The large contribution of projected HFC emissions to future climate forcing

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The consumption and emissions of hydrofluorocarbons (HFCs) are projected to increase substantially in the coming decades in response to regulation of ozone depleting gases under the Montreal Protocol. The projected increases result primarily from sustained growth in demand for refrigeration, air-conditioning (AC) and insulating foam products in developing countries assuming no new regulation of HFC consumption or emissions. New HFC scenarios are presented based on current hydrochlorofluorocarbon (HCFC) consumption in leading applications, patterns of replacements of HCFCs by HFCs in developed countries, and gross domestic product (GDP) growth. Global HFC emissions significantly exceed previous estimates after 2025 with developing country emissions as much as 800% greater than in developed countries in 2050. Global HFC emissions in 2050 are equivalent to 9–19% (CO_2-eq. basis) of projected global CO_2 emissions in business-as-usual scenarios and contribute a radiative forcing equivalent to that from 6–13 years of CO_2 emissions near 2050. This percentage increases to 28–45% compared with projected CO_2 emissions in a 450-ppm CO_2 stabilization scenario. In a hypothetical scenario based on a global cap followed by 4% annual reductions in consumption, HFC radiative forcing is shown to peak and begin to decline before 2050.

HCFC consumption | radiative forcing | scenarios

Global production and use of chlorofluorocarbons (CFCs) and halons have decreased significantly as a result of the phaseout schedules of the 1987 Montreal Protocol and its subsequent amendments and adjustments (1). The use of HCFCs and HFCs have increased as replacements for CFCs and halons in developed (non-A5) and developing (A5) countries that are parties to the Protocol (1, 2). HCFCs are low-ozone-depletion-potential substitutes for high-ozone-depleting-potential substances, particularly CFCs and halons, and were classified under the Protocol as "transitional substitutes" during the time it took to commercialize new ozone-safe alternatives and replacements. Ultimately, HCFCs will be phased out globally under the Montreal Protocol leaving much of the application demand for refrigeration, AC, heating and thermal-insulating foam production to be met by HFCs (2). The demand for HCFCs and/or HFCs in many applications is expected to increase in both developed and developing countries, but especially in Asia, in the absence of regulations. HFCs do not deplete the ozone layer but, along with CFCs and HCFCs, are greenhouse gases that contribute to the radiative forcing (RF) of climate (2, 3). Thus, the transition away from ozone depleting substances (ODSs) has implications for future climate.

The technical, economic and environmental trade-offs of replacing CFCs and HCFCs with HFCs and hydrocarbons have been analyzed for refrigerators, chillers, and AC (4–6). Hydrocarbons, ammonia and CO_2, which generally have lower Global Warming Potentials (GWPs) than HFCs, have been found suitable for systems with small refrigerant charges where a refrigerant leak would not pose an unacceptable flammability or toxicity risk and for industrial systems with large refrigerant charges expertly managed for fire and toxicity risk. HFCs are the preferred refrigerant in consumer products requiring a large charge, where hydrocarbon flammability is problematic (6). The use of HFCs is expected to be minor in many other applications because other low-GWP compounds and not-in-kind (i.e., non-halocarbon based) technologies are available. Overall, not-in-kind technologies are not expected to initially satisfy as large a fraction of future demand as was the case during the CFC phaseout (7).

Multiple scenarios of global HFC emissions are available from SRES (8) and IPCC/TEAP (2). These scenarios are now of limited use because of limited range of years (IPCC/TEAP) or outdated assumptions concerning the transition from HCFCs to HFCs (SRES). The SRES GWP-weighted emissions for refrigeration and AC are ≈20% below what we infer here from observed atmospheric mixing ratios for 2007 (*SI Text*). The 2007 HFC emissions for these applications from IPCC/TEAP (2) are somewhat higher, but this scenario ends in 2015. Others (9–11) have reported HFC scenarios similar to the SRES assumptions and do not consider a more detailed market development as discussed here.

We report new baseline scenarios for the consumption and emissions of HFCs to 2050 based only on existing policies. As in the SRES scenarios, the growth in demand for these compounds is based on GDP and population (8, 12). However, the new scenarios incorporate more recent information such as (*i*) rapid observed growth in demand, substantiated by atmospheric observations, for products and equipment using HCFCs and HFCs in developing countries (see *SI Text*); (*ii*) reported increases in consumption of HCFCs in developing countries; (*iii*) replacement patterns of HCFCs by HFCs as reported in developed countries; (*iv*) accelerated phaseout schedules of HCFCs in developed and developing countries, and; (*v*) increases in reported use of HFC-134a in mobile AC in developed and developing countries. The analysis results in significantly larger emissions in 2050 than could be expected based on previous projections.

Montreal Protocol regulation of HCFCs and other ODSs already has protected both ozone and climate (13, 14). HFCs are in the "basket of gases" regulated under the 1997 Kyoto Protocol (15), a global treaty to reduce developed-country emissions of greenhouse gases. We use the new emission scenarios and GWPs of HFCs to calculate their CO_2-equivalent emissions and RF contributions to global climate forcing. The results are compared with "business-as-usual" SRES CO_2 emissions and those required to stabilize CO_2 concentrations at 450 and 550 parts per

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Table 1. Replacement pattern of HCFC consumption by HFC consumption adopted for developing countries

Compound	Consumption	R-404A	R-410A	HFC-134a	HFC-245fa	Not-in-kind
HCFC-22	66.5%	35%	55%			10%
HCFC-141b	30.0%				50%	50%
HCFC-142b	3.5%			50%		50%
Total HFC consumption		23%	37%	2%	15%	23%

The replacement pattern is the same as found for developed countries based on a DuPont analysis*. Consumption values represent developed country usage. R-404A is a blend of HFC-143a (52%), HFC-125 (44%), and HFC-134a (4%). R-410A is a blend of HFC-32 (50%) and HFC-125 (50%). HFC-245fa is as surrogate for both it and HFC-365mfc, an alternative compound, for insulating foam production. Not-in-kind refers here to nonfluorocarbon applications or alternative technologies.

million (ppm) (16, 17). We also consider a range of hypothetical mitigation options, some of which reflect current policy proposals, to demonstrate how projected consumption and, hence, RF in 2050 could be reduced. Finally, the need to consider the potential for changes in overall energy efficiency in HFC and HCFC applications is discussed.

New HFC Baseline Scenarios

The growth rates for population and GDP in developed and developing countries for the new HFC baseline scenarios were adopted from the 4 SRES storylines (A1, A2, B1, and B2). The scenarios include HFC-134a, HFC-152a, HFC-245fa, and HFC-365mfc and the blends R-404A and R-410A (see Table 1, Table S1, and *SI Text*).* The use and emissions of other HFCs (e.g., HFC-227ea, HFC-236fa, and HFC-43–10mee) are currently small and are not included in the scenarios. Emissions and atmospheric mixing ratios of HFCs are calculated for the baseline scenarios based on the principles that for each HFC (*i*) annual global demand, production, and consumption are equal, (*ii*) annual consumption is added to individual compound banks for each applications, (*iii*) constant emission factors prescribe the fractions annually released from the respective banks, and (*iv*) demand is not constrained by new regulations. The release rates from banks, which depend on the application, cause time delays of years to decades between consumption and emissions (see *SI Text*).

The new baseline scenarios use HCFC consumption data (1) from 1989 to 2007 as the starting point for the demand for HCFCs in developing countries. Consumption in developing countries increased from 1989 to 2007 by ≈20% per year, only in part due to CFC consumption decreases over this period (Fig. 1*A*). The total consumption of CFCs + HCFCs (in kilotons per year) in developing countries increased by ≈8% per year from 1998 to 2007, larger than the mean annual increase in GDP from 1990 to 2010 of 4–6% per year in Asia, Africa and Latin America in the SRES scenarios. These increases in consumption are confirmed by long-term growth and recent acceleration of growth in observed atmospheric mixing ratios of HCFCs (18, 19). Recent changes in northern-latitude observations are consistent with less developed country use and more developing country use of HCFCs (18). In the new scenarios, HCFC consumption in developing countries from 2003 to 2007 is extrapolated linearly through 2012, after which the Montreal Protocol sets limits on HCFC consumption.

The demand for HCFCs in developing countries is assumed to grow by 3.8–6.3% per year, proportional to SRES GDP, from 2013 to 2050 (8, 12). The difference between the HCFC demand and the Montreal Protocol limits is satisfied in the scenarios with HFCs and not-in-kind replacements (Fig. 1) according to the replacement pattern found in developed countries (Table 1). HCFC consumption is divided among HCFC-22 (66.5%), HCFC-141b (30%), HCFC-142b (3.5%), based on the average distribution found by UNEP in developing countries between 2002 and 2006 (20). The resulting HFC consumption is limited, per application, to the per capita consumption of HFCs projected for the USA in 2020, the year in which the developed-country HCFC phaseout is virtually complete. Increases in the fraction of not-in-kind replacements for HCFC applications beyond the value in Table 1 (23%) would reduce projected HFC emissions.

The new baseline scenarios include the accelerated HCFC phaseout agreed to by the Montreal Protocol Parties in September 2007 (21). Under the agreement, HCFC consumption in developing countries will be frozen in 2013 at the average production levels in 2009–2010. More importantly, the Parties agreed to cut production and consumption in developing countries by 10% in 2015, 35% by 2020 and 67.5% by 2025 with the phaseout virtually complete in 2030. Before the 2007 agreement, developing countries could maintain 2015 consumption levels until 2040. The HCFC cumulative emissions reduction attributable to the accelerated phaseout is estimated to be 12–15 $GtCO_2$-eq (22).

Developed countries have agreed to reduce HCFC consumption by 75% in 2010 and 90% in 2015 with the phaseout virtually complete in 2020. The HCFC phaseout is already mostly completed in Europe and Japan and well on its way in the USA. The consumption of HFCs in developed countries in the baseline scenarios (Fig. 1) starts with the reported HFC sales in the European Union (EU) (23) and in Japan (see *SI Text*) in 2007 and projected demand for HFCs in the USA for 2007 to 2020 (24). The HFC demand in Europe is increased annually by 2% per year and in Japan by 2.7% per year from 2008 to 2020 to account for the final conversion of HCFCs to HFCs and population growth (see *SI Text*). Annual HFC demand increases in the USA by an average of 7.4% per year from 2008 to 2020 (24). From 2020 to 2050 the consumption grows proportional to the population following SRES (growth range of 0.1–0.4% per year). The annual total consumption in developed countries is defined as the sum in the USA, Europe, and Japan increased by 17% to account for the HFC demand in other developed countries.

Projections for HFC-134a are calculated separately from the other HFCs. The baseline scenarios take into account rapidly growing consumption of HFC-134a for mobile AC. Globally >80% of 4-wheel passenger cars and commercial vehicles are equipped with AC systems that use HFC-134a (2, 25). In developed countries ≈50% of the annual consumption of HFC-134a is for the manufacture and service of mobile AC. The baseline scenario takes into account that in Europe the use of HFC-134a for mobile AC in new cars will be phased out between 2011 and 2017 (26). HFC-134a must be replaced by refrigerants with a GWP (100-year) <150. The consumption of HFC-134a for mobile AC in developing countries is estimated based on of the number of vehicles in 2006, the average lifetime of the vehicles (15 years), the emission of HFC-134a per vehicle over its lifetime (1,400 g), and a conservative 80% market penetration of mobile AC systems in new vehicles (25). The consumption of HFC-134a

*McFarland M (2008) Potential climate benefits of a global cap and reduction agreement for HFCs. Presentation at 20th meeting of the Parties to the Montreal Protocol, Doha, Qatar.

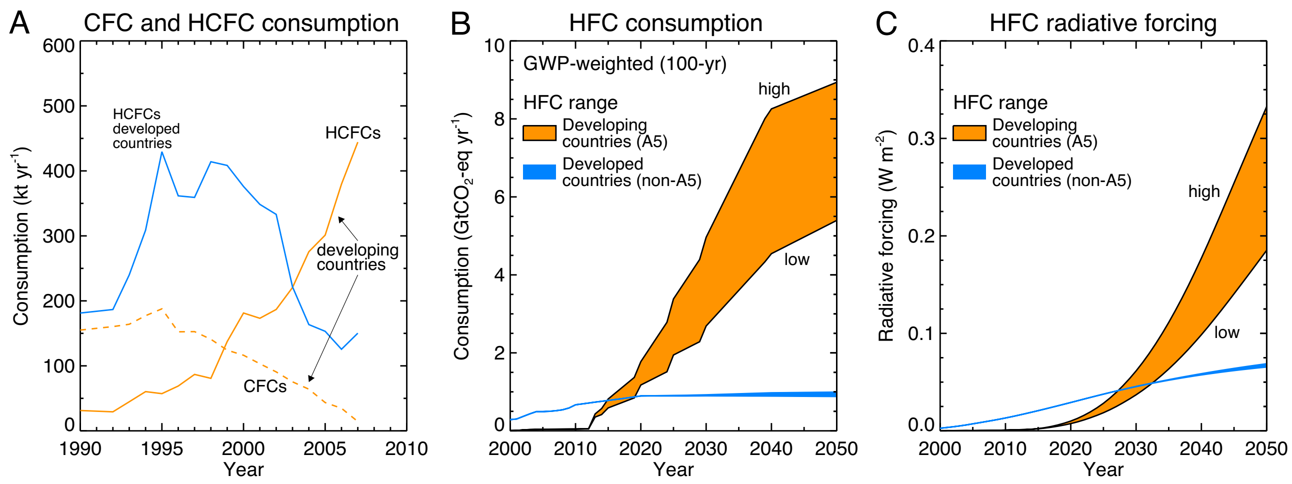

Fig. 1. CFC and HCFC consumption (*A*), HFC consumption (*B*), and HFC RF (*C*) for 2000–2050 in developing (A5) and developed (non-A5) countries. The CFC and HCFC mass consumption values in *A* are derived from reported data (1). The shaded regions for GWP-weighted consumption in *B* and RF in *C* are bounded by high and low limits as defined by the upper and lower ranges of the baseline scenarios in both developed and developing countries. The consumption values expressed in equivalent $GtCO_2$ per year in *B* are sums over the consumption of individual HFC compounds each multiplied by their respective GWP (100-year time horizon) (3).

for this application grows in the scenarios with the same rate as for other applications.

The baseline scenarios do not include HFC-23 because its use as a substitute for ODSs is negligible. Estimated future demand for HFC-23, which is an unintentional byproduct in the production of HCFC-22, is small compared with other leading HFCs, especially past 2015 (2, 27). Nevertheless, continued emissions of HFC-23 have significant potential to contribute to climate forcing because of its large GWP [14,800 (100-year)].

GWP-Weighted Consumption and Emissions

The new HFC baseline scenarios are shown in Figs. 1 and 2 as consumption, emissions, and RF values between 2000 and 2050. Consumption and emissions are scaled to CO_2-equivalent values, using 100-year GWPs (3) (Table S2). The high and low limits of the HFC ranges shown in the figures follow from the differences in GDP and population growth in the underlying SRES scenarios. The high end of the range for developing countries follows A1 and the low end follows A2, both determined primarily by GDP. For developed countries the range, driven primarily by population, follows A2 on the high end and B2 on the low end. Per-capita HFC demand (i.e., market penetration) is expected to saturate in developed country markets in the next decade and in developing countries *ca.* 2040 at the high end of the scenario range. Total HFC GWP-weighted consumption grows strongly from 2012, primarily in developing countries, reaching 6.4–9.9

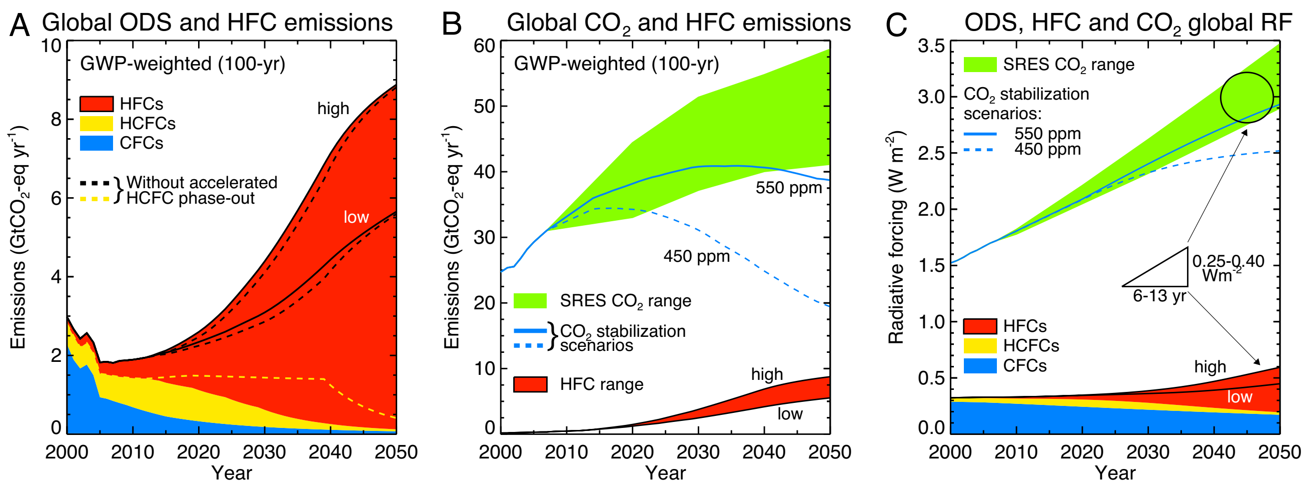

Fig. 2. Global ozone-depleting substances (ODSs) and HFC emissions (*A*), global CO_2 and HFC emissions (*B*), and ODS, HFC, and CO_2 global RF (*C*) for the period 2000–2050. Global emissions are the total from developing and developed countries. The CFC data include all principal ODSs in the Montreal Protocol except HCFCs. The emissions of individual gases are multiplied by their respective GWPs (direct, 100-year time horizon) to obtain aggregate emissions expressed in *A* and *B* as equivalent $GtCO_2$ per year (3). The color-shaded regions show emissions and RFs as indicated in the panel legends. The high and low labels identify the upper and lower limits, respectively, in the global baseline scenarios. The dashed lines in *A* show the HCFC and HFC scenario values calculated without the emission changes caused by the 2007 accelerated HCFC phaseout. Shown for reference in *B* and *C* are emissions and RF for the range of SRES CO_2 scenarios and the 450- and 550-ppm CO_2 stabilization scenarios (16, 17). The CO_2 data from 2000 to 2007 are based on reported emissions and observed concentrations. The triangle in *C* shows the range of HFC RF in 2050 from the baseline scenarios compared with the range in years needed to obtain the same RF change from CO_2 emissions in the SRES scenarios near 2050.

Table 2. Consumption, emissions and RF, and a comparison of RF with CO_2 RF increases for HFC baseline and mitigation scenarios

Scenario	Consumption in 2013–2050 ($GtCO_2$-eq)*	Emissions in 2013–2050 ($GtCO_2$-eq)*	RF in 2050 ($W\ m^{-2}$)	Years of CO_2 RF increase equal to HFC RF change 2050§: IPCC/SRES CO_2 Scenerios	Years of CO_2 RF increase equal to HFC RF change 2050§: IPCC 550-ppm CO_2 stabilization scenario
Totals for baseline scenario range	146–231	110–170	0.25–0.40	6–13	11–18
		Mitigation scenarios			
Reductions from Lieberman-Warner proposal for USA	13–14	10–11	0.024–0.026	0.6–1.0	1.1–1.2
Reductions from global ban mobile AC, EU style regulation†	7–10	6–8	0.017–0.025	0.4–0.8	0.8–1.1
Reduction from global mitigation					
Freeze from 2014/2024‡	69–118	45–77	0.12–0.20	3–7	5–9
Freeze & -2% year^{-1} from 2014/2024‡	91–148	59–97	0.15–0.25	3–9	7–11
Freeze & -4% year^{-1} from 2014/2024‡	106–171	70–113	0.18–0.30	4–10	8–13

*The values are multiplied by their GWPs (100-year time horizon) to obtain equivalent $GtCO_2$ year^{-1}. Range corresponds to high and low limits in the range of baseline scenarios (see text).

†Limits for European cars on the use of HFCs with a GWP >150 in mobile AC is included in the baseline scenario with an estimated reduction in total consumption of 1.7 $GtCO_2$-eq from 2013–2050.

‡Freeze starts in 2014 in developed and in 2024 in developing countries, both at the previous year's level. Reduction of 2%/year and 4%/year are relative to the freeze level.

§Calculated as (years) x (annual growth rate of CO_2 RF in 2050) = (HFC RF of RF reduction in 2050) for each scenario.

$GtCO_2$-eq per year in 2050 (Fig. 1*B*). The consumption in developing countries becomes larger than that in the developed countries before 2020 and exceeds that in developed countries by up to 800% by 2050, a reflection of larger populations and higher GWP growth in these countries. With emissions closely following consumption, but lagging by a few years, total GWP-weighted HFC emissions are 5.5–8.8 $GtCO_2$-eq per year by 2050 (Fig. 2 *A* and *B*). Total direct-GWP-weighted emissions of CFCs + HCFCs decrease between 2000 and 2050, whereas HFC emissions monotonically increase, exceeding those of CFCs + HCFCs after *ca.* 2020 (Fig. 2*A*). Global HFC consumption (mass basis) in 2050 in the baseline scenario is 2.3–3.5 times the 1989 peak value of global CFC + HCFC consumption.

The total GWP-weighted HFC emissions for the new baseline scenarios are significantly larger than those of SRES by 2020 (Fig. S1*a*). In 2050, the comparable SRES emissions are in the range of 1.3–2.3 $GtCO_2$-eq per year (13, 27), a factor of 4 lower. Lower SRES values are expected based on historical events and current market information as noted in the Introduction. More specifically, the greater emissions in the new baseline scenarios are largely the result of higher starting points (2008) for HFC consumption in combination with the use of HFCs with higher GWPs (*SI Text*). The new scenarios assume consumption of the refrigerant blends R-410A and R-404A in some applications instead of HFC-134a in most applications as was assumed in SRES. HFC-125 and HFC-143a are the primary components of R-410A and R-404A. These blends have higher GWPs than HFC-134a (see *SI Text*), thereby increasing the weighted emissions. The larger use of R-410A and R-404A in developing countries is assumed to follow the pattern in developed countries (6) as supported by emissions of the component HFCs derived from atmospheric concentrations observed through 2007. The GWP-weighted emissions in 2007 of HFC-125 and HFC-143a derived from atmospheric measurements are $\approx$0.068 and 0.064 $GtCO_2$-eq per year, respectively; these values are 2–3 times larger than SRES values of 0.028 and 0.027 $GtCO_2$-eq per year, respectively (see *SI Text*). These higher values raise the starting point for the 2050 projections above SRES values and, hence, all future values. The GWP-weighted emissions of HFC-134a derived from observed atmospheric concentrations are $\approx$0.18 $GtCO_2$-eq per year, slightly lower than the 0.20 $GtCO_2$-eq per year in SRES.

In adopting the accelerated phaseout of HCFCs in 2007, the Montreal Protocol Parties agreed to promote the use of HCFC alternatives that minimized the impact on climate (21). The significant influence of the acceleration on HCFC emissions in the next few decades is shown in Fig. 2*A*. In contrast, the influence of the accelerated phaseout on the projected emissions of CFCs + HCFCs + HFCs is small, with direct-GWP-weighted increases between 2020 and 2050 bounded by 0.4 $GtCO_2$-eq per year for both the high and low range limits. The small overall impact results because the accelerated HCFC phaseout, whereas it increases the replacement rate of HCFCs with HFCs, does not mandate the use of replacement compounds with overall lower GWPs. The replacement pattern in Table 1 causes the average GWP of HFCs consumed after the phaseout to be larger than the average of the replaced HCFCs (Table S2).

The new scenario results are put into context by comparing to projected global CO_2 emissions. In 2050 in the 4 SRES scenarios (i.e., no adoption of a CO_2 stabilization target), CO_2 concentrations will be >500 ppm and rising, and emissions will be 40–60 $GtCO_2$ per year (27). Projected HFC emissions are 9–19% of these CO_2 values. Instead, if the scenarios are chosen to be those of long-term CO_2 stabilization at atmospheric mixing ratios of 450 and 550 ppm (16, 17), the projected HFC emissions in 2050 are 28–45% and 14–23%, respectively, of CO_2 emissions (Fig. 2*B*). These percentages would increase beyond 2050, without HFC regulation or even with constant HFC emissions, because CO_2 emissions continue to decrease monotonically in these stabilization scenarios.

These climate-forcing comparisons, using GWPs with a 100-year time horizon yield an HFC consumption of 6.4–9.9 $GtCO_2$-eq per year in 2050 (Fig. 1*B*). If, instead, a 20-year time horizon is used, the consumption increases to 12.6–20.0 $GtCO_2$-eq per year. With a 500-year time horizon, the consumption decreases to 2.1–3.2 $GtCO_2$-eq per year. The climate forcing significance of a given time series of HFC emissions is highly sensitive to the time-horizon assumed because the HFC lifetimes (Table S2) are short compared with the CO_2 lifetime ($\approx$100–1000s years).

Radiative Forcing

Calculated RFs provide a direct measure of the climate influence of greenhouse-gas accumulation in the atmosphere. RF

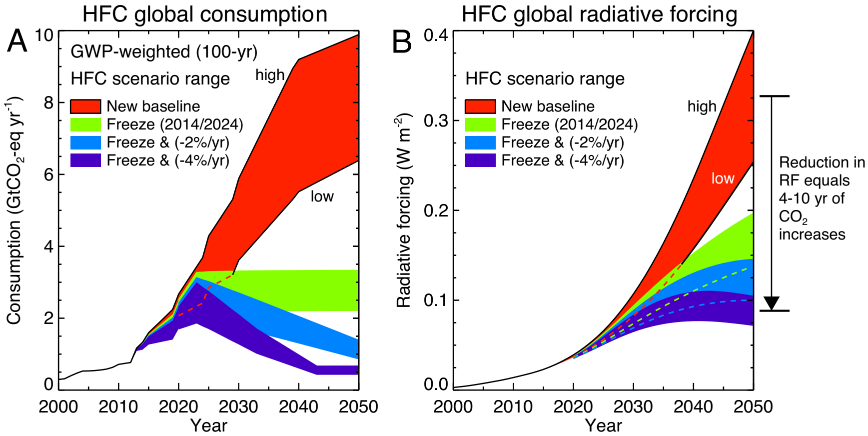

Fig. 3. Global HFC consumption (*A*) and RF (*B*) for the new baseline scenarios and chosen mitigation scenarios for the period 2000–2050. The baseline scenarios (red) represent global HFC values (i.e., the sum of developing and developed country values in Fig. 1). The consumption values in *A* are multiplied by their GWPs (100-year time horizon) to obtain equivalent $GtCO_2$ per year (3). Three mitigation scenarios are shown: a freeze in consumption in 2014 for developed countries and in 2024 for developing countries at the previous year's level (green); and 2% per year (blue) and 4% per year (purple) annual decreases relative to the freeze level. The reduction of consumption in the mitigation scenarios has a maximum of 80%.

values are derived from atmospheric concentrations of contributing gases and their radiative efficiencies and do not depend on their GWPs. The projected RF from global HFCs monotonically increases throughout the baseline scenarios (Fig. 1*C* and Fig. S1*b*). The RF contribution from developing countries surpasses that of developed countries around 2030 (Fig. 1*C*), ≈10 years later than found in the comparison of GWP-weighted emissions (Fig. 1*B*). In 2050, the RF of global HFCs is in the range of 0.25–0.40 W·m^{-2}, which is more than a factor of 3 larger than SRES HFC values (Fig. S1*b*). In a comparison with the SRES CO_2 scenarios in 2050, the HFC RF fraction is 7–12% of the CO_2 values. The HFC RF in 2050 is equal to 6–13 years of RF growth from CO_2 in the 2050 time frame (Table 2). In the comparison with the 450- and 550-ppm CO_2 stabilization scenarios the HFC fraction increases to 10–16% and 9–14%, respectively (Fig. 2*C*).

HFC Mitigation Scenarios

The potentially large contribution of HFC emissions to future climate forcing in the coming decades has attracted the attention of policymakers seeking climate protection. A recent regulatory development that influenced the new HFC scenarios is the EU F-gas directive on mobile AC (26) as discussed above. Other regulatory actions that might affect future emissions include: USA cap-and-reduction proposals on HFCs, the intention of the European Commission to reduce HFC emissions through a climate treaty (28), and proposals of individual states in the USA. In addition, the Montreal Protocol Parties have expressed concern over the potential future climate contribution of HFCs (29).

Five modifications to the new baseline scenarios illustrate the impact of potential future regulatory actions. The first is the cap and reduction of HFC consumption in the USA proposed in the Lieberman–Warner (LW) Climate Security Act (30). In LW, HFC CO_2-eq consumption in the USA is reduced in steps between 2012 and 2040 to achieve a 70% reduction relative to a predefined 2012 level. The second is a global phaseout between 2011 and 2017 of mobile-AC refrigerants with a 100-year GWP >150, as is in place in the EU. The third is a freeze in HFC consumption in developed countries in 2014 and in developing countries in 2024, each at the previous year's level. Adopting a later freeze date for developing countries follows the practice of the Montreal Protocol. The fourth and fifth scenarios start with the 2014/2024 freeze followed by annual decreases in consumption of 2% per year and 4% per year, respectively, with a maximum reduction of 80%. The GWP-weighted emissions and RF results for these scenarios are shown in Fig. 3 and Table 2.

The LW scenario reduces cumulative GWP-weighted HFC consumption by 13–14 $GtCO_2$-eq over the 2013–2050 period and yields a small reduction in RF of ≈0.025 W·m^{-2} in 2050. The global ban on high-GWP HFCs in mobile AC reduces consumption by 7–10 $GtCO_2$-eq over the 2013–2050 period and RF by 0.017–0.025 W·m^{-2} in 2050. The ranges result from the variation in GDP and population growth in the baseline scenarios. Both of these mitigation scenarios yield an RF reduction that is equal to ≈0.4–1 year of CO_2 RF growth in the 2050 time frame. The global-freeze scenario yields reductions in cumulative consumption of 69–118 $GtCO_2$-eq over the 2013–2050 period and in RF of 0.12–0.20 W·m^{-2} in 2050. The freeze followed by 4% per year annual decreases in consumption yields reductions of 106–171 $GtCO_2$-eq over the 2013–2050 period and 0.18–0.30 W·m^{-2} by 2050. The latter reduction corresponds to 4–10 years of CO_2 RF growth in the 2050 time frame using the SRES scenarios or 8–13 years of CO_2 RF growth, using the 550-ppm CO_2 stabilization scenario. With the 4% per year annual decreases, HFC RF reaches a peak *ca.* 2040 and is decreasing before 2050 (Fig. 3*C*). Thus, in the scenarios considered here, a global freeze followed by modest annual reductions in both developed and developing countries is more effective in limiting the RF contribution from HFCs than is a single regional cap and reduction of HFCs.

The example mitigation scenarios presented here limit consumption of HFCs, not emissions. Mitigation options limiting consumption, as used in the Montreal Protocol, and those limiting emissions (containment), as in the Kyoto Protocol, have different implications. These different policy strategies for HFCs in refrigeration and AC have been explored for Germany (31). The comparison showed that containment strategies are generally more effective in reducing emissions in the short term, whereas strategies based on consumption limits (as in a phaseout or phasedown) have the potential for greater reductions in the long term. With limits on emissions, the banks of HFCs generally increase implying increased importance of bank management, recovery, and destruction. Limits on consumption are expected to stimulate containment in the short term and development and deployment of new technologies in the longer term. Furthermore, limits on consumption are easier to enforce with only a few producers worldwide compared with limits on emissions with hundreds of millions of pieces of equipment and, hence, sources of emissions.

Importance of Energy Efficiency

In the analysis of the new scenarios, only the direct contribution to climate forcing due to HFC emissions was considered. Indirect climate forcings associated with HFC or other halocarbon usage derive from the energy used or saved during the application or product lifetime and energy used to manufacture the product, including the HFC it uses. For example, insulating foam products in buildings and appliances reduce energy consumption and refrigeration, and AC systems consume energy over their lifetimes. Analyses of the total potential climate impact of specific refrigeration and AC systems, for example, can be estimated by life cycle climate performance models that account for all direct and indirect contributions (2, 25, 32). Thus, an evaluation of the total climate forcing resulting from the global transition from HCFCs to HFCs and possible HFC mitigation scenarios requires consideration of both direct and indirect impacts over all associated halocarbon and not-in-kind application lifecycles.

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Supporting Information

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Estimated Consumption and Emissions of HFCs in Refrigeration and Air-Conditioning. Future HFC consumption and emissions depend on the rate of growth in demand for products made with and containing HFCs, the service frequency and practices, the useful life of the product and whether HFCs are recovered and reused or destroyed. A range of consumption (demand) growth rates of 3.8–6.3% per year for developing countries (1, 2) are used in the new scenarios developed here. The resulting HFC consumption is limited, per application, to the per capita consumption of HFCs projected for the USA in 2020, the year in which the HCFC phaseout is virtually complete.

Demand for refrigeration and air conditioning products made with and containing HFCs is a function of (*i*) climate factors such as seasonal temperature and humidity, (*ii*) macroeconomic parameters such as population, rate of urbanization, number of households, persons per residence, GDP/capita, income distribution, electrification and other infrastructure, and (*iii*) microeconomic parameters such as product and energy price. Middle and higher income households are generally saturated with products implying a demand only for service and replacement. However, demand by first-time rural or newly urbanized buyers is limited only by the access to electricity and the number of consumers entering income levels sufficient to afford the purchase and operating costs. For example, growth in the middle class segment in India between 1998 and 2002 resulted in appliance growth of 11% per year whereas economic GDP growth was only ≈6% per year (3). In China, 70% of refrigerators are sold in rural areas and 55% of all home appliances sold in China are refrigerators (4). Between 1980 and 2000, urban ownership of refrigerators in China increased from near zero to 80% in urban areas and to 12% in rural areas. Between 1992 and 2004 urban ownership of room air-conditioners in China increased from near zero to 30% (5). Chinese rural refrigerator and air conditioner markets of 1 billion people are 10–15 years behind urban markets in saturation (6).

When personal income increases above poverty levels, refrigeration and AC are among the first products purchased, and when income falls, refrigeration and AC are among the last comforts abandoned. When people earn enough income to buy an automobile, AC is rapidly becoming a standard feature. Automobile AC is popular because it is inexpensive in mass production, it is an option that helps maintain the car value at resale, and it offers comfort on the hottest days. Climate change itself may affect the demand for refrigeration and AC, but it is not considered here.

Growth in appliance demand does not always stop at market saturation. For example, the AC market penetration in Japan is 200% (i.e., 2 units per household) (7). With AC very rare in rural China and with only ≈30% market penetration in urban China, the potential for substantial growth exists.

The underlying assumptions used here lead to HFC scenarios consistent with estimates by other authors, including market research firms, and are confirmed by atmospheric measurements of HFCs over the past 2 decades. For example, Reister (8) and Taddiqi (9) estimate appliance and electric demand from economic growth, and McNeil and Letschart (3), Pachauri (10) and Tatiétsé et al. (11) present forecast appliance demand based on household income. Sinton and Fridley (12) describe comprehensive modeling that integrates appliance sales forecasts, energy efficiency improvements, and energy consumption trends.

Details of the Individual HFCs Included in the Baseline Scenarios. Emissions and atmospheric mixing ratios of HFCs are calculated for the baseline scenarios based on the principles that for each HFC (*i*) annual demand, production, and consumption are equal (unless restricted by regulation), (*ii*) annual consumption is added to individual compound banks (i.e., the amounts present in applications), and (*iii*) constant emission factors prescribe the fractions annually released from the respective banks (13). The release rates from banks, which depend on the application, are consistent with time delays of several years to a few decades between consumption and emissions. Although fixed in our analysis, emission factors could change over time, thereby affecting future concentrations. Where available, observed mixing ratios of HFCs are used to initialize the calculations.

The emission factors depend on the HFC application, not the specific HFC compound, and are assumed to be similar to those of the HCFCs in the same application (12). Thus, the factors are based on a comparison between derived emissions of HCFCs and reported production (13). Most compounds have a dominant application (e.g., HFC-32, HFC-125, and HFC-143a for refrigeration and AC, HFC-134a for mobile AC, HFC-245fa for insulating foams) so a single emission factor is used for each compound.

R-404A is an HFC blend (52% HFC-143a, 44% HFC-125, and 4% HFC-134a by weight) used mainly for commercial refrigeration. It replaces R-502 (a blend containing CFC-115 and HCFC-22) and HCFC-22.

R-410A is an HFC blend (50% HFC-32 and 50% HFC-125 by weight) for use in AC systems, heat pumps, and for some commercial and industrial refrigeration replacing HCFC-22.

HFC-32 (CH_2F_2) is used mainly in blends of HFCs for AC and refrigeration (e.g., R-410A, R-407). The consumption from 1994 to 2007 is derived from the consumption of HFC-125, based on relative percentage use in blends. The applied bank emission factor is 0.13 (as derived for HCFC-22 (13)). The consumption from 2008 to 2050 follows the demand for R-410A in developed and developing countries. There are no reported atmospheric observations of mixing ratios of HFC-32. Our baseline scenario results in mixing ratios of ≈5 ppt in 2010.

HFC-125 (CHF_2CF_3) is mainly used in blends of HFCs (e.g., R-404A, R-410A) for AC and refrigeration. The consumption from 2001 to 2006 is based on AFEAS (14). Consumption before 2001 is estimated from emissions derived from observed atmospheric mixing ratios from the NOAA/ESRL network (L. Miller, B. Miller, SA Montzka, personal communication). The applied emission factor is 0.13 (as derived for HCFC-22 (13)). Global emissions derived from these observations are ≈19 kt·year^{-1} in 2007. The consumption from 2008 to 2050 is determined by the demand for R-404A and R-410A.

HFC-134a (CH_2FCF_3) is mainly used for refrigeration, mobile AC, some stationary AC and insulating foam production, but also in HFC blends (e.g., R-404A). The consumption from 1990 to 2006 is based on AFEAS (14). An emission factor of 0.15 is derived based on the reported consumption and emissions derived from the observed atmospheric mixing ratios (15, 16) over the period 1998–2007. The same emission factor is also applied in the scenarios from 2008 to 2050. Global emissions derived from these observations are ≈120 kt·year^{-1} in 2007. The consumption from 2008 to 2050 in developing countries follows the demand for R-404A, HFC-142b, and the demand for mobile AC. The consumption from 2008 to 2050 in developed countries grows proportional to population for refrigeration, insulating foam production, and AC.

HFC-143a (CH_3CF_3) is mainly used in blends of HFCs (e.g., R-404A) for AC and refrigeration. The consumption from 1985 to 2005 is estimated using emissions derived from observed atmospheric mixing ratios from the NOAA/ESRL network (L. Miller, B. Miller, SA Montzka, personal communication) and an emission factor of 0.13 (as derived for HCFC-22 (13)). Global emissions derived from these observations are ≈14 kt·year^{-1} for 2007. The consumption from 2008 to 2050 is determined by the demand for R-404A.

HFC-152a (CH_3CHF_2) is mainly used as blowing agent for plastic foam and as an aerosol propellant (17), but also in some HFC blends. No information is available on historical consumption. Consumption from 1990 to 2006 is therefore estimated using emissions derived from observed atmospheric mixing ratios from the AGAGE network (16, 18) and an emission factor of 0.80 (19). Global emissions derived from these mixing ratio observations are ≈52 kt·year^{-1} in 2007. The consumption from 2008 to 2050 follows the demand growth in developed countries. In the absence of any data, no use of HFC-152a in developing countries was assumed for these scenarios. This assumption should not have a significant impact on the new scenarios because of the relatively low GWP of this compound compared with other HFCs.

HFC-245fa ($CHF_2CH_2CF_3$) is mainly used as blowing agent for insulating foam, replacing HCFC-141b, in North America. Historical consumption is estimated using emissions derived from observed atmospheric mixing ratios (20) and an emission factor of 0.05 (as derived for HCFC-141b (13)). Global emissions derived from these observations are ≈5–6 kt·year^{-1} in 2005 (20). The consumption from 2008 to 2050 follows the demand for HCFC-141b.

HFC-365mfc ($CH_3CF_2CH_2CF_3$) is mainly used as a blowing agent for insulating foams in Europe, replacing HCFC-141b. Historical consumption is estimated using emissions derived from observed mixing ratios (16, 21) and an emission factor of 0.05 (as derived for HCFC-141b (13)). European emissions derived from these observations are ≈2–4 kt·year^{-1} in 2007. The consumption from 2008 to 2050 follows the demand growth in developed countries. The consumption of HFC-245fa in developing countries is included in the HFC-365mfc values.

Emissions of individual HFCs corresponding to the upper and lower range of the baseline scenarios are presented by decade from 2000 to 2050 in Table S1. The consumption and emissions of other HFCs (e.g., HFC-227ea, HFC-236fa, HFC-43–10mee) are expected to be very small and are not considered in the new baseline scenarios.

Comparison of New Baseline Scenarios with SRES Scenarios. The new baseline HFC emissions are ≈4 times larger than those of SRES in 2050 (Fig. S1) for 2 principal reasons. First, the starting points (2008) for consumption of individual HFCs in the scenarios are substantially higher than assumed in SRES. Second, consumption of HFC-125 and HFC-143a is larger in the new scenarios than in SRES because SRES assumed this consumption was met mostly by HFC-134a, which has a lower GWP than these HFCs. The current consumption values for HFC-125 and HFC-143a are supported by their emissions as estimated from observed atmospheric mixing ratios. Higher starting points account for ≈2/3 of the increase in GWP-weighted emissions in 2050 and HFC-125 and HFC-143a consumption approximately accounts for the remaining 1/3.

HFC and HCFC Use in Europe and Japan. In 2007, the total HFC and HCFC consumption in the European Union (EU) was ≈89 kt (22) and 21 kt (23), respectively. HCFC consumption must be phased out by 2020. In the scenarios it is assumed that these HCFCs are replaced by HFCs. Therefore, to account for the complete conversion to HFCs, the 2007 HFC consumption is increased annually by 1.6% per year through 2020, plus by an additional 0.4% per year to account for population growth according to the SRES scenario.

In 2007, the total HFC and HCFC consumption in Japan was 34.2 kt and 11.8 kt, respectively (http://www.jfma.org/database/shipment.pdf). The HFC consumption is distributed over the individual compounds using the distribution in the EU in 2007 (22). The 2007 HFC consumption is increased annually by 2.3% per year through 2020 to account for the HCFC phaseout, plus an additional 0.4% per year to account for population growth according to the SRES scenario.

Major Applications, GWPs, Lifetimes and Radiative Efficiencies. The major applications, atmospheric lifetimes, GWPs, and radiative efficiencies of the most relevant HCFCs and HFCs for this study are shown in Table S2. The table also contains the consumption-weighted average values for HCFCs and HFCs. The consumption-weighted average GWP (100-year time horizon) for the HFCs is 2362. This value is derived using the consumption of all compounds in developing countries in the year 2040; this value does not vary by scenario. The average GWP (100-year time horizon) for the combination of HFCs used in the current SRES scenarios is ≈25% lower.

Meaning of "Phaseout" Under the Montreal Protocol. Within the Montreal Protocol, a "phaseout" halts most production and consumption of a compound, but allows, by definition, its continued use as a process agent and feedstock in the production of products and chemicals. The Protocol also allows continued production for specific uses deemed important to society by the Parties under the "Essential Use Exemption." So far, Parties to the Montreal Protocol have authorized Essential Use Exemptions only after the phaseout date and have not yet agreed that there will be such exemptions for HCFCs.

Emissions and RF of HFCs and ODSs with and Without Montreal Protocol Regulations. In Fig. S2 and Fig. S3 the new HFC baseline scenarios are shown for the period 1960–2050 together with scenarios of ozone-depleting substances with and without the Montreal Protocol regulations (24). The global emissions are shown in Fig. S2 and the RF in Fig. S3.

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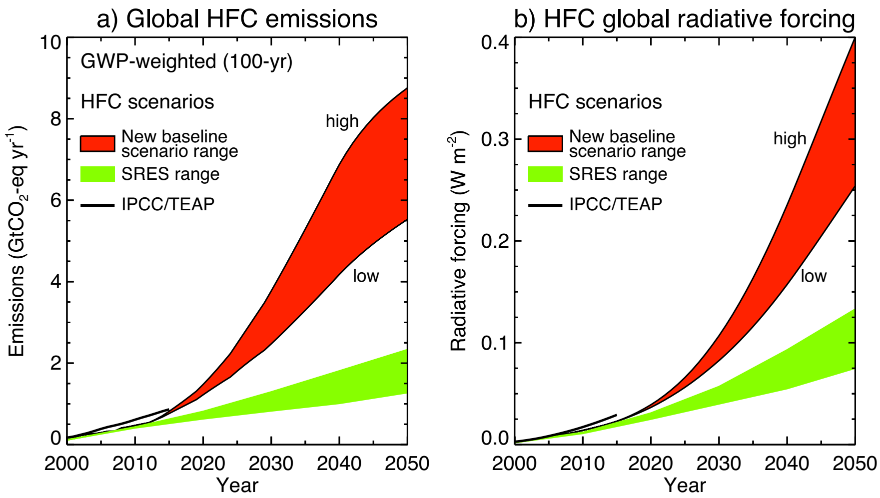

Fig. S1. Global HFC emissions (*a*) and RF (*b*) in the new baseline and SRES (26) scenarios for the period 2000–2050 and in the IPCC-TEAP scenario for 2000–2015 (27). The emission values are multiplied by their GWPs (100-year time horizon) to obtain equivalent $GtCO_2$ per year (25). The color-shaded regions are bounded by the upper and lower limits of the respective scenarios.

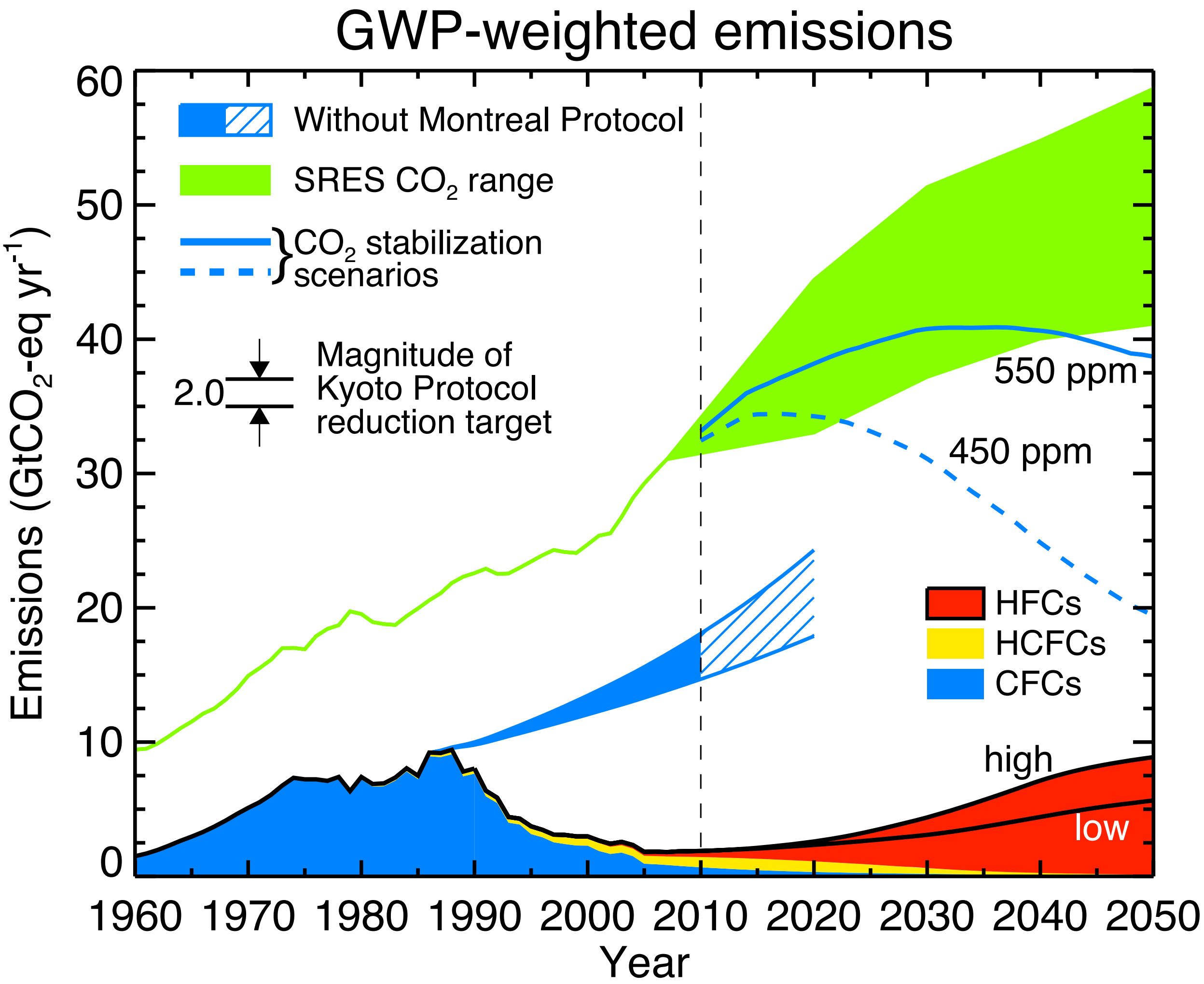

Fig. S2. Global CFC, HCFC, HFC, and CO_2 emissions for the period 1960–2050, and global CFC emissions for 1987–2020 following a scenario in which there is no Montreal Protocol regulation (24). The CFC data include all principal ODSs in the Montreal Protocol except HCFCs. Global emissions are the total from developing and developed countries. The emissions of individual compounds are multiplied by their respective GWPs (direct, 100-year time horizon) to obtain aggregate emissions expressed as equivalent $GtCO_2$ per year (25). The color-shaded regions show ranges of emissions of CFCs, HCFCs, HFCs, and CO_2 as indicated in the panel legends. The high and low labels identify the upper and lower limits in the global baseline scenarios. Shown for reference are emissions for the range of SRES CO_2 scenarios and the 450- and 550-ppm CO_2 stabilization scenarios (28, 29). The CO_2 emissions for 1960–2007 are from global fossil fuel and cement production (30).

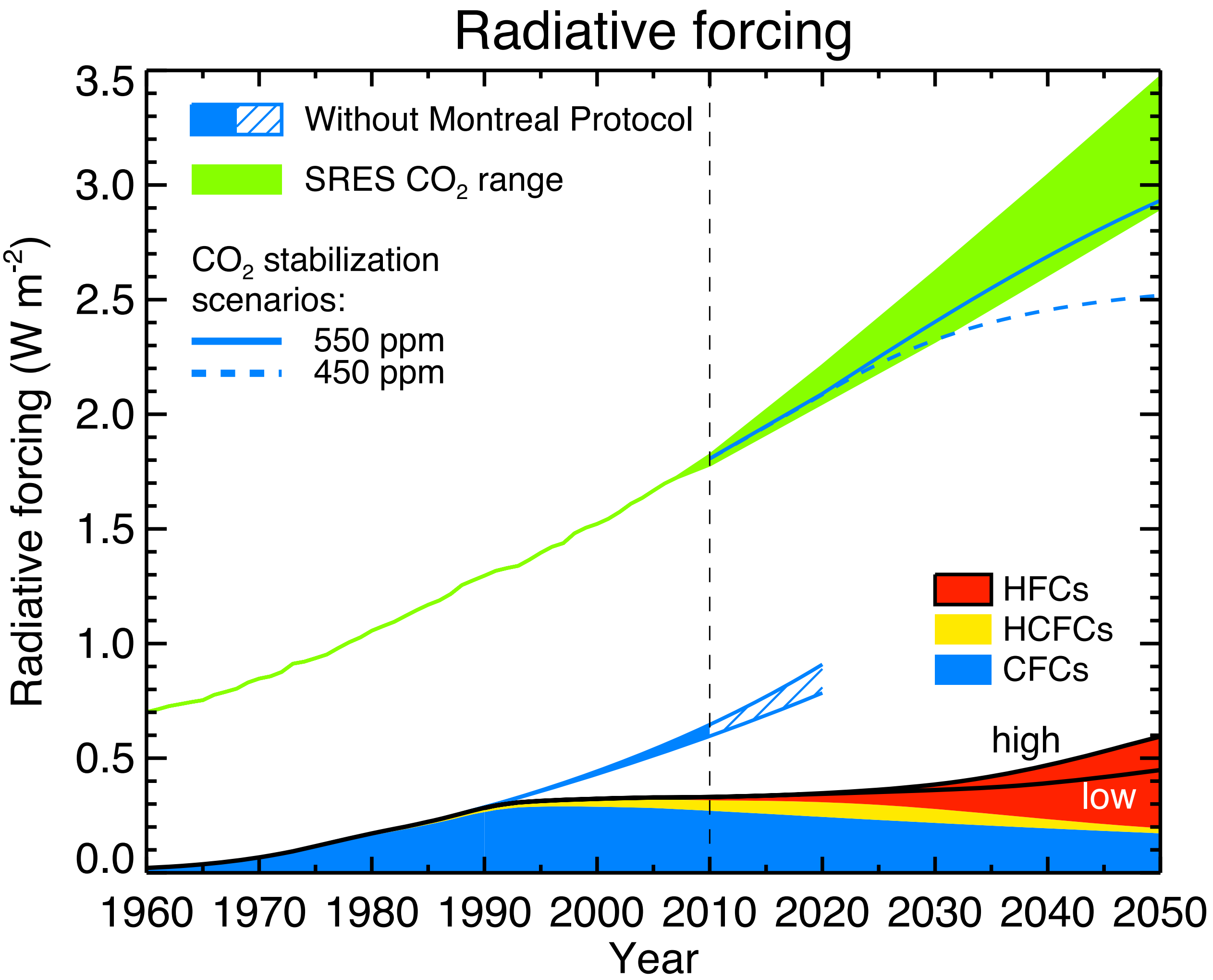

Fig. S3. Global direct radiative forcing (RF) values for CFCs, HCFCs, HFCs, and CO_2 for the period 1960–2050, and global direct RF for CFCs during the period 1987–2020 following a scenario in which there is no Montreal Protocol regulation (24). The CFC data include all principal ODSs in the Montreal Protocol except HCFCs. Global RF is the total from developing and developed countries. The color-shaded regions show ranges of RF of CFCs, HCFCs, HFCs, and CO_2 as indicated in the panel legends. The ''high'' and ''low'' labels identify the upper and lower limits in the global baseline scenarios. Shown for reference are RF for the range of SRES CO_2 scenarios and the 450- and 550-ppm CO_2 stabilization scenarios (28, 29). The CO_2 data from 1960 to 2007 are based on observed concentrations.

Table S1. Total global CFC and HCFC emissions and compound-specific HFC emissions (kt·year^{-1}) in the baseline scenarios

Year	CFCs	HCFCs	HFC-32	HFC-125	HFC-134a	HFC-143a	HFC-152a	(HFC-245fa + HFC-365mfc)*
Baseline scenario: lower range								
1990	927	207	<1	<1	<1	<1	2	0
2000	261	312	4	9	77	6	17	0
2010	80	438	18	34	161	20	59	16
2020	46	497	87	142	225	65	77	49
2030	28	292	209	332	276	146	79	114
2040	18	113	376	593	334	257	82	213
2050	12	48	506	796	379	343	83	313
Baseline scenario: upper range								
1990	927	207	<1	<1	<1	<1	2	0
2000	261	312	4	9	77	6	17	0
2010	80	438	18	34	161	20	59	16
2020	46	497	111	180	239	81	77	59
2030	28	292	337	532	330	231	79	170
2040	18	113	641	1008	438	432	80	346
2050	12	48	804	1261	555	540	81	574

The upper and lower range corresponds the overall range found for the 4 SRES scenarios: A1, A2, B1, B2. For developed countries the 4 scenarios are close together with A2 representing the high end and B2 the low end of the range. A1 yields the high end of the range for developing countries (and for the sum of developed and developing) and A2 yields the low end of the range. Because in the baseline scenarios HFC-152a is used mainly in developed countries, the emissions of HFC-152a are somewhat higher in the lower range than in the upper range.

*HFC-245fa and HFC-365mfc, assumed for insulating foam production, have similar thermodynamic and atmospheric properties. The sum of the emissions of both compounds is shown here.

Table S2. Major applications, lifetimes, direct global warming potentials and radiative efficiencies of the major HCFCs and HFCs

Compound	Main applications	Lifetime, years	GWP, 20-year	GWP, 100-year	GWP, 500-year	Radiative efficiency ($W \cdot m^{-2} \cdot ppb^{-1}$)
HCFC-22	Refrigeration, AC	12	5,160	1,810	549	0.2
HCFC-141b	Insulating foams	9.3	2,250	725	220	0.14
HCFC-142b	Insulating foams	17.9	5,490	2,310	705	0.2
HFC-32	Refrigeration, AC	4.9	2,330	675	205	0.11
HFC-125	Refrigeration, AC	29	6,350	3,500	1,100	0.23
HFC-134a	Refrigeration, AC, Mobile AC, Insulating foams	14	3,830	1,430	435	0.16
HFC-143a	Refrigeration, AC	52	5,890	4,470	1,590	0.13
HFC-152a	Plastic foams, Aerosols	1.4	437	124	38	0.09
HFC-245fa	Insulating foams	7.6	3,380	1,030	314	0.28
HFC-365mfc	Insulating foams	8.6	2,520	794	241	0.21
R-404A*	Refrigeration, AC		6,010	3,922	1,328	
R-410A†	Refrigeration, AC		4,340	2,088	653	
Average values weighted by consumption in developing countries						
HCFCs		11.4	4,299	1,502	456	
HFCs		21.7‡	4,582‡	2,362‡	766‡	

Values taken from IPCC (26).

*R-404A is a blend of HFC-143a (52%), HFC-125 (44%), and HFC-134a (4%).

†R-410A is a blend of HFC-32 (50%) and HFC-125 (50%).

‡Values corresponding to the year 2040.