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Growth of climate change commitments from HFC banks and emissions

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Abstract

Chlorofluorocarbons (CFCs) are the primary cause of ozone depletion, and they also contribute to global climate change. With the global phaseout of CFCs and the coming phaseout of hydrochlorofluorocarbons (HCFCs), the substitute hydrofluorocarbons (HFCs) are increasingly used. While CFCs were originally used mainly in applications such as spray cans and were released within a year after production, concern about the ozone layer led to reductions in rapid-release applications, and the relative importance of slower-release applications grew. HFCs are now mainly used in refrigerators and air-conditioners (AC) and are released over years to a decade after production. Their containment in such equipment represents banks, which are building up as production grows. A key finding of our work is that the increases of HFC banks represent a substantial unseen commitment to further radiative forcing of climate change after production of the chemicals ceases. We show that earlier phaseouts of HFCs would provide greater benefits for climate protection than previously recognized, due to the avoided buildup of the banks. If, for example, HFC production were to be phased out in 2020 instead of 2050, not only would about 91–146 $GtCO_2eq$ of cumulative emission be avoided from 2020 to 2050, but an additional bank of about 39–64 $GtCO_2eq$ is also avoided in 2050. Choices of later phaseout dates lead to larger commitments to climate change unless growing banks of HFCs from millions of dispersed locations are collected and destroyed.

1 Introduction

Concern about damage to the Earth's ozone layer prompted the signing of the Montreal Protocol in 1987, an international treaty that has since been hailed as one of the most successful environmental agreements. The halocarbons that were the primary cause of ozone loss are also potent greenhouse gases (Ramanathan, 1975), and reductions in emissions of these gases have benefitted both the ozone layer and efforts to reduce

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anthropogenic climate change (Velders et al., 2007). At the time that the Protocol was developed, chlorofluorocarbons were the primary halocarbons addressed, and most of the emissions of these gases occurred rapidly (within about a year after production) during the process of operation, in applications such as spray cans, metered-dose medical inhalers, open cell foams, and solvents (Fig. 1) (Fisher and Midgley, 1994; Gamlen et al., 1986). By reducing production and consumption of rapidly-released gases in each country, measures taken under the Protocol quickly led to changes in emissions of CFCs, with very little time lag. While CFCs are no longer produced or used anywhere in the world, a small amount of emission of these gases continues (see Fig. 2), due mainly to release from applications where their use involves containment and storage, i.e., a bank of material. The primary banks are in refrigeration and air conditioning (AC) applications, from which gases are released on a time scale of years to about a decade (medium time scale), and in closed cell foams, from which they are released over multiple decades (long time scale, e.g., in building insulation). This represents a legacy, or commitment, of continued environmental impact from past production of CFCs, but its magnitude is relatively small since so much use of CFCs occurred in rapid-release applications.

Substitute processes and chemicals that replace the CFCs have evolved in the decades since the Montreal Protocol entered into force. Many applications now employ approaches that do not require halocarbons at all, referred to as "not-in-kind" substitutions; an example is the widespread use of hydrocarbons rather than halocarbons in spray cans today. CFCs have also been replaced by other halocarbons. Initially, some uses of CFCs were replaced with HCFCs, which have a reduced impact on ozone, and now increasingly with HFCs, which do not deplete ozone at all. The contributions of HCFCs and HFCs to climate change depend upon their atmospheric lifetimes and corresponding Global Warming Potentials (GWPs). GWPs are one type of measure of the relative impact of a gram of a greenhouse gas compared to carbon dioxide over one hundred years (see, e.g., IPCC/TEAP, 2005). Most HFCs currently used have relatively long atmospheric lifetimes (e.g., HFC-134a, with a lifetime of about 13 yr) and GWPs

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in excess of 1000, and are sometimes referred to as high-GWP HFCs. Throughout this paper, we refer to high-GWP HFCs unless otherwise noted. HCFCs are now scheduled to be phased out globally in 2040, and are already being replaced by HFCs (as well as a lesser amount of not-in-kind materials and technologies). As a result, atmospheric HFC concentrations are rapidly growing, by 10–15 % per year from 2006–2010 (UNEP, 2011a). The increase of concentrations implies a growing contribution of HFCs to radiative forcing of climate change, which could become substantial compared to carbon dioxide under some circumstances (Gschrey et al., 2011; Velders et al., 2009).

Figure 1 shows that the substitution with HCFCs and HFCs (as compared to CFCs) coincided with a shift away from rapid-release applications to applications involving containment, particularly refrigeration and AC (see also McCulloch et al., 2003). Further, environmental concerns led to tighter systems that increase the time the material spends in equipment (e.g., by the use of improved hoses that leak less in mobile AC). As a result of the shift to longer time scale uses, each additional year of production in HCFCs and HFCs leads to an increasing buildup in banks. The unseen and growing commitment to climate change from the HFCs produced but not yet released has not been clearly discussed or quantified, and is the focus of this paper.

HFCs are among the basket of gases of the Kyoto Protocol. Since 2009, there have been discussions among the Parties to the Montreal Protocol about including the HFCs under this protocol as well, and limiting their consumption and production to avoid a potentially large future contribution to climate change. The progression from CFCs to HFCs and the accompanying changes in banks create a new issue for policy design that poses several options: (i) doing nothing and allowing the banks to build up and be released, causing further climate change, (ii) taking steps to collect and destroy the banks as part of a phaseout schedule or (iii) planning a phaseout schedule at an earlier time that avoids the buildup of the banks. Here we show that the benefits of earlier HFC phaseouts will be greater than previous estimates, where only emissions, concentrations, and radiative forcing were considered but not banks (UNEP, 2011a; Velders et al., 2012), since actions taken sooner will avoid the buildup of banks of these gases. Equiv-

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alent climate protection could be achieved with later phaseout dates if the banks are collected and destroyed at those times. Indeed, in some countries, banked CFCs from refrigerators and AC are already collected and destroyed. However, while production and consumption controls involve no more than a few dozen chemical manufacturers and a few hundred countries, there are many millions of individual refrigeration and AC units, making later recovery and destruction a more complex option than reducing production. Below we evaluate the relevant bank sizes and climate impacts that would be associated with different HFC phaseout dates, as well as the benefits obtained through earlier phaseouts in both emissions and banks.

2 Applications of halocarbons

In Table 1 the applications of the specific CFCs, HCFCs, and HFCs illustrated in Fig. 1 are listed and grouped according to the delay times (banking times) between production and emission. About 64 % of CFC emission in the period just before the Montreal Protocol was signed came from applications with short banking times, as aerosol propellant, cleaning agents, and open cell foams (Fig. 1). In addition, extensive emissive use as solvents occurred at that time for two different ozone-depleting gases, methyl chloroform and carbon tetrachloride. Emissive applications made up about 11 % of HCFCs in the middle of the last decade, during which they were extensively used, and are projected to make up about 6 % of the HFC emissions in coming decades based on calculations from Velders et al. (2009). The HFC emissions in the scenario of Gschrey et al. (2011) show a very similar mix of applications with short (about 5 %), medium (about 89 %), and long (about 6 %) banking times, although their total emission levels are about half the levels of the scenario of Velders et al. (2009) in 2050.

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3 Scenarios of halocarbons

The CFC and HCFC scenarios used here are the baseline scenarios from WMO (2011). These use observed mixing ratios to estimate historical annual average emissions (top-down), the bottom-up banks estimates by UNEP (2009a), if available, for the year 2008, the reported production of halocarbons from UNEP (2010), and the phase-out schedules of the Montreal Protocol as constraints. The bottom-up bank estimates are based on inventories of the number of units of equipment containing CFCs and HCFCs and the amount of halocarbons present in the equipment. Emission factors, which represent the fraction of the individual banks that are released each year, are derived from the ratio of the top-down derived emissions and the bank estimates over the period 1999 to 2008, and are used to calculate the depletion of the bank and annual emissions, past 2008. Historical bank sizes could also be estimated from solely historic production data and top-down derived emission, but banks derived this way have larger and unknown uncertainties, because they are the result of an accumulating difference between two numbers (Daniel et al., 2007).

The HFC scenarios used in this study are the upper and lower range scenarios of Velders et al. (2009). These scenarios can be characterized as business-as-usual scenarios in the sense that they assume that the current patterns of replacement of CFCs and HCFCs with HFCs and other substances and technologies, as observed in the past few years in developed countries, continue unchanged and will also apply to developing countries. These scenarios do not consider global regulations of technological developments on the use and emissions of HFCs. They project the demand and emissions of HFCs for developed and developing countries based on growth in population and economy from 2010 to 2050 (IPCC, 2000). The demand in developed countries is assumed to be proportional to the projected growth in population and the demand in developing countries is proportional to the growth in gross domestic product (GDP). The per capita HFC demand in developing countries is limited to the per capita demand in developed countries, and is determined for each type of application. The HFC

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demand past 2050 is fully saturated; i.e. the demand up to 2100 is kept constant at the 2050 level (see also Xu et al., 2013). Annual emissions are calculated as a constant fraction of the bank. The fractions, or emission factors for most HFCs are based on the fractions observed for the HCFCs they replace.

The mix of chemicals and technologies that will be used to replace the HCFCs are key to the HFC emissions in these scenarios since the HCFCs are scheduled to be phased out globally by 2040 following the regulations of the Montreal Protocol. In the scenarios (Velders et al., 2009), 90 % of the HCFC use in refrigeration and stationary AC applications is assumed to be replaced with blends of HFC-32, HFC-125, HFC-134a, and HFC-143a while 10 % is assumed to use not-in-kind technologies or chemicals. Half of the HCFC use in foams is replaced with HFC-134a, HFC-245fa, and HFC-365mfc, while the other half is replaced with not-in-kind technologies or chemicals. A small demand for HFC-152a for specialty industrial aerosols is continued in the scenarios. The phaseout of HFC-134a for mobile AC in Europe in 2017 is included in the scenario, while in other countries, the use of HFC-134a is continued unabated. In the scenarios this mix of HFCs and not-in-kind aternatives remains constant for the whole time period considered.

The business-as-usual scenarios of Velders et al. (2009) are used here as reference for the production, banks, and emissions of HFCs. These scenarios are at the upper range of published HFC scenarios. Other scenarios differ because they assume different and/or temporally changing replacement patterns for HCFCs with HFCs and not-in-kind technologies, and different growth rates for the demand and market saturation (Gschrey et al., 2011). However, because the Gschrey et al. (2011) scenarios display a similar mix of short, medium, and long banking time applications to those of the reference scenario of Velders et al. (2009), the relative role of the banks as a fraction of emissions in those scenarios would be similar to that displayed here, albeit with smaller absolute values for both banks and emissions. Some other scenarios, such as several of the Representative Concentration Pathways (RCPs) (Meinshausen et al., 2011) also include strong mitigation actions in line with actions on other greenhouse

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gases. However, for the RCP scenarios information on banks is not available. The magnitude of future production and demand are important for our calculations; an under- or overestimation of them will also give an under- or overestimation of the future size of the banks.

The Multilateral Fund of the Montreal Protocol is currently funding projects in developing countries to meet their 2015 target in the HCFC phaseout. In 2015, the HCFC use in developing countries may not exceed 90 % of the average 2009–2010 use. The projects currently proposed almost all deal with the use of HCFCs for foams. In the HFC scenarios of Velders et al. (2009) and Gschrey et al. (2011) the projected emissions of HFC for foams are much smaller than the use for refrigeration and AC applications (see the 10 % contribution of the applications with long banking times in Fig. 1) so uncertainties in these applications' replacements are not critical to our calculations.

Besides the reference scenarios, two HFC reduction scenario sets are analyzed relative to each reference scenario. In the first set of hypothetical scenarios, the production of HFCs is phased out in 2020, 2030, 2040, or 2050, while in the second scenario the banks of HFCs are collected and destroyed in 2020, 2030, 2040, or 2050 on top of the production phaseout. These changes are abrupt rather than gradual and are intended as illustrative; they do not include economic considerations. Taken together, this set of scenarios illustrates the climate benefits that could be achieved with earlier production phaseouts, the effects that doing nothing would have, and sizes of the banks that could need to be collected and destroyed at later times should the Parties deem that to be the preferred option.

4 GWP-weighted production, emissions, and banks

The potential climate effects of the transition from using CFCs to HCFCs and HFCs is shown in Fig. 2 in terms of CO_2-equivalent production, emissions, and bank sizes, using GWPs with a 100 yr time horizon. The projected maximum GWP-weighted HFC production in 2050 is about equal to the maximum CFC production in the 1980s, while

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the maximum HCFC production is much less, consistent with these being largely used as transition compounds. The differences in maximum production of these halocarbons are in part due to differences in GWPs of the halocarbons, but are also the result of the use of not in kind substitutes, especially for CFCs (McFarland, 1999). The large values for the HFCs in 2050 are mainly caused by growth (particularly of GDP in the developing world) in the long-term projections. Like other issues around sustainability, as the developing world continues to develop, demand for industrial products increases rapidly.

The GWP-weighted emissions of HFCs show a very similar behavior to the growth of CFCs before the late 1980s, but the buildup of the banks is quite different (Fig. 2 and Table 2). The CFC banks peaked at about 25 $GtCO_2eq$ around 1990, while the HFC banks are projected to have the potential to reach more than twice this size, about 50–80 $GtCO_2eq$, at the end of the 21th century. This is another illustration of the impact of HFCs being used largely in slower-release applications, in contrast to CFCs (see also Fig. S1, Supplement).

Table 2 shows that in the year of maximum CFC GWP-weighted emissions, i.e. 1988, the bank was about 2.8 times the annual emission, while in 2014 when HCFC emissions are projected to peak, the HCFC bank is about 5.6 times the annual emission. This ratio is even larger for the projected HFC emissions, 6.6 in 2030 and 7.2 in 2050.

The GWP-weighted halocarbon banks and emissions shown in Fig. 2 and Table 2 are significant for climate change when compared to the historic and projected CO_2 emissions. The CFC annual GWP-weighted emissions were about 40 % of the annual CO_2 emissions in 1988, while the CFC bank in that year was slightly larger than the CO_2 emissions, implying that another year's worth of CO_2eq emission remained in the bank at that time. The annual HFC emissions in our scenarios reach up to 12 % of the upper range CO_2 emissions (RCP8.5) in 2050 and 75 % of the CO_2 scenario with strong mitigation (RCP3PD). The importance of the HFC bank becomes evident when compared with the annual CO_2 emissions. The bank may become 39–64 $GtCO_2eq$ compared with an annual CO_2 emission of 12–74 $GtCO_2eq\,yr^{-1}$ in 2050 (Table 2). So,

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the estimated HFC bank sizes range from a factor of less than 1 to more than 5 yr's worth of CO_2eq emissions in 2050 for the scenarios compared here.

The effects of possible phaseouts of HFC production in certain years are also shown in Fig. 2. The figure shows the continuing emissions that would occur after a phaseout if the banks are not destroyed: after a production phaseout, the banks decline slowly in about 20 yr, as the HFCs are emitted during this period. Because of the consistently increasing HFC production through 2050, the earlier the phaseout, the shorter is the period the banks can build up and the smaller is the final bank size at the phaseout date. If, for example, the HFC production were to be phased out in 2020 instead of 2050, the cumulative emissions avoided would be about 91–146 $GtCO_2$eq from 2020 to 2050, while a bank of about 39–64 $GtCO_2$eq is also avoided in 2050, an additional benefit to climate protection of about 40 %. This comparison exemplifies how an analysis that, for example, just examines emissions and radiative forcing time series through 2050 would understate the full climate benefits of an earlier HFC production phaseout.

Figure 3 presents cumulative production, emission, and banks vs. time for the scenarios. Figure 3 can be compared to Fig. 2, and helps to show what is gained by the avoided banks (as compared to consideration of emissions and concentrations only) for any choice of phaseout time desired. The arrows on the figure show, for example, how a phaseout ten years earlier than 2050 corresponds with 60–96 $GtCO_2$eq of avoided production, of which 50–80 $GtCO_2$eq occurs through avoided emission and 10–16 $GtCO_2$eq comes from a smaller bank.

5 Radiative forcing

The contribution of halocarbons to radiative forcing of climate change depends on the product of the global average concentrations and the radiative efficiencies (radiative forcing per molecule). The radiative forcings of the halocarbon scenarios considered here are shown in Fig. 4 and Table S1 (see Supplement). The radiative forcing of the CFCs peaked around 2000 and slowly decreased since then, while that of the HCFCs

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is projected to peak just after 2020. In the business as usual scenario, the radiative forcing of the HFCs is projected to continue increasing throughout the 21th century, and may reach values of more than 0.5 $W m^{-2}$.

Figure 4 also shows the effects of HFC phaseouts at various times on radiative forcing. While the HFC emissions continue for about 20 yr after a production phaseout due to emission from the banks if they are not destroyed as noted above, the HFCs continue to contribute to radiative forcing for a further several decades, as the gases are slowly removed from the atmosphere by natural processes. For example, with an HFC production phaseout in 2050, the radiative forcing decreases slowly from a maximum of 0.26–0.42 $W m^{-2}$ in 2054 to 0.07–0.11 $W m^{-2}$ in 2100. However, this is still more than 0.4 $W m^{-2}$ less than the forcing in 2100 in the scenario of constant emissions after 2050. At their peak, these radiative forcings are about 8–14 % of the CO_2 forcing from the mid-range of RCP scenarios (RCP4.5 and RCP6, Meinshausen et al., 2011) (Fig. 4). While the absolute forcing is important in determining the total amount of warming since pre-industrial times, the rate of increase in forcing is important in determining the rate of transient temperature rise. The rate of increase in radiative forcing by HFCs in the reference scenario is 0.010–0.017 $W m^{-2} yr^{-1}$ in 2050, which is about half the rate of increase in CO_2 forcing of 0.025–0.035 $W m^{-2} yr^{-1}$ in 2050 from the mid-range RCP scenarios, which illustrates how large the HFC contribution could become compared to other forcing agents if there are no controls.

With an earlier HFC phaseout in 2020, a significant bank and accumulation in the atmosphere would be avoided. Their contribution to radiative forcing then always remains small, and in 2050 it is smaller than the current forcing of HFCs of about 0.02 $W m^{-2}$ (Velders et al., 2012).

6 Committed climate forcing of HFC banks

The buildup of the HFC banks is shown in Fig. 2, and the HFC contribution to radiative forcing is depicted in Fig. 4 for the reference scenario and scenarios with a phaseout

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in production. The potential additional effects of collection and destruction of the HFC banks on reductions in radiative forcing are further illustrated in Fig. 5 and Table S1. The effect of destroying the bank is initially zero, increases almost immediately as some of the banks would have been released and then decreases rapidly. If the banks are not destroyed, the HFCs would be emitted from them in about decade, and the corresponding contribution to the atmospheric abundance would decrease according to the lifetimes of the HFCs. For example, if the bank is allowed to grow unabated until 2050 it reaches 39–64 $GtCO_2eq$ in our baseline scenarios. If destroyed instantaneously in 2050, the radiative forcing is reduced by 0.09–0.14 $W m^{-2}$ around 2060 and 0.03–0.05 $W m^{-2}$ in 2100, relative to the scenario in which the HFCs are gradually emitted from the bank but in which production is eliminated. It is evident that in a scenario in which the bank destruction starts earlier, the size of the banks is smaller, as is the effect of the destruction on the radiative forcing. These reductions in radiative forcing can also be viewed as the radiative forcing that arises from the post-2020, -2030, -2040, and -2050 banks if the banks were not collected and destroyed, relative to the scenarios with only a production phaseout in the same years.

Figures 4 and 5 show that the maximum reduction in radiative forcing is obtained with both a production phaseout and collection and destruction of the bank. In a hypothetical scenario where a production phaseout and bank destruction occurs in 2050, the radiative forcing decrease from 2050 to 2070 is 0.15–0.24 $W m^{-2}$, with equal contributions from the production phaseout and bank destruction. By 2100, the radiative forcing reduces to 0.04–0.06 $W m^{-2}$, with the production phaseout contributing most of the change, about 0.19–0.29 $W m^{-2}$ and the bank destruction only 0.03–0.05 $W m^{-2}$. The relatively greater importance of the production phaseout by 2100 is because once production is eliminated in 2050, there are not a lot of HFCs remaining in the atmosphere from what was in the bank in 2050. Without additional production from 2050 on, nothing further gets added to the bank after then.

The effects on the radiative forcing of the production phaseout and bank destruction would be smaller when using other scenarios that have lower future HFC emissions as

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a reference (Gschrey et al., 2011; Meinshausen et al., 2011), but the increasing importance of the bank can be expected to be similar in a relative sense when compared with cumulative production.

7 Montreal Protocol

The Montreal Protocol has controlled production and consumption of ODSs. The amounts of ODSs present in banks have not been regulated under the Protocol. Controlling production and consumption was easier to carry out, and it addressed key environmental effects when most of the use was emissive, so that what was produced/consumed in a given year was also emitted in the same year. We have shown here that this not true anymore for the HFCs now used as alternatives for ODSs, because the relevant applications are much less emissive and banks that persist for years are significant and will become larger if production continues. This implies new issues and choices for policymakers if they want to control HFCs using the expertise and the institutions of the Montreal Protocol, as agreed by the more than 100 countries that signed the Bali declaration in 2011 (UNEP, 2011b).

Earlier phaseouts of HFCs would yield benefits for climate protection that are about 40 % larger than estimates based on concentrations and radiative forcing in 2050 alone, due to the added impact of avoided banks. Options to reduce the use of high-GWP HFCs are available for several sectors (UNEP, 2011a, 2013) and include fiber insulation materials. Non-HFC substances with low GWPs, such as hydrocarbons, ammonia, and CO_2 in some refrigeration systems as well as alternative HFCs with atmospheric lifetimes on the order of days or weeks, and consequently very low GWPs, are now being introduced for foams and aerosols (e.g., HFC-1234ze) and mobile AC (e.g., HFC-1234yf). In the selection of possible alternative substances and or technologies for high-GWP HFCs, the indirect climate effects that arise from the energy used or saved during the application or product's full life cycle needs to be considered. Policymakers could also choose to limit future emissions of HFCs by collection and destruction of

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banks. In that case, the accessibility of the banks is important. Halocarbons in foams are harder and more costly to collect and destroy than those present in refrigeration and AC applications (UNEP, 2009b), but foams make up only a small fraction (10–15 %) of the total projected HFC bank. Also, it should be noted that the HFC banks are dispersed across the globe to a much greater extent than are the HFC production facilities, impacting the relative ease of adopting a capture and destruction approach.

8 Conclusions

The Montreal Protocol entered into force in the late 1980s, when most of the regulated chlorofluorocarbon (CFC) use occurred in rapid-release applications such as spray cans, while current uses of the hydrofluorocarbon (HFC) substitutes for CFCs have shifted to applications where the gases are contained for years, or banked, in refrigeration and air conditioning equipment. We showed that this transition has unrecognized policy implications. The buildup of HFC banks represents an unseen commitment to further climate change after production of the chemicals ends unless the banks are collected and destroyed. We showed that earlier phaseouts of HFCs would provide greater benefits for climate change (by as much as 40 %) than suggested by previous estimates, because of reduction of the banks.

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Xu, Y., Zaelke, D., Velders, G. J. M., and Ramanathan, V.: The role of HFCs in mitigating 21st century climate change, Atmos. Chem. Phys., 13, 6083–6089, doi:10.5194/acp-13-6083-2013, 2013.

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Table 1. Main applications of CFCs up to about 1990 and of HCFCs and HFCs currently.

Applications	CFCs	HCFCs	HFCs
Short banking times (< 1 yr)			
Aerosol propellant	CFC-11 CFC-12 CFC-113		HFC-134a HFC-152a HFC-227ea
Cleaning agent (solvent)	CFC-113	HCFC-141b HCFC-225ca HCFC-225cb	HFC-43-10mee
Open cell foam blowing	CFC-11 CFC-113	HCFC-141b HCFC-142b HCFC-22	HFC-134a HFC-152a
Medium banking times (1 to 10 yr)			
Refrigeration and stationary air conditioning	CFC-11 CFC-12 CFC-114 CFC-115	HCFC-22	HFC-23[a,b] HFC-32[a] HFC-125[a] HFC-134a[a] HFC-143a[a]
Mobile air conditioning	CFC-12		HFC-134a
Fire extinguishing		HCFC-123	HFC-23 HFC-125 HFC-227ea
Long Banking times (> 10 yr)			
Closed cell foam blowing	CFC-11 CFC-12	HCFC-141b HCFC-142b HCFC-22	HFC-134a HFC-245fa HFC-365mfc

[a] Mainly used in blends.

[b] The largest emissions of HFC-23 occur as a byproduct of HCFC-22 production. Such emissions are not taken into account in the scenarios discussed here.

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Table 2. Emissions and banks of CFCs, HCFCs, and HFCs, and emissions of CO_2.

		Halocarbons[a]			
	Year (x)	Emission ($GtCO_2eq\,yr^{-1}$)	Cumulative emission (1950 to x) ($GtCO_2eq$)	Bank ($GtCO_2eq$)	CO_2 emission[b] ($GtCO_2eq\,yr^{-1}$)
CFCs	1988[c]	8.8	154[d]	24.6	22
HCFCs	2014[c]	1.0	19	5.6	32–37
HFCs	2020	1.2–1.5	11–12	7.5–9.0	33–42
	2030	2.5–3.8	29–36	16–25	26–51
	2040	4.2–6.9	61–87	29–47	16–62
	2050	5.5–8.8	109–166	39–64	12–74

[a] The CFC and HCFC emissions and banks are from the baseline scenarios (WMO, 2011). The HFC emissions and banks are the upper and lower ranges of the scenarios of Velders et al. (2009).
[b] The CO_2 emissions are from fossil and industrial uses. The ranges are from the upper and lower RCP scenarios (Meinshausen et al., 2011).
[c] Years with maximum emissions in the baseline scenario.
[d] The cumulative CFC emissions from 1950 to 2014 are 226 $GtCO_2eq$.

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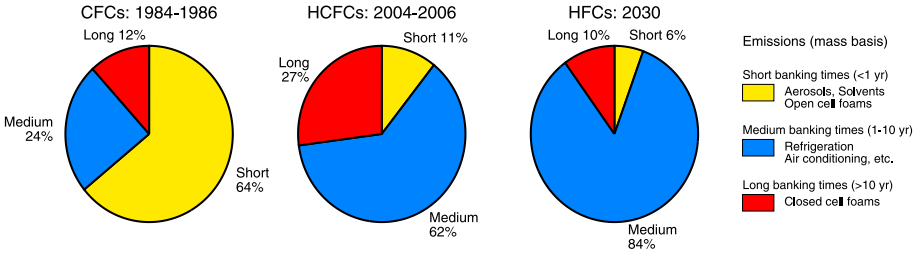

Fig. 1. Contributions of different types of applications to the emissions (mass basis) of CFCs, HCFCs, and of HFCs. The applications differ in the delay times between production and emission (banking times, see Table 1). The CFCs and HCFCs emissions (AFEAS, 2009) are shown for those years when they were used extensively and reductions in their emission were not affected much by Montreal Protocol regulations. HFC emissions are the average of the upper and lower range scenarios for 2030 from Velders et al. (2009).

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Growth of climate change commitments from HFC banks and emissions

G. J. M. Velders et al.

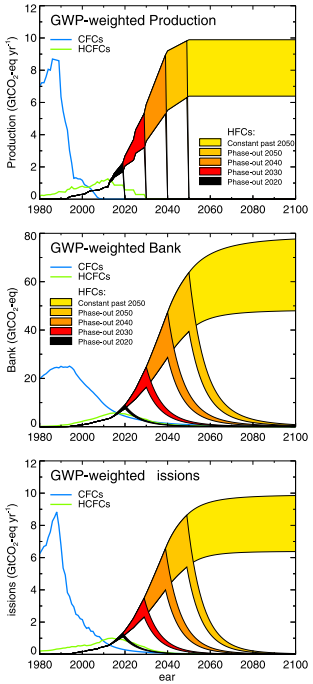

Fig. 2. GWP-weighted production, bank, and emissions of halocarbons and their contributions to radiative forcing for the period 1980 to 2100. Calculated direct GWP-weighted data (100 yr time horizon) and associated radiative forcing values are shown for the baseline scenarios of the CFCs and HCFCs (WMO, 2011) and the upper and lower ranges of the HFC scenarios from Velders et al. (2009). Four additional scenarios are shown in which there is a global phaseout in production of HFCs in 2020, 2030, 2040, or 2050. The GWPs used here are those used in the reference scenarios, i.e. of WMO (2011) for the CFCs and HCFCs, and IPCC (2007) for the HFCs. Radiative forcing values represent net changes from the start of the industrial era (ca. 1750) to present.

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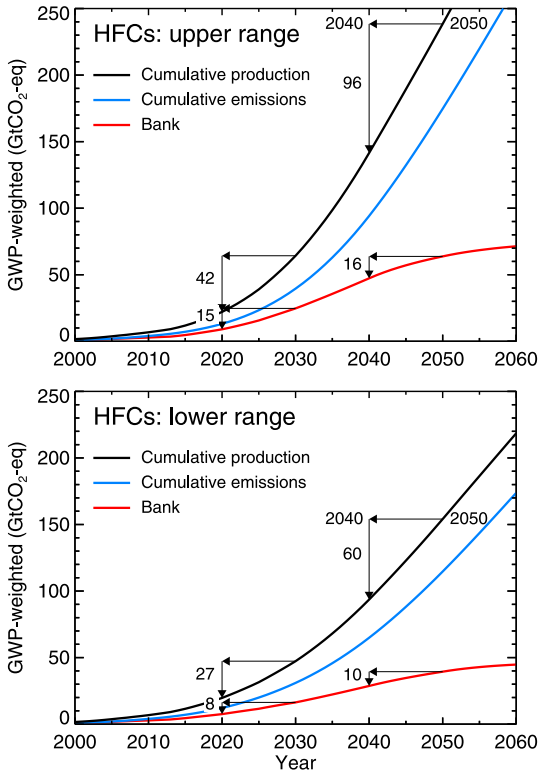

Fig. 3. Cumulative GWP-weighted production and emission and instantaneous GWP-weighted bank of the HFC upper and lower range scenarios of Velders et al. (2009). The cumulative production equals the sum of the cumulative emission and the bank. The arrows illustrate two examples of the climate benefits of an earlier phaseout in terms of both avoided emissions and reduced banks.

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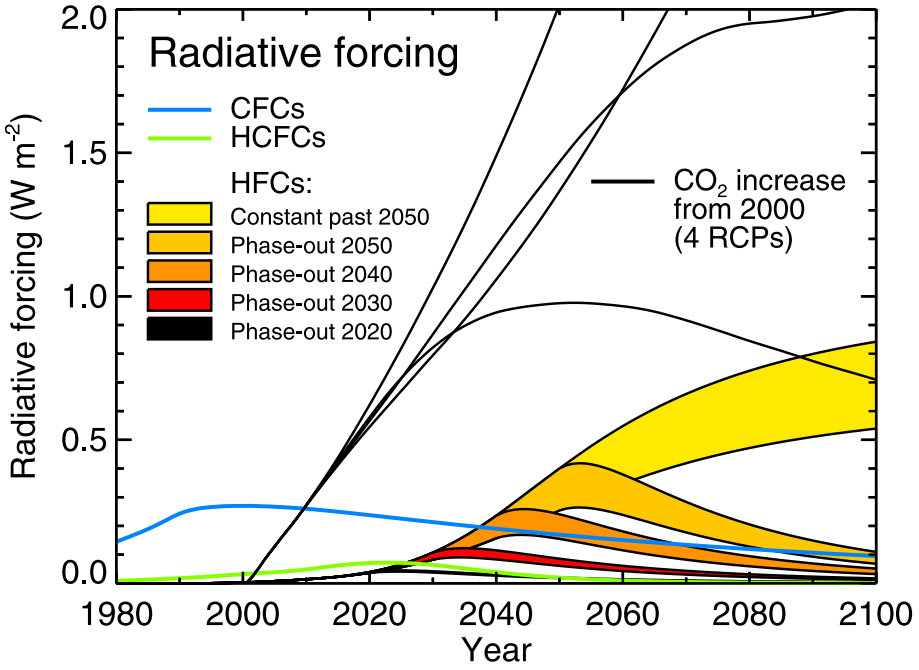

Fig. 4. Radiative forcing of halocarbons for the period 1980 to 2100 and increase in CO_2 radiative forcing from 2000. The radiative forcings of halocarbons are shown for the baseline scenarios of the CFCs and HCFCs from WMO (2011) and the upper and lower ranges of the HFC scenarios from Velders et al. (2009). Four additional scenarios are shown in which there is a global production phaseout of HFCs in 2020, 2030, 2040, or 2050, as in Fig. 2. No bank destruction is assumed. For CO_2 the radiative increases relative to 2000 are shown for the four RCP scenarios (Meinshausen et al., 2011). The radiative forcing values represent net changes from the start of the industrial era (ca. 1750) to present.

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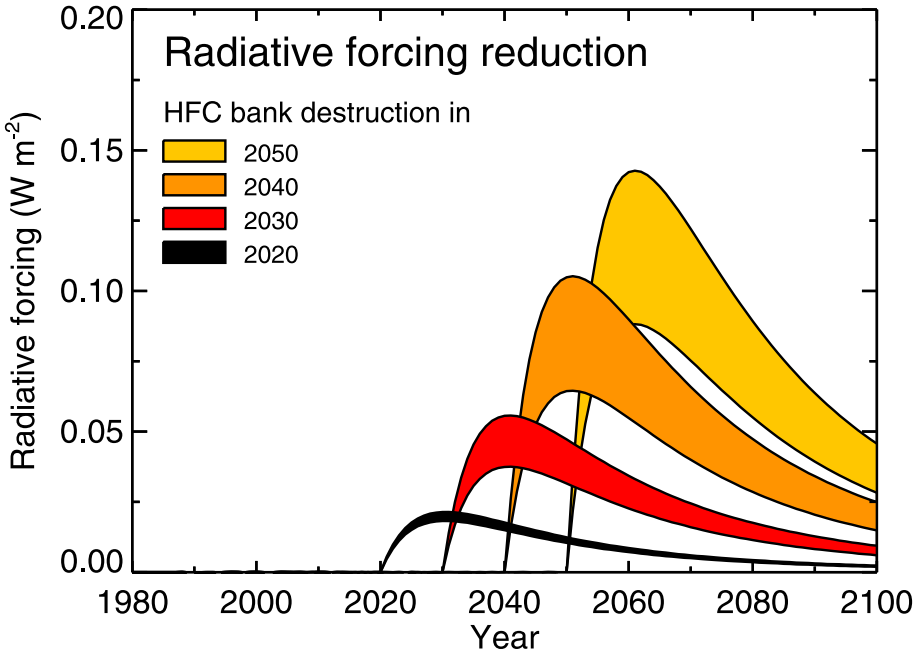

Fig. 5. Reductions in radiative forcing from destruction of the HFC banks in 2020, 2030, 2040, or 2050 relative to the case with only a production phaseout in that same year. This is equivalent to the radiative forcing contribution from the HFC bank post-2020, -2030, -2040, and -2050 in the production phaseout scenarios. This reduction plus the production phaseout gives the maximum possible effect, i.e. the zero emissions scenario. The ranges correspond to the upper and lower HFC reference scenarios from Velders et al. (2009).

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