Supporting Information

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SI Text

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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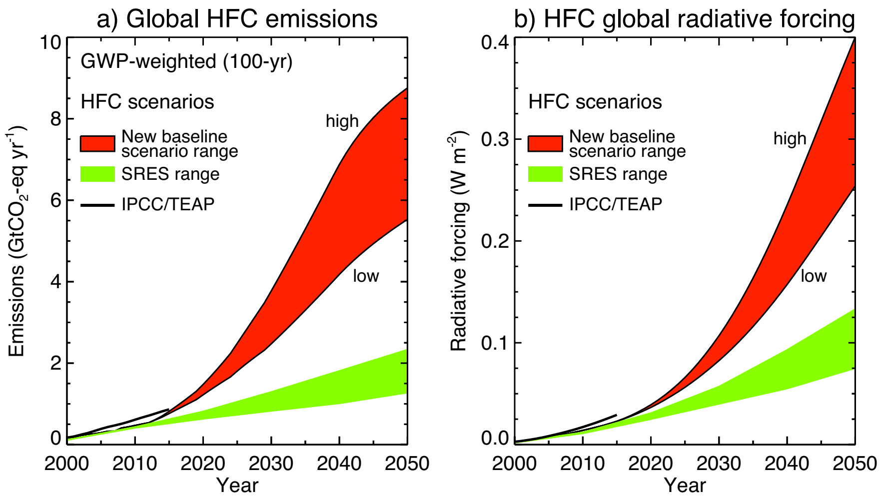

Fig. S1. Global HFC emissions (*a*) and RF (*b*) in the new baseline and SRES (26) scenarios for the period 2000–2050 and in the IPCC-TEAP scenario for 2000–2015 (27). The emission values are multiplied by their GWPs (100-year time horizon) to obtain equivalent $GtCO_2$ per year (25). The color-shaded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

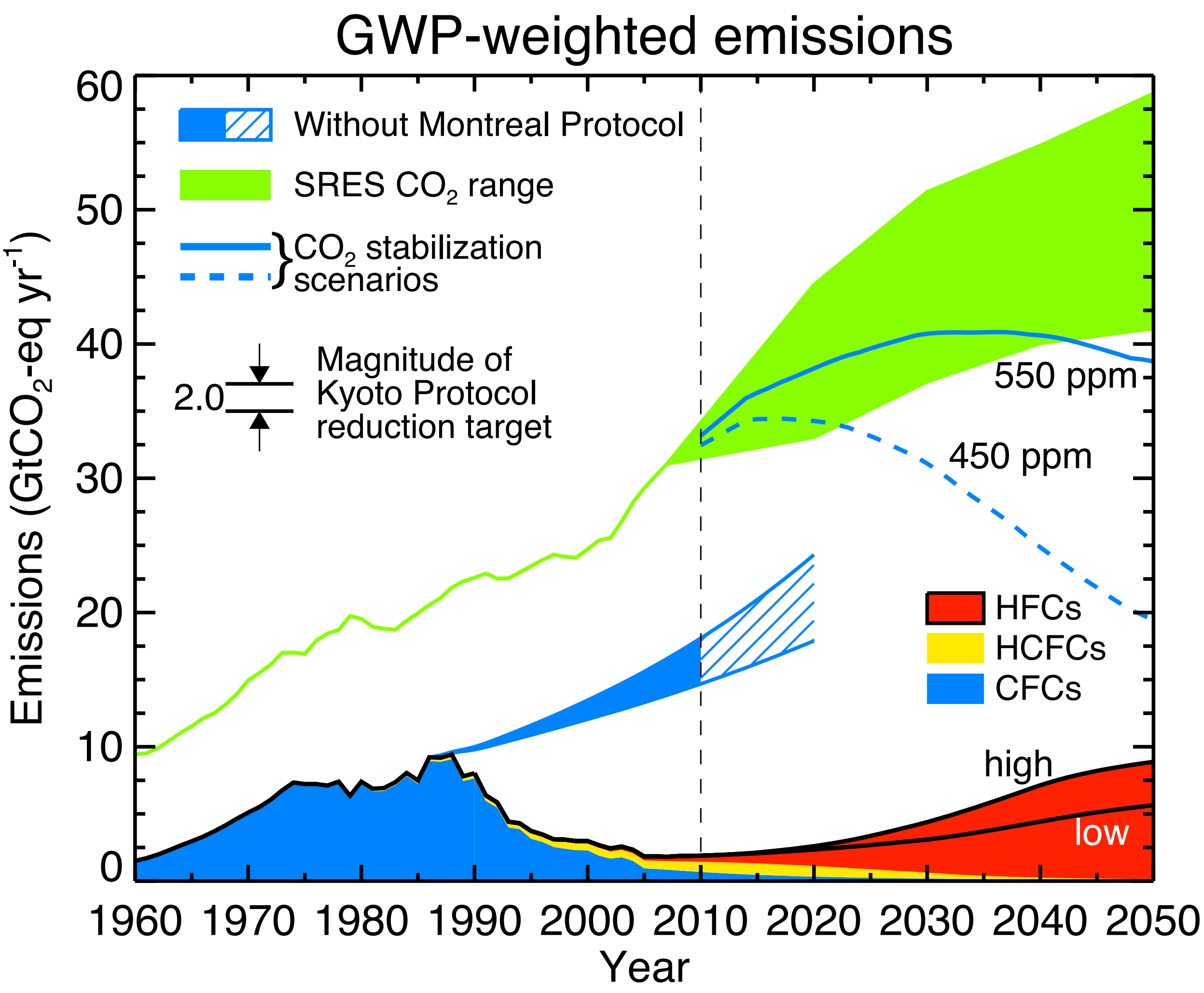

Fig. S2. Global CFC, HCFC, HFC, and CO_2 emissions for the period 1960–2050, and global CFC emissions for 1987–2020 following a scenario in which there is no Montreal Protocol regulation (24). The CFC data include all principal ODSs in the Montreal Protocol except HCFCs. Global emissions are the total 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).

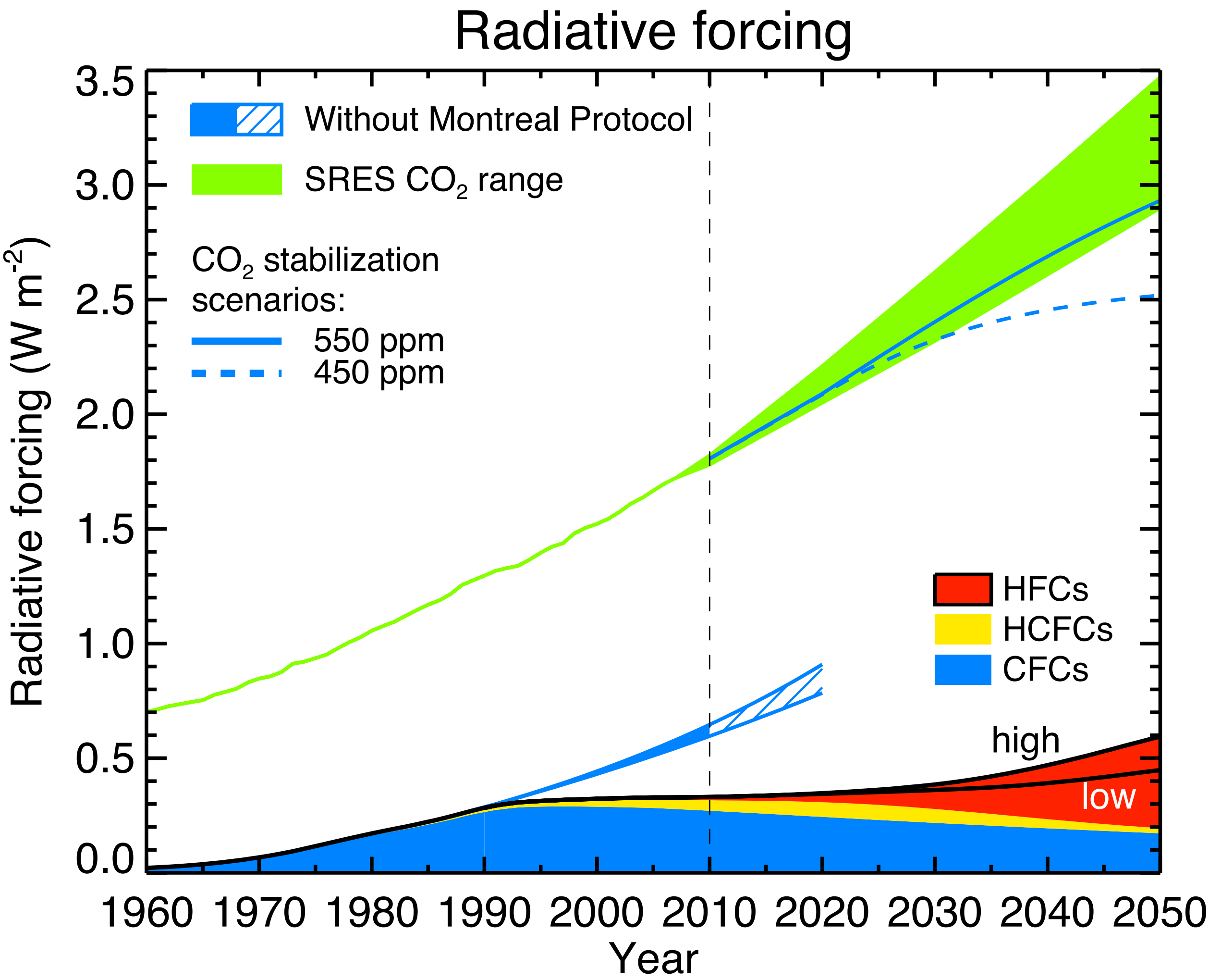

Fig. S3. Global direct radiative forcing (RF) values for CFCs, HCFCs, HFCs, and CO_2 for the period 1960–2050, and global direct RF for CFCs during the period 1987–2020 following a scenario in which there is no Montreal Protocol regulation (24). The CFC data include all principal ODSs in the Montreal 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.