which serve as the basis for the TSD's discussion of attribution. Because these aerosol effects are already included in all the IPCC studies, we conclude that the scientific literature on global dimming does not alter any of the conclusions from the assessment literature, as summarized in the TSD.

3.2.3 Existence of GHG Effect

Comment (3-42):
A commenter (2818) requests that the derivation for radiative forcing be presented (mentioning the HITRAN [High-Resolution Transmission Molecular Absorption] database). Another commenter (10071.2) requests the same data, claiming that infrared radiation only matters for the bottom 800 m of the atmosphere, and therefore the thickness of the full atmosphere should not be used to compute radiative forcing. The commenter suspects that the forcing numbers are chosen to make the models produce the right results, and that CO_2 cannot cause global warming.

Response (3-42):
Radiative forcing for gases is usually calculated within global circulation models using some form of line by line or other radiative code. The IPCC Third Assessment Report includes a discussion of these issues in Chapter 6.3 (Ramaswamy et al., 2001). The citation for the commonly used approximate expression $5.35 \ln(C/C_0)$ (the log of the current concentration of CO_2 over the pre-industrial concentration) is Myhre et al. (1998), which uses three different approaches to calculate radiative forcing (line by line, narrow band, or broad band). Myhre used the HITRAN database (information on that database can be found at http://www.cfa.harvard.edu/hitran//). Forster et al. also include a discussion on radiative forcing calculations, where they find that "Collins et al. (2006) performed a comparison of five detailed line-by-line models and 20 GCM radiation schemes. The spread of line-by-line model results were consistent with the ±10% uncertainty estimate for the LLGHG RFs (long-lived GHG radiative forcings) adopted in Ramaswamy et al. (2001) and a similar ±10% for the 90% confidence interval is adopted here. However, it is also important to note that these relatively small uncertainties are not always achievable when incorporating the LLGHG forcings into GCMs. For example, both Collins et al. (2006) and Forster and Taylor (2006) found that GCM radiation schemes could have inaccuracies of around 20% in their total LLGHG RF (see also Sections 2.3.2 and 10.2)." GISS Model E is also available publicly (http://www.giss.nasa.gov/tools/modelE/), and therefore the commenter can easily acquire the actual radiative code for at least one major model, along with the documentation of how the radiative forcing equations are developed from theoretical principles and laboratory experiments, and tested against satellite measurements of atmospheric radiative fluxes. We find that these radiative equations match the best available science, and are widely available for scrutiny.

The statement that infrared radiation only matters in the bottom 800 m of the atmosphere is consistent with the scientific literature. Radiative forcing is commonly report as top of the atmosphere forcing, not at

800 m. CO_2 and other GHGs interact with infrared radiation in the full tropospheric column (and indeed, in the stratosphere as well) both in reality and in the model code.

Comment (3-43):

A commenter (3160.1) contends that long-wave infrared (IR) radiation from GHGs cannot heat the ocean as it can only penetrate 1 mm into the surface. The commenter also argues that increases in long-wave IR radiation in the upper troposphere at 220°K cannot impact surface temperatures of 288°K due to the Second Law of Thermodynamics, and that therefore the application of "radiative forcing" concepts to climate models is flawed.

Response (3-43):

We disagree with the assertion by the commenter, which was not supported by any peer-reviewed literature. We find that long-wave IR radiation can and does heat the oceans despite a small direct penetration distance. Increasing the skin temperature of the ocean changes the rate of heat flux into or out of the ocean, thereby leading to ocean warming compared to the counterfactual without long-wave IR radiation. An empirical test of this logical assumption was recently performed by Millett (2006), who showed that incident infrared radiation on the sea surface modulated the heat flow from the ocean to the atmosphere in a way consistent with this theory. Similarly, increasing high-altitude IR will lead to increases in surface temperatures both due to direct radiative effects and decreased temperature differentials leading to a decrease in outward flux. This interaction of high-altitude radiative interactions and surface temperatures is not in contradiction to the Second Law of Thermodynamics; rather, it is consistent with basic textbook physics, has been used throughout the scientific literature, and explains many observed features of the atmosphere (see also response 3-45 on thermodynamic impossibility). Therefore, both theory and experiment contradict the assertion of the commenter.

Comment (3-44):

One commenter (3440.1) claims that the blackbody temperature of the Earth due to solar radiation would be 278.5° K, and that therefore the sum total of the greenhouse effect is only 8.5° K. The commenter goes on to calculate a climate sensitivity parameter as nine-tenths of the surface temperature divided by the solar irradiance and shows that their calculation of this parameter is much less than the IPCC estimate. The commenter then uses another approach based on dividing the previously calculated 8.5 degrees by the 100 W/m^2 of greenhouse effect and again calculates a value of lambda much lower than the IPCC. The commenter requests that EPA undertake its own study of climate sensitivity, as a crucial parameter in determining endangerment.

Response (3-44):

See Section III.A. of the Findings, "The Science on Which the Decisions Are Based" and Volume 1: Section 1, for our response to comments on the use of the assessment literature and our decision that it was not necessary for EPA to conduct an independent assessment of the science. We also find that this comment includes several calculation errors: for example, it does not appear that the commenter took into account the reflective albedo of the Earth (about 0.3) when calculating the blackbody temperature of the Earth to be 278.5K: repeating the calculation with that albedo yields the more standard 255K for the Earth's blackbody temperature, leaving 32K for the total greenhouse effect. We are unclear as to why the commenter used the equation of blackbody temperature over total solar irradiance to calculate a climate sensitivity parameter, but the average W/m^2 solar irradiance on the surface of the Earth would be a more appropriate number to include in that equation than the total solar irradiance at noon at the top of the atmosphere (e.g., multiply by ¼ for the Earth's area, followed by 0.7 for the albedo effect). Using the commenter's methodology (which is flawed) the resulting climate sensitivity parameter would be

0.9*(255/238) = 0.96° K/W/m^2. As to the commenter's calculation of climate sensitivity by diving the greenhouse temperature by the total forcing, as previously shown, the commenter was off by a factor of 4 in his or her calculation of the temperature, and because water and clouds are considered to be part of the feedback when calculating sensitivity, it is inappropriate to include them in the forcing side of the equation. CO_2, CH_4, N_2O, and ozone together account for about 35 to 50 W/m^2 (Kiehl and Trenberth, 1997). Therefore, using the commenter's methodology (which is flawed), 32/42 = 0.76° K/W/m^2. Both 0.96 and 0.76 are close to the IPCC estimates. Therefore, we find that the commenter has provided no convincing evidence to counter the assessments of climate sensitivity studies in the IPCC and subsequent assessment reports.

Comment (3-45):
A number of commenters believe that anthropogenic global warming is impossible, many citing arguments made by Gerlich and Tscheuschner (2009). Several commenters (e.g., 0430) note that the greenhouse effect is not like a real greenhouse. Several claim that it is thermodynamically impossible because heat cannot be transferred from a cool substance to a warmer substance (0430, 2210.5): for example, blankets cannot make you warmer than body temperature (1707, 0183.1,). Another thermodynamic argument for the impossibility of the greenhouse effect was proposed by two commenters (2210.3, 4509) citing Gerlich and Tscheuschner (2009) who states that the greenhouse effect as commonly formulated violates the Second Law of Thermodynamics. Another commenter (0711.1) requests evidence of any peer-reviewed climate change paper that does not rely on computer simulation. Another theory (2887.1) holds that long-wave radiation will cause increased evaporation of the surface ocean, negating any heat increase. One commenter (0535) submitted a non-peer reviewed paper providing a different explanation for the net energy budget of the Earth, with no role for warming by CO_2.

Response (3-45):
The evidence for the atmospheric greenhouse effect is well supported by the scientific literature. The objections raised by a number of commenters to the basic thermodynamics are without grounds. We are well aware that the greenhouse effect is not at all like a real greenhouse. However, the analogy of a blanket is a little bit better: and indeed, sufficiently insulating blankets can cause overheating. GHGs (blankets) will, by reducing the rate of heat loss, raise the surface temperature of the Earth (body) until a new thermodynamic balance is achieved between incoming solar radiation (internal body heating) and outgoing thermal radiation (in the case of a blanket, including convection and non-radiative processes). This process works regardless of whether the atmosphere (blanket) is cooler than the surface (body). We are aware of the paper by Gerlich and Tscheuschner, and we have determined that the conclusions of the paper are inconsistent with the well-supported literature regarding the mechanism of the greenhouse effect. For example, as a disproof of the greenhouse effect, the paper by Gerlich and Tscheuschner presents the example of a pot of water, noting that the bottom of the pot will be cooler if it is filled with water than if it is empty. Contrary to the assertion in the paper, the primary thermal effect of adding water to the pot is not a reduction in heat transfer, but rather an increase of thermal mass. We assert that a more appropriate example for the paper to have examined would have been the addition of a lid to a pot of water, which reduces the rate of heat loss, and leads to an increase of heating of the water compared to a case with no lid. The paper by Gerlich and Tscheuschner is also inconsistent with the scientific literature with regards to the interpretation of radiative balance diagrams and the assertion that there is no "mean temperature" of the Earth, in contrast to the hundreds of peer-reviewed publications and many assessment reports which use both concepts.

Comment (3-46):

Two commenters (0183.1, 1707) submitted links to a non peer-reviewed paper, "Climate Change and Long-Term Fluctuations of Commercial Catches - The Possibility of Forecasting." The commenters claim that this paper shows that temperature is a function of rotational velocity of the Earth (e.g., length of day), and the commenters also claim that CO_2 cannot warm the atmosphere because at 400 parts per million (ppm) it would need to reach hundreds of degrees in order to change the temperature of the whole atmosphere by a fraction of a degree. These commenters also claim that water vapor only serves to increase the heat capacity of the atmosphere, thus making it more difficult to warm. They also claim that radiative energy is not additive (e.g., they claim that 101 W/m^2 + 100 W/m^2 = 101 W/m^2).

Response (3-46):
We disagree with this comment and find that the commenter misunderstands fundamental scientific processes. The rotational velocity of the Earth can have some effect on temperature; for example, at the extreme, a tide-locked planet will be very hot on the sun side and very cold on the dark side. However, there is no evidence that changes in the velocity have or could cause the observed changes of temperature over the last century.

We also disagree with the commenters' analysis of radiative properties of CO_2, which is in contradiction to basic scientific principles. Because CO_2 molecules can transfer absorbed heat to neighboring molecules through collisions, there is no need for them to reach hundreds of degrees Celsius in order to raise the average temperature. A similar argument holds for water vapor in the atmosphere: though water does have a high heat capacity, if the water wasn't in the atmosphere, it would be in the oceans and would still contribute to the thermal mass of the Earth system. Finally, radiation is indeed additive—two equal infrared sources will heat a target more than one source individually.

Comment (3-47):
A commenter (2210.1) proposes several reasons that CO_2 does not absorb IR radiation; 1) because it is saturated during the daytime because of the sun, only a millionth of photons of outbound radiation would be captured; 2) because absorption by gases only causes electron excitation and re-radiation, not heating; and 3) because experiments that show otherwise are contaminated by heating of surfaces and heat transfer through conduction.

Response (3-47):
There is compelling evidence for the absorption of IR radiation in the atmosphere by CO_2 as shown by experiment and theory. Satellites and ground-based instruments can measure atmospheric transmission spectra and detect the influence of different atmospheric components, and these measurements are inconsistent with the assertions by the commenter. Also, see response 3-42 describing the derivation of radiation code in models.

Comment (3-48):
A commenter (2818) states that GHGs cool the atmosphere by 100°C, otherwise the Earth would have the same temperature as the maximum temperature on the moon (121°C). Another commenter (10071.2) claims that "You always hear that GHGs warm the surface by 33° C, but most sources forget to mention that they also cool the atmosphere by more than 100° C. If the atmosphere was just nitrogen, with no greenhouse gases, the temperature of atmosphere would be about 121° C (249° F), well above the boiling point of water. It is the greenhouse gases that cool the atmosphere."

Response (3-48):
The scientific literature is clear that GHGs have a warming effect on the temperature of the Earth. The existence of an atmosphere and oceans explains why the surface of the Earth does not reach the high temperatures reached by the sun-side of the moon; this is not a function of GHGs. The atmosphere and oceans also serve to keep the night-side of the Earth from reaching the –233°C that the moon reaches. The average temperature of the moon is actually less than the average temperature of the Earth. The average temperature of the Earth is 33°C higher than the theoretical blackbody temperature, and the difference is attributed mainly to GHGs. Venus (see response 3-49) is another example demonstrating that GHGs do not cool the surface. Therefore, we disagree with the assertion of the commenter that GHGs are a cooling influence.

Comment (3-49):
A commenter (2210.1) states that Venus is not an example of the greenhouse effect but is merely warmer because it is closer to the sun. Another commenter (2210.5) attributes Venus' warmth to higher atmospheric pressure because compression causes temperature increases (for example, this occurs when inflating a bicycle tire, due to the proportional relationship between pressure and temperature represented in the ideal gas law, pV=nRT, i.e., pressure times volume equals amount of gas times temperature times a constant), and that a 95% CO_2 atmosphere is actually cooler than a 100% biatomic atmosphere would be.

Response (3-49):
Venus is warmer than the Earth both because of the greenhouse effect and because of its distance to the sun; in contrast, Mercury is cooler than Venus despite being even closer to the sun. Were Venus' atmosphere to be transparent to radiation, then the surface temperature of Venus would be determined only by the blackbody radiation of the surface, and the pressure of the atmosphere would not change this equilibrium temperature. There is a large body of literature on Venus' climate; one example is Bullock and Grinspoon (2001)—all of which show that CO_2 is a significant contributor to the planet's warmth. Because volume is not held constant, it is not appropriate to use the ideal gas law to determine the temperature on the surface of Venus based only on knowledge about its pressure. Therefore, the scientific literature shows clearly that the temperature of Venus is an example of a greenhouse effect, in contrast to the assertion by the commenters.

Comment (3-50):
The commenter states the CO_2 does not cause reflection because a boundary between heterogeneous substances is necessary for reflection or refraction, and because any heating of the air would cause it to rise and therefore cool as it expands: therefore, the greenhouse effect can only occur in stationary atmospheres. Also, the commenter argues that gases only radiate at the upper boundary layer of the troposphere: below that, they only transfer energy through conduction and convection.

Response (3-50):
The mechanism of warming by CO_2 is not reflection, but rather absorption of infrared radiation, followed either by radiation or collisional energy transfer mechanisms. The expansion and cooling resulting from the rise of warm gases is reflected in the temperature profile of the atmosphere (e.g., the adiabatic lapse rate). However, in the case of absorbing heat from an external source, even if the particular packet of gas that absorbed the heat rises and cools, there must be a corresponding packet of gas which sinks and warms, leading to warming of the atmosphere regardless. Therefore, the critiques of the commenter are not consistent with scientific understanding.

Comment (3-51):
One commenter (3013) mentions Mars and states that even given the lower atmospheric pressure, his calculation shows that it has twice as much CO_2 as Earth, and further claims that the National Aeronautics and Space Administration (NASA) found that the even with this high CO_2 concentration, the atmosphere of Mars does not retain heat.

Response (3-51):
The commenter did not provide any evidence for his claim that NASA has found that the atmosphere of Mars does not retain heat. Mars does have an atmosphere that is mainly carbon dioxide, but because of the low atmospheric pressure, it is only 16 times the quantity of carbon dioxide on Earth. At the same time, it receives less than 45% as much sunlight, so the increased radiative forcing from the CO_2 is not sufficient to make up for the decrease in solar insolation. Thus, the commenter's claim that the atmosphere of Mars does not retain heat is not consistent with the scientific literature.

3.2.4 CO_2 and Past Global Warming Episodes

Comment (3-52):
A large number of commenters (e.g., 0169, 0373.1, 0401, 0455, 0482.1, 0591, 0639.1, 0661, 0664, 0700.1, 0921, 1017.1, 1309.1, 1312, 1519, 1616.1, 1961, 2666, 2759, 2890.1, 2952.1, 2980, 3013, 3497.1, 3596.1, 3679.1, 3722, 3769.1, 3722R87, 4003, 4206, 4632R48, 5858, 6712, 7025, 10197) argue that atmospheric CO_2 concentrations were not the cause of past periods of global warming and are therefore not the cause of the current period of warming.

Numerous commenters (e.g., 0153, 0169, 0373.2, 0455, 0482.1, 0525, 0534, 0591, 0639.1, 0661, 0664, 1309.1, 1312, 1519, 2666, 2759, 2890.1, 2952.1, 2980, 3013, 3497.1, 3596.1, 3679.1, 3722, 3769.1, 4003, 3722R87, 4632R48, 9799.1, 10197) similarly state that increased CO_2 concentrations lag temperature change and that atmospheric CO_2 concentrations did not drive past periods of climate change but rather were an effect of temperature increases caused by other mechanisms. A document written by Alan Carlin and provided by commenter 4003, for example, stated: "Logic demands that cause must precede effect. Increases in air temperature drive increases in atmospheric CO_2 concentration, and not vice versa."

One commenter (3596.1) stated, "Studies identify periods of time when CO_2 levels were two to four times higher than the current level (Pagani et al., 2005), and these carbon dioxide spikes followed increases in temperature by hundreds or thousands of years. This contradicts EPA's prime assertion that carbon dioxide and the other specified greenhouse gases drive warming."

Response (3-52):
Although the assessment literature (see, for example, Jansen et al., 2007) indicates that the primary initiator of past periods of warming over at least the past 3 million years was orbital forcing, which refers to changes in the seasonal and latitudinal distribution of incoming solar radiation linked to regular variations in the Earth's orbit around the sun. CO_2 and GHGs were an important amplifier of these past periods of global warming. As stated in Jansen et al., "It is *very likely* that glacial-interglacial CO_2 variations have strongly amplified climate variations, but it is *unlikely* that CO_2 variations have triggered the end of glacial periods. Antarctic temperature started to rise several centuries before atmospheric CO_2 during past glacial terminations." Jansen et al. note that the forcing from GHGs during the last glacial maximum was 2.8 W/m^2 lower than the preindustrial era, compared to 3.2 W/m^2 of cooling from reflective ice sheets, and about 1 W/m^2 of cooling from dust, and 1 W/m^2 of cooling from vegetation changes. Therefore, GHGs were a significant contributor to the temperature difference between glacial

maxima and interglacials. The reason why CO_2 can be an initiator in present times when it was only an amplifier previously is that previously CO_2 concentrations changed only in response to climatic changes, but in the current period, CO_2 concentrations are changing due to human emissions. CO_2 serves as both a cause and an effect. Therefore, we disagree that CO_2 and other GHGs cannot be the cause of the current period of warming. Indeed, projected concentrations of GHGs may contribute as much forcing by the end of the century as the total difference in forcing between glacial and interglacial periods from all causes combined.

In order to clarify the relationship between GHGs and temperature over geologic time, we have added a text box to Section 5 of the TSD. It states the following in regard to temperature changes over the past million years in relation to CO_2 concentrations:

> According to the IPCC (Jansen et al., 2007): “The ice core record indicates that GHGs co-varied with Antarctic temperature over glacial-interglacial time scales, suggesting a close link between natural atmospheric GHG concentrations and temperature.” Evidence strongly suggests that the timings of the glacial-interglacial cycles are paced by the variations in the orbit of the earth; however, the large response of the climate system implies a strong amplification of the initial orbital forcing (Jansen et al., 2007). Jansen et al. (2007) conclude: “It is *very likely* that glacial-interglacial CO_2 variations have strongly amplified climate variations, but it *unlikely* that CO_2 variations have triggered the end of glacial periods.” Antarctic temperatures started to rise several centuries before atmospheric CO_2 during past glacial terminations. CO_2 (and other GHG) changes over glacial to interglacial transitions therefore contribute to, but do not initiate, the temperature changes seen.

Regarding the reference to Pagani et al. (2005): The abstract of Pagani et al. (2005) states: “Our results demonstrate that pCO_2 ranged between 1000 to 1500 parts per million by volume in the middle to late Eocene, then decreased in several steps during the Oligocene, and reached modern levels by the latest Oligocene. The fall in pCO_2 likely allowed for a critical expansion of ice sheets on Antarctica...” Therefore, Pagani et al. are effectively stating that historically, high levels of CO_2 lead to sufficient warming to prevent Antarctic ice sheets from forming. This contradicts the implication of the commenter that CO_2 cannot drive warming. Neither the underlying assessment literature nor the TSD’s summary of that literature concludes that carbon dioxide initiated, for example, the glacial-interglacial cycles, but rather that the science clearly shows that CO_2 served as a positive feedback during that period.

Comment (3-53):
A number of commenters (e.g., 0401, 0921, 1017.1, 2750, 4206) argue that the concentration of CO_2 in the atmosphere and the Earth’s temperature are not currently and never have been correlated, and many of these commenters provided graphs in support of that argument. Commenter 0373.2, for example, provided a graph that, according to the commenter, shows that there is “absolutely no correlation between CO_2 concentration in the atmosphere and the Earth’s temperature.”

Commenter 3596.1 argues that “global temperatures and atmospheric CO_2 concentrations have not been associated over geologic time.” The commenter cites a study (Rothman, 2002) that, according to the commenter, shows that for the majority of the last half of a billion years atmospheric CO_2 concentrations have fluctuated between two and four time present value and stated that at this scale there is no correlation between increased CO_2 and increased temperature. The commenter stated that EPA should address the geologic temperature record, which, according to the commenter, seems to suggest that a direct correlation between CO_2 and global temperature may not exist.

Response (3-53):

We firmly disagree that atmospheric CO_2 concentrations and the Earth's temperature do not show correlations. The extensive evidence supporting our conclusion that recent (1950 to present) CO_2 concentrations are causally linked to the observed temperature record is discussed in Section 3.1 of this volume of our Response to Comment document. EPA's responses addressing the correlation between CO_2 and temperature over geologic time are addressed in the response 3-52.

We note that several commenters provided graphs they claimed show that CO_2 and temperature were never correlated in the distant past. The origins of these graphs were generally unclear and no underlying data were provided. This issue has been extensively addressed in the assessment literature, and the commenters have not made a compelling case that atmospheric CO_2 concentrations do not affect the Earth's temperature. The provided reference of Rothman (2002) is not consistent with the reconstructions in the assessment literature that are based on multiple independent proxies. Royer et al. (2004) assessed Rothman's methodology and found that the proxy method used by Rothman did not properly account for interactions of the proxy with terrestrial matter from rivers, seawater temperatures, or oxygen concentrations, all of which contribute to the proxy signal.

Comment (3-54):

Several commenters (e.g., 0339, 3440.1, 7026) note that CO_2 concentrations in the distant past have at times been much higher than at present. Commenter 0639.1, for example, stated: "There have been ice ages when carbon dioxide content has been high in the thousands of part per million." Commenter 0661 stated that the current concentration of CO_2 is "dwarfed by not only peaks, but by long term concentrations as high as 7000 ppm, which did not cause an end to the Earth".

One commenter (0541) notes that CO_2 was high during previous a ice age (the late Ordovician) and that therefore it cannot lead to warming; another commenter (3440.1) said that CO_2 was high during the Cambrian and Triassic when calcite and aragonite corals formed and therefore corals can survive acidification; and another (0639.1) asked if raising CO_2 by 100 ppm caused 1 degree warming, why 5000 ppm concentrations in the past didn't cause 40 degrees of warming and kill everything. Commenter 2914 argued that higher CO_2 levels existed in the past and the Earth has survived dramatic changes in atmospheric composition such as the Precambrian appearance of oxygen, demonstrating that it is unlikely that the world will end.

One commenter (11454.1) provides a quote from Heaven & Earth (Plimer, 2009) on historical CO_2 concentrations: "The current CO_2 content of the atmosphere is the lowest it has been for thousands of millions of years and life (including human life) has thrived at times when CO_2 has been significantly higher." Another commenter (3394.1) objected that the statement that CO_2 concentrations exceed the natural range for the past 650,000 years is not supported by the cited Chapter 2 of Working Group 1.

Response (3-54):

Although GHG concentrations in the distant past have substantially exceeded current levels, the existence of high GHG concentrations in the very distant past does not demonstrate that there are not negative consequences of high concentrations in the present, as addressed in the assessment literature. First, the current atmospheric concentrations of CO_2 and CH_4 very likely exceed by far the natural range of at least the last 650,000 years (Jansen et al., 2009), and at least 800,000 years for CO_2 specifically (Karl et al., 2009) (see responses on historical CO_2 concentrations in Volume 2) meaning that concentrations as high as the present may not have existed during the time in which anatomically modern humans have existed (in contrast to the quote from Plimer, for which no evidence was provided). Second, as a consequence of these elevated concentrations, the combined rate of increase in positive radiative forcing due to CO_2, CH_4, and N_2O is very likely unprecedented in at least the past 16,000 years (Jansen et al., 2007). Third, as discussed in Section 3.1, there exists robust evidence that the current very high atmospheric concentrations of GHGs in the atmosphere are causally linked to recent climate changes.

It is important to note that past climates associated with present-day level GHG concentrations were much warmer than today. According to the IPCC, the Mid-Pliocene (about 3.3 million to 3 million years ago), for example, was characterized by a climate substantially warmer than our own. Global mean temperatures for this time period are estimated by climate models to have been about 2 to 3°C (3.6 to 5.4°F) above pre-industrial levels, "providing an accessible example of a world that is similar in many respects to what models estimate could be the Earth of the late 21st century" (Jansen et al., 2007). Furthermore, a very recent study published in *Science* (Tripati et al., 2009) indicates that CO_2 concentrations have not reached as high as current levels for a sustained period in at least 15 million years. The study found that when the partial pressure of CO_2 was last sustained at levels similar to its current level during the Middle Miocene (approximately 14 million to 20 million years ago) temperatures were 3 to 6˚C warmer and sea level 25 to 40 meters higher than at present.

With respect to the comment that very high levels of atmospheric GHG concentrations did not "cause an end to the Earth," we note that the "end to the Earth" is not an issue for this finding. Rather, this finding is about whether elevated GHG concentrations are reasonably anticipated to endanger public health or welfare.

Finally, for EPA's response to comments on the relationship between coral health and ocean acidification and past CO_2 levels please see Volume 7 of the Response to Comments document.

Comment (3-55):

One commenter (3136.1) contends that "[t]his is not the first time that the climate was this warm in the Holocene." The commenter argues that a study by Kaufman et al. (2004) found that for 2,000 years, from 9,000 to 10,000 years ago, Alaskan temperatures averaged 3˚ F higher, and that there have been three similarly warm periods in Alaska between the years 0 to 300, 850 to 1200, and 1800 to present. The commenter further argued that "Thompson Webb III et al. (1998) found timings similar to MacDonald et al (2000): northwestern and northeastern North America were more than 4˚F warmer than the baseline from 7,000-9,000 and 3,000-5,000 years ago, respectively… The lack of historical perspective in the TSD reduces its credibility as a basis for an endangerment finding."

Response (3-55):

The IPCC (Jansen et al., 2007) assessed both the Kaufman and MacDonald studies referenced by the commenter. On the basis of these and other studies, IPCC found that there is evidence for local multi-centennial periods warmer than the last decades by up to several degrees in the early to mid-Holocene. Although temperatures in some regions were warmer than present during earlier parts of the Holocene, the IPCC additionally noted that these local warm periods were very likely not globally synchronous and that that the tendency for high-latitude summer temperature maxima to occur early in the Holocene (8,000 to 10,000 years ago) points to a direct influence of orbital forcing. Jansen et al. (2007) find: "When forced by 6 ka [kiloannum] orbital parameters, state-of-the-art coupled climate models and EMICs [Earth System Model of Intermediate Complexity] capture reconstructed regional temperature and precipitation changes…whereas simulated global mean temperatures remain essentially unchanged (<4˚C; Masson-Delmotte et al., 2005b), just as expected from the seasonality of the orbital forcing."

In any case, the TSD summarizes the assessment science regarding the significant uncertainties associated with large-scale surface temperature reconstructions. With specific regard to temperatures from earlier parts of the Holocene, we report the following in the TSD (see Box 5.1): "According to the IPCC (Jansen et al., 2007), current data limitations limit the ability to determine if there were multi-decadal periods of global warmth compared to the last half of the 20th century prior to about 1000 years ago."

Comment (3-56):
Commenter (3535) submitted a reference to Soon et al. (2007) on "the secondary role of CO_2 and methane forcing." According to the commenter, Dr. Soon asked that EPA consider several of his papers.

Response (3-56):
The paper by Soon et al. allocates a secondary role to CO_2 and CH_4 in explaining glacial-interglacial responses. That GHG changes lagged the start of temperature change during the glacial-interglacial transitions is fairly non-controversial: as described in response 3-52, changes in GHGs likely amplify changes initiated by snow and ice retreat triggered by orbitally caused changes in patterns of solar insolation. The paper by Soon offers no compelling counterargument to the standard explanation. Soon's conclusion that "there is no quantitative evidence that varying levels of minor GHGs like CO_2 and CH_4 have accounted for even as much as half of the reconstructed glacial-interglacial temperature changes" is not inconsistent with the estimate in the IPCC chapter on paleoclimate, which calculates that CO_2 and CH_4 accounted for a radiative perturbation of 2.8 W/m^2 for the last glacial maximum compared to 5.2 W/m^2 from other sources such as ice sheets, vegetation changes, and aerosols. Soon critiques Figure 6.5 from the IPCC for being misleading by showing CO_2 and CH_4 to be large compared to orbitally moderated global radiative influences, but the text of the chapter is clear that the key orbital moderation is of seasonal hemispheric insolation not global insolation. Therefore, the paper by Soon does not change any conclusions summarized in the TSD.

Comment (3-57):
A commenter (11454.1) provided a quote from Heaven & Earth (Plimer, 2009) that Little Ice Age ended in 1850, so temperature rise after that point is to be expected, and "the post-1850 temperature rise cannot be related to post-1850 industrialization and must be related to natural processes." Other commenters (e.g., 2890, 3432.1, 3446.1) made similar comments that the recent warming can be explained as being a recovery from the little ice age. One commenter (3722) provided an analysis by Dr. Akasofu that explained recent temperature rise by attributing a constant half-degree rise per century since 1800, and possibly since 1600, to natural causes. Dr. Akasofu stated that the linear nature of the rise indicates natural variability.

Response (3-57):
We disagree with the commenters that warming in the past 50 years can be explained as a recovery from the little ice age. The IPCC addresses various reconstructions of temperature change in the last several centuries in Jansen et al. (2007). A pertinent chart is presented on page 477, showing various forcing reconstructions over time, and simulated NH (northern hemisphere) temperatures based on those forcings. The clear message is that temperature change is based both natural and anthropogenic factors. From 1850 to 1950, there was a decrease in volcanic activity, an increase in solar radiative forcing, and an increase in forcing due to long-lived gases from anthropogenic activities (presumably mostly land-use change and agriculture during that period). The combination of these three factors contributed to increasing temperature during that era. However, since 1950, as stated in the TSD, "it is very unlikely that the global pattern of warming observed during the past half century is due to only known natural external causes (solar activity and volcanoes) since the warming occurred in both the atmosphere and ocean and took place when natural external forcing factors would likely have produced cooling (Hegerl et al., 2007)." This conclusion is also based on spatial patterns of change, and the concurrent cooling of the stratosphere.

The IPCC includes the caveat that “It is important to note that many of the simulated temperature variations during the pre-industrial period shown in Figure 6.13 have been driven by assumed solar forcing, the magnitude of which is currently in doubt.” However, there exist reasonable explanations, which are consistent with natural forcing contributing significantly to the warming from 1850 to 1950, while there do not exist well-supported explanations that attribute the warming from 1950 to present mainly to natural changes. The concept of “recovery” seen in a number of comments is not pertinent: over long timescales, the Earth’s climate system shifts in response to changes in forcing, whether anthropogenic or natural. What appears to be “recovery” is actually the response to a new shift in these forcings. The time scale of such a response is expected to occur most quickly immediately after the shift in forcing, with diminishing changes over time as the system reaches a new equilibrium. Long-term unforced linear trends in temperature are not an expected feature of natural variability, contrary to the assertion by a commenter.

Thus, there is no well-supported evidence that the recent warming can be explained as a recovery from the little ice age.

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