

# 1 **Growth of climate change commitments from HFC banks** 2 **and emissions**

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## 15 **Abstract**

16 Chlorofluorocarbons (CFCs) are the primary cause of ozone depletion, and they also  
17 contribute to global climate change. With the global phaseout of CFCs and the coming  
18 phaseout of hydrochlorofluorocarbons (HCFCs), the substitute hydrofluorocarbons (HFCs)  
19 are increasingly used. While CFCs were originally used mainly in applications such as spray  
20 cans and were released within a year after production, concern about the ozone layer led to  
21 reductions in rapid-release applications, and the relative importance of slower-release  
22 applications grew. HFCs are now mainly used in refrigerators and air-conditioners (AC) and  
23 are released over years to a decade after production. Their containment in such equipment  
24 represents banks, which are building up as production grows. A key finding of our work is  
25 that the increases of HFC banks represent a substantial unseen commitment to further  
26 radiative forcing of climate change also after production of the chemicals ceases. We show  
27 that earlier phaseouts of HFCs would provide greater benefits for climate protection than  
28 previously recognized, due to the avoided buildup of the banks. If, for example, HFC  
29 production were to be phased out in 2020 instead of 2050, not only could about 91-146  
30 GtCO<sub>2</sub>-eq of cumulative emission be avoided from 2020 to 2050, but an additional bank of  
31 about 39-64 GtCO<sub>2</sub>-eq could also be avoided in 2050. Choices of later phaseout dates lead to

32 larger commitments to climate change unless growing banks of HFCs from millions of  
33 dispersed locations are collected and destroyed.

## 34 **1. Introduction**

35 Concern about damage to the Earth's ozone layer prompted the signing of the Montreal  
36 Protocol in 1987, an international treaty that has since been hailed as one of the most  
37 successful environmental agreements. The halocarbons that were the primary cause of ozone  
38 loss are also potent greenhouse gases (Ramanathan, 1975), and reductions in emissions of  
39 these gases have benefitted both the ozone layer and efforts to reduce anthropogenic climate  
40 change (Velders et al., 2007). At the time that the Protocol was developed,  
41 chlorofluorocarbons were the primary halocarbons addressed, and most of the emissions of  
42 these gases occurred rapidly (within about a year after production), in applications such as  
43 spray cans, metered-dose medical inhalers, open cell foams, and solvents (Figure 1) (Fisher  
44 and Midgley, 1994; Gamlen et al., 1986). Citizen actions and national regulation already led to  
45 reductions in the use of CFCs in spray cans in some countries before the Protocol was signed  
46 (Andersen and Sarma, 2002). By reducing production and consumption of rapidly-released  
47 gases in each country, measures taken under the Protocol quickly led to further changes in  
48 emissions of CFCs, with very little time lag. While CFC production is phased out globally, a  
49 small amount of emission of these gases continues (see Figure 2), due mainly to release from  
50 applications where their use involves containment and storage, i.e., a bank of material. The  
51 primary banks are in refrigeration and air conditioning (AC) applications, from which gases  
52 are released on a time scale of years to about a decade (medium time scale), and in closed cell  
53 foams, from which they are released over multiple decades (long time scale, e.g., in building  
54 insulation). This represents a legacy, or commitment, of continued environmental impact from  
55 past production of CFCs, but its magnitude is relatively small since so much use of CFCs  
56 occurred in rapid-release applications and because production for the longer time scale release  
57 applications has been in decline for over two decades.

58 Substitute processes and chemicals that replace the CFCs have evolved in the decades since  
59 the Montreal Protocol entered into force. Motivated by environmental concerns, many  
60 applications now employ approaches that do not require halocarbons at all, referred to here as  
61 'not-in-kind' substitutions; an example is the widespread use of hydrocarbons rather than  
62 halocarbons in spray cans today. CFCs have also been replaced by other halocarbons.  
63 Initially, some uses of CFCs were replaced with HCFCs, which have a reduced impact on

64 ozone, and now increasingly with HFCs, which do not deplete ozone at all. The contributions  
65 of emissions of HCFCs and HFCs to climate change depend upon their atmospheric lifetimes  
66 and radiative efficiencies and thereby on their Global Warming Potentials (GWPs) ), as well  
67 as the total emission and hence the abundance. The GWP is an index comparing the integrated  
68 radiative forcing of an emission of a greenhouse gas, integrated over typically one hundred  
69 years, relative to that of emitting the same mass of carbon dioxide (see, e.g., IPCC/TEAP  
70 (2005)). Most HFCs currently used have relatively long atmospheric lifetimes (e.g., HFC-  
71 134a, with a lifetime of about 13 years) and GWPs in excess of 1000, and are sometimes  
72 referred to as high-GWP HFCs. Throughout this paper, we refer to high-GWP HFCs unless  
73 otherwise noted (see Section 7). HCFCs are now scheduled to be phased out globally in 2040,  
74 and are already being replaced by HFCs (as well as by a lesser amount of not-in-kind  
75 materials and technologies). As a result, atmospheric HFC concentrations are rapidly  
76 growing, by 10-15% per year from 2006-2010 (UNEP, 2011a). The increase in concentrations  
77 implies a growing contribution of HFCs to radiative forcing of climate change, which could  
78 become substantial in comparison to carbon dioxide under some circumstances (Gschrey et  
79 al., 2011;Velders et al., 2009;Velders et al., 2012).

80 CFCs used in rapid-release applications, like spray cans and solvents, were largely replaced  
81 with not-in-kind alternatives right away after environmental concerns were recognized.  
82 Because of these same concerns, HCFCs and HFCs were always only used in limited amounts  
83 for rapid-release applications. Figure 1 shows that the substitution of CFCs with HCFCs and  
84 HFCs coincided with a shift away from rapid-release applications to applications involving  
85 containment, particularly refrigeration and AC (see also McCulloch et al. (2003)). Further,  
86 environmental concerns led to tighter systems that increase the time the material spends in  
87 equipment (e.g., by the use of improved hoses that leak less in mobile AC). As a result of the  
88 shift to longer time scale uses, each additional year of production in HCFCs and HFCs leads  
89 to an increasing buildup in banks. The unseen and growing commitment to climate change  
90 from the HFCs produced but not yet released has not been clearly discussed or quantified, and  
91 is the focus of this paper. In several previous HFC scenario studies (Velders et al.,  
92 2009;Velders et al., 2012;Gschrey et al., 2011;IPCC/TEAP, 2005;Meinshausen et al.,  
93 2011;UNEP, 2009a) banks have been considered in the modelling approach, but the focus in  
94 discussing climate change effects was only on emissions and radiative forcing, and the fact  
95 that the time lag between production and emissions results in a bank and associated hidden  
96 climate impacts was not discussed.

97 HFCs are among the basket of gases of the Kyoto Protocol. Since 2009, there have been  
98 discussions among the Parties to the Montreal Protocol about including the HFCs under this  
99 protocol as well, and limiting their consumption and production to avoid a potentially large  
100 future contribution to climate change. The progression from CFCs to HFCs and the  
101 accompanying changes in banks create a new issue for policy design that poses several  
102 options: (i) doing nothing and allowing the banks to build up and be released, causing further  
103 climate change, (ii) taking steps to collect and destroy the banks as part of a phaseout  
104 schedule, or (iii) planning a phaseout schedule at an earlier time that avoids the buildup of the  
105 banks. Here we show that the benefits of earlier HFC phaseouts will be greater than previous  
106 estimates, where emissions, concentrations, and radiative forcing were considered, but not the  
107 effects of the banks remaining at the end of the period examined (UNEP, 2011a; Velders et al.,  
108 2012), since actions taken sooner will avoid the buildup of banks of these gases. Equivalent  
109 climate protection could be achieved with later phaseout dates if the banks are collected and  
110 destroyed at those times. Indeed, in some countries, banked CFCs from refrigerators and AC  
111 are already collected and destroyed. However, while production and consumption controls  
112 involve no more than a few dozen chemical manufacturers and a about two hundred countries,  
113 there are many millions of individual refrigeration and AC units, making later recovery and  
114 destruction a more complex option than reducing production. Below we evaluate the relevant  
115 bank sizes and climate impacts that would be associated with different HFC phaseout dates, as  
116 well as the benefits in terms of both emissions and banks obtained through earlier phaseouts.

## 117 **2. Applications of halocarbons**

118 In Table 1 the applications of the specific CFCs, HCFCs, and HFCs illustrated in Figure 1 are  
119 listed and grouped according to the delay times (banking times) between production and  
120 emission. About 64% of CFC emission in the period just before the Montreal Protocol was  
121 signed came from applications with short banking times, such as aerosol propellants, cleaning  
122 agents, and open cell foams (Figure 1). In addition, extensive emissive use as solvents  
123 occurred at that time for two additional ozone-depleting gases, methyl chloroform and carbon  
124 tetrachloride. Emissive applications made up about 11% of HCFC emissions in the middle of  
125 the last decade, during which they were extensively used, and are projected to make up about  
126 6% of the HFC emissions in coming decades based on calculations from Velders et al. (2009).  
127 The HFC emissions in the scenario of Gschrey et al. (2011) show a very similar mix of  
128 applications with short (about 5%), medium (about 89%), and long (about 6%) banking times,

129 although their total emission levels are about half the levels of the scenario of Velders et al.  
130 (2009) in 2050.

### 131 **3. Scenarios of halocarbons**

132 The CFC and HCFC scenarios used here identical to the baseline scenario from WMO (2011).  
133 These scenarios apply the following constraints: i) observed mixing ratios to estimate  
134 historical annual average emissions (top-down), ii) bottom-up banks estimates by UNEP  
135 (2009a), if available, for the year 2008, iii) reported production of halocarbons from UNEP  
136 (2010), and iv) phaseout schedules of the Montreal Protocol; see Velders and Daniel (2014)  
137 for a more extensive description. The bottom-up bank estimates for 2008 are based on  
138 inventories of the number of units of equipment containing CFCs and HCFCs and the amount  
139 of halocarbons present in the equipment. In other years, the bank at the start of a particular  
140 year is equal to the sum of the bank in the previous year and production from that year, with  
141 the emission from that year subtracted. Historical bank sizes could also be estimated from  
142 solely historic production data and top-down derived emission, but banks derived this way  
143 have larger and unknown uncertainties, because they are the result of an accumulating  
144 difference between two numbers (Daniel et al., 2007). Emission factors, which represent the  
145 fraction of the total bank of specific ODSs that are released each year, are derived from the  
146 ratio of the top-down derived emissions and the bank estimates over the period 1999 to 2008,  
147 and are used to calculate the depletion of the bank and annual emissions, past 2008. These  
148 emission factors are overall factors applied to the total bank of a specific ODS. Possible future  
149 changes in these factors are not taken into account in the scenario. But such changes are  
150 probably small for all CFCs and HCFCs, since currently most individual CFCs and HCFCs  
151 are emitted from a single type of application. For example, CFC-11 is currently emitted  
152 almost completely from closed-cell foams, while CFC-12 is emitted from stationary  
153 refrigeration and AC.

154 The HFC scenarios used in this study are the upper- and lower-range scenarios of Velders et  
155 al. (2009). These scenarios can be characterized as business-as-usual scenarios in the sense  
156 that they assume that the current patterns of replacement of CFCs and HCFCs with particular  
157 HFCs and other substances and technologies, as observed in the past few years in developed  
158 countries, continue unchanged and will also apply to developing countries. These scenarios do  
159 not consider global regulations of technological developments on the use and emissions of  
160 HFCs, nor do they incorporate changing market conditions since 2009. They project the

161 demand and emissions of HFCs for developed and developing countries based on growth in  
162 population and economy from 2010 to 2050 (IPCC, 2000). The demand in developed  
163 countries is assumed to be proportional to the projected growth in population and the demand  
164 in developing countries is proportional to the growth in gross domestic product (GDP). The  
165 per capita HFC demand in developing countries is limited to the per capita demand in  
166 developed countries, and is determined for each type of application. The HFC demand past  
167 2050 is fully saturated; i.e. the demand up to 2100 is kept constant at the 2050 level (see also  
168 Xu et al. (2013)). Annual emissions are calculated as a constant fraction of the bank. The  
169 fractions, or emission factors for most HFCs are based on the fractions observed for the  
170 HCFCs they replace.

171 The mix of chemicals and technologies that will be used to replace the HCFCs are key to the  
172 HFC emissions in these scenarios since the HCFCs are scheduled to be phased out globally by  
173 2040 following the regulations of the Montreal Protocol. In the scenarios (Velders et al.,  
174 2009), 90% of the HCFC use in refrigeration and stationary AC applications is assumed to be  
175 replaced with blends of HFC-32, HFC-125, HFC-134a, and HFC-143a while 10% is assumed  
176 to use not-in-kind technologies or chemicals. Half of the HCFC use in foams is replaced with  
177 HFC-134a, HFC-245fa, and HFC-365mfc, while the other half is replaced with not-in-kind  
178 technologies or chemicals. A small demand for HFC-152a for specialty industrial aerosols is  
179 continued in the scenarios. The phaseout of HFC-134a for mobile AC in Europe in 2017 is  
180 included in the scenario, while in other countries, the use of HFC-134a is continued unabated.  
181 In the scenarios this mix of HFCs and not-in-kind alternatives remains constant for the whole  
182 time period considered.

183 The magnitude of future production and demand are important for our calculations; an under-  
184 or overestimation of them will also give an under- or overestimation of the future size of the  
185 banks. These scenarios of Velders et al. (2009), with their projections of production, banks,  
186 and emissions of HFCs, are at the upper range of published HFC scenarios. Other scenarios  
187 differ because they assume different and/or temporally changing replacement patterns of  
188 HCFCs with HFCs and not-in-kind technologies, and different growth rates for the demand  
189 and market saturation (Gschrey et al., 2011). However, because the Gschrey et al. (2011)  
190 scenarios display a similar mix of short, medium, and long banking time applications to those  
191 of the reference scenario of Velders et al. (2009), the relative role of the banks as a fraction of  
192 emissions and radiative forcing in those scenarios would be similar to that displayed here,  
193 albeit with smaller absolute values for both banks, emissions, and radiative forcing. Some

194 other scenarios, such as several of the Representative Concentration Pathways (RCPs)  
195 (Meinshausen et al., 2011) also include strong mitigation actions in line with actions on other  
196 greenhouse gases. However, for the RCP scenarios, information on banks is not available,  
197 only emissions, mixing ratios, and radiative forcings have been reported.

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

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

#### 215 **4. GWP-weighted production, emissions, and banks**

216 The potential climate effects of the transition from using CFCs to HCFCs and HFCs is shown  
217 in Figure 2 in terms of CO<sub>2</sub>-equivalent (CO<sub>2</sub>-eq) production, emissions, and bank sizes, using  
218 GWPs with a 100-yr time horizon. CO<sub>2</sub>-eq is used as a simplified climate metric to compare  
219 different quantities in terms of their integrated radiative forcing over this time horizon.  
220 However, it is important to recognize that even for two emission scenarios of identical CO<sub>2</sub>-  
221 eq, if the emitted gases have different lifetimes, the effects on climate will be different at  
222 different times (Myhre and Shindell, 2013). For example, in the case of identical CO<sub>2</sub>-eq  
223 emissions, the shorter lifetimes of HFCs (compared with the atmospheric residence time of  
224 CO<sub>2</sub>) will result in a faster and larger short-term climate response to radiative forcing changes

225 (e.g., on a 20-year time horizon) after HFC emissions than the much longer and nearly  
226 irreversible response after CO<sub>2</sub> emissions (Solomon et al., 2009). The projected maximum  
227 GWP-weighted HFC production in 2050 is about equal to the maximum CFC production in  
228 the 1980s, while the maximum HCFC production is much less, consistent with these being  
229 largely used as transition compounds. The differences in maximum production of these  
230 halocarbons are in part due to differences in GWPs of the halocarbons, but are also the result  
231 of the use of not-in-kind (non-halocarbon) substitutes, especially for CFCs (McFarland,  
232 1999). The large values for the HFCs in 2050 are mainly caused by growth (particularly of  
233 GDP in the developing world) in the long-term projections. Like other issues around  
234 sustainability, as the developing world continues to develop, demand for industrial products is  
235 likely to increase rapidly.

236 The GWP-weighted emissions of HFCs show a very similar behavior to the growth of CFCs  
237 before the late 1980s, but the buildup of the banks is quite different (Figure 2 and Table 2).  
238 The CFC banks peaked at about 25 GtCO<sub>2</sub>-eq around 1990, while the HFC banks are  
239 projected to have the potential to reach more than twice this size, about 50-80 GtCO<sub>2</sub>-eq, at  
240 the end of the 21<sup>th</sup> century. This is another illustration of the impact of HFCs being used  
241 largely in slower-release applications, in contrast to CFCs (see also Figure S1, Supplementary  
242 Material).

243 Table 2 shows that in the year of maximum CFC GWP-weighted emissions, i.e. 1988, the  
244 bank was about 2.8 times the annual emission, while in 2014 when HCFC emissions are  
245 projected to peak, the HCFC bank is about 5.6 times the annual emission. This ratio is even  
246 larger for the projected HFC emissions, greater than 6 in 2030 and 7 in 2050.

247 The GWP-weighted halocarbon banks and emissions shown in Figure 2 and Table 2 are  
248 significant for climate change when compared to the historic and projected CO<sub>2</sub> emissions.  
249 The CFC annual GWP-weighted emissions were about 40% of the annual CO<sub>2</sub> emissions in  
250 1988, while the CFC bank in that year was slightly larger than the annual CO<sub>2</sub> emissions,  
251 implying that another year's worth of CO<sub>2</sub>-eq emission remained in the bank at that time. The  
252 annual HFC emissions in our scenarios reach up to 12% of the upper range annual CO<sub>2</sub>  
253 emissions (RCP8.5) in 2050 and 75% for the CO<sub>2</sub> scenario with strong mitigation (RCP3PD).  
254 In these scenarios, the HFC bank grows to 39-64 GtCO<sub>2</sub>-eq compared with an annual CO<sub>2</sub>  
255 emission of 12-74 GtCO<sub>2</sub>-eq yr<sup>-1</sup> in 2050 (Table 2). So, the estimated HFC bank sizes range



256 from a factor of less than 1 to more than 5 year's worth of CO<sub>2</sub>-eq emissions in 2050 for the  
257 scenarios compared here.

258 The effects of possible phaseouts of HFC production in certain years are also shown in Figure  
259 2. The figure shows the continuing emissions that would occur after a phaseout if the banks  
260 are not destroyed: after a production phaseout, the banks decline slowly over about 20 years,  
261 as the HFCs are emitted during this period. Because of the consistently increasing HFC  
262 production through 2050, the earlier the phaseout, the shorter is the period the banks can build  
263 up and the smaller is the final bank size at the phaseout date. If, for example, the HFC  
264 production were to be phased out in 2020 instead of 2050, the cumulative emissions avoided  
265 would be about 91-146 GtCO<sub>2</sub>-eq from 2020 to 2050, while a bank of about 39-64 GtCO<sub>2</sub>-eq  
266 is also avoided in 2050, an additional benefit to climate protection of about 40% compared  
267 with the cumulative emissions reduction alone. This comparison exemplifies how an analysis  
268 that, for example, just examines emissions and radiative forcing time series through 2050  
269 would understate the full climate benefits of an earlier HFC production phaseout.

270 Figure 3 presents cumulative production, emission, and banks versus time for the scenarios.  
271 Figure 3 can be compared to Figure 2, and helps to show what is gained by the avoided banks  
272 (as compared to consideration of emissions and concentrations only) for any choice of  
273 phaseout time desired. The arrows on the figure show, for example, how a phaseout ten years  
274 earlier than 2050 corresponds with 60-96 GtCO<sub>2</sub>-eq of avoided production, of which 50-80  
275 GtCO<sub>2</sub>-eq is manifested in avoided emission and 10-16 GtCO<sub>2</sub>-eq in a smaller bank.

## 276 **5. Radiative forcing**

277 The contribution of halocarbons to radiative forcing of climate change depends on the product  
278 of the global average concentrations and the radiative efficiencies (generally given as  
279 radiative forcing per ppt). The radiative forcings of the halocarbon scenarios considered here  
280 are shown in Figure 4 and Table S1 (see Supplementary Material). The radiative forcing of  
281 the CFCs peaked around 2000 and slowly decreased since then, while that of the HCFCs is  
282 projected to peak just after 2020. In the business as usual scenarios, the radiative forcing of  
283 the HFCs is projected to continue increasing throughout the 21<sup>th</sup> century, and may reach  
284 values of more than 0.5 W m<sup>-2</sup>.

285 Figure 4 also shows the effects of HFC phaseouts at various times on radiative forcing. While  
286 the HFC emissions continue for about 20 years after a production phaseout due to emission  
287 from the banks if they are not destroyed as noted above, the HFCs continue to contribute to  
288 radiative forcing for a further several decades, as the gases are slowly removed from the  
289 atmosphere by natural processes. For example, with an HFC production phaseout in 2050, the  
290 radiative forcing decreases slowly from a maximum of 0.26-0.42 W m<sup>-2</sup> in 2054 to 0.07-0.11  
291 W m<sup>-2</sup> in 2100. However, this is still more than 0.4 W/m<sup>2</sup> less than the forcing in 2100 in the  
292 scenario of constant production after 2050. At their peak, these radiative forcings are about 8-  
293 14% of the CO<sub>2</sub> forcing from the mid-range of RCP scenarios (RCP4.5 and RCP6)  
294 (Meinshausen et al., 2011) (Figure 4). While the absolute forcing is important in determining  
295 the total amount of warming since pre-industrial times, the rate of increase in forcing is  
296 important in determining the rate of transient temperature rise. The rate of increase in  
297 radiative forcing by HFCs in the reference scenario is 0.010-0.017 W m<sup>-2</sup> yr<sup>-1</sup> in 2050, which  
298 is about half the rate of increase in CO<sub>2</sub> forcing of 0.025-0.035 W m<sup>-2</sup> yr<sup>-1</sup> in 2050 in the mid-  
299 range RCP scenarios, illustrating how large the HFC contribution could become compared to  
300 other forcing agents if there are no controls.

301 With a HFC phaseout in 2020, a significant bank and accumulation in the atmosphere would  
302 be avoided. Their contribution to radiative forcing then always remains small, and in 2050 it  
303 is smaller than the current forcing of HFCs of about 0.02 W m<sup>-2</sup> (Velders et al., 2012).

## 304 **6. Committed climate forcing of HFC banks**

305 The buildup of the HFC banks is shown in Figure 2, and the HFC contribution to radiative  
306 forcing is depicted in Figure 4 for the reference scenarios and scenarios with a phaseout in  
307 production. The potential additional effects of collection and destruction of the HFC banks on  
308 reductions in radiative forcing are further illustrated in Figure 5 and Table S1. The effect of  
309 destroying the bank is initially zero, and increases almost immediately, as some of the banks  
310 would have been released, and then decreases rapidly. If the banks are not destroyed, the  
311 HFCs would be emitted from them in about decade, and the corresponding contribution to the  
312 atmospheric abundance would decrease according to the lifetimes of the HFCs. For example,  
313 if the bank is allowed to grow unabated until 2050 it reaches 39-64 GtCO<sub>2</sub>-eq in our baseline  
314 scenarios. If destroyed instantaneously in 2050, the radiative forcing is reduced by 0.09-0.14  
315 W m<sup>-2</sup> around 2060 and 0.03-0.05 W m<sup>-2</sup> in 2100, relative to the scenario in which the HFCs  
316 are gradually emitted from the bank but in which production is eliminated. It is evident that in

317 a scenario in which the bank destruction starts earlier, the size of the banks is smaller, as is the  
318 effect of the destruction on the radiative forcing. These reductions in radiative forcing can  
319 also be viewed as the radiative forcing that arises from the post-2020, -2030, -2040, and -2050  
320 banks if the banks were not collected and destroyed, relative to the scenarios with only a  
321 production phaseout in the same years.

322 Figures 4 and 5 show that the maximum reduction in radiative forcing is obtained with both a  
323 production phaseout and collection and destruction of the bank. In a hypothetical scenario  
324 where a production phaseout and bank destruction occurs in 2050, the radiative forcing  
325 decrease from 2050 to 2070 is 0.15-0.24 W m<sup>-2</sup>, with equal contributions from the production  
326 phaseout and bank destruction. By 2100, the radiative forcing reduces to 0.04-0.06 W m<sup>-2</sup>,  
327 with the production phaseout contributing most of the change, about 0.19-0.29 W m<sup>-2</sup>, and the  
328 bank destruction only 0.03-0.05 W m<sup>-2</sup>. The relatively greater importance of the production  
329 phaseout by 2100 occurs because once production is eliminated in 2050, most of the HFCs  
330 that originated from the 2050 bank have been destroyed by natural processes in the  
331 atmosphere. Without additional production from 2050 on, nothing further gets added to the  
332 bank after that time.

333 The effects on the radiative forcing of the production phaseout and bank destruction would be  
334 smaller when using other scenarios that have lower future HFC emissions as a reference  
335 (Gschrey et al., 2011; Meinshausen et al., 2011), but the previously unseen importance of the  
336 future bank can be expected to be similar in a relative sense when compared with cumulative  
337 production.

## 338 **7. Montreal Protocol**

339 The Montreal Protocol has controlled production and consumption of ozone-depleting  
340 substances (ODSs). The amounts of ODSs present in banks have not been regulated under the  
341 Protocol. Controlling production and consumption was easier to carry out, and it addressed  
342 key environmental effects when most of the use was emissive, so that what was  
343 produced/consumed in a given year was also emitted in the same year. We have shown here  
344 that this not true anymore for the HFCs now used as alternatives for ODSs, because the  
345 relevant applications are much less emissive and banks that persist for years are significant  
346 and will become larger if production continues. This implies new issues and considerations  
347 for policymakers if they want to control HFCs using the expertise and the institutions of the

348 Montreal Protocol, as agreed by the more than 100 countries that signed the Bali declaration  
349 in 2011 (UNEP, 2011b).

350 Earlier phaseouts of HFCs would yield benefits for climate protection that are significantly  
351 larger, about 40% in terms of GWP-weighted emissions, than estimates based on  
352 concentrations and radiative forcing in 2050 alone, due to the added impact of avoided banks.  
353 Options to reduce the use of high-GWP HFCs are available for several sectors (UNEP, 2011a,  
354 2013) and include fiber insulation materials. Non-HFC substances with low GWPs, such as  
355 hydrocarbons, ammonia, and CO<sub>2</sub> are used in some refrigeration systems. Alternative HFCs  
356 with atmospheric lifetimes on the order of days or weeks, and consequently very low GWPs,  
357 are now being introduced for foams and aerosols (e.g., HFC-1234ze) and mobile AC (e.g.,  
358 HFC-1234yf). In the selection of possible alternative substances and or technologies for high-  
359 GWP HFCs, the indirect climate effects that arise from the energy used or saved during the  
360 application or product's full life cycle needs to be considered. Policymakers could also choose  
361 to limit future emissions of HFCs by collection and destruction of banks. In that case, the  
362 accessibility of the banks is important. Halocarbons in foams are harder and more costly to  
363 collect and destroy than those present in refrigeration and AC applications (UNEP, 2009b),  
364 but foams make up only a small fraction (10-15%) of the total projected HFC bank. Also, it  
365 should be noted that the HFC banks are dispersed across the globe to a much greater extent  
366 than are the HFC production facilities, affecting the relative ease of adopting a capture and  
367 destruction approach.

## 368 **8. Conclusion**

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

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461

462

463 **Tables**

464

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

Applications	CFCs	HCFCs	HFCs
<b>Short banking times (&lt; 1 y)</b>			
Aerosol propellant	CFC-11		HFC-134a
	CFC-12		HFC-152a
	CFC-113		HFC-227ea
Cleaning agent (solvent)	CFC-113	HCFC-141b	HFC-43-10mee
		HCFC-225ca	
		HCFC-225cb	
Open cell foam blowing	CFC-11	HCFC-141b	HFC-134a
	CFC-113	HCFC-142b	HFC-152a
		HCFC-22	
<b>Medium banking times (1 to 10 y)</b>			
Refrigeration and stationary air conditioning	CFC-11	HCFC-22	HFC-23 <sup>1,2</sup>
	CFC-12		HFC-32 <sup>1</sup>
	CFC-114		HFC-125 <sup>1</sup>
	CFC-115		HFC-134a <sup>1</sup>
			HFC-143a <sup>1</sup>
Mobile air conditioning	CFC-12		HFC-134a
Fire extinguishing		HCFC-123	HFC-23
			HFC-125
			HFC-227ea
<b>Long Banking times (&gt; 10 y)</b>			
Closed cell foam blowing	CFC-11	HCFC-141b	HFC-134a
	CFC-12	HCFC-142b	HFC-245fa
		HCFC-22	HFC-365mfc

466 1) Mainly used in blends.

467 2) The largest emissions of HFC-23 occur as a byproduct of HCFC-22 production. Such  
468 emissions are not taken into account in the scenarios discussed here.

469

470 Table 2 Emissions and banks of CFCs, HCFCs, and HFCs, and emissions of CO<sub>2</sub>.

	Year (x)	Halocarbons <sup>1</sup>			CO <sub>2</sub> emission <sup>2</sup> (GtCO <sub>2</sub> -eq yr <sup>-1</sup> )
		Emission (GtCO <sub>2</sub> -eq yr <sup>-1</sup> )	Cumulative emission (1950 to x) (GtCO <sub>2</sub> -eq)	Bank (GtCO <sub>2</sub> -eq)	
CFCs	1988 <sup>3</sup>	8.8	154 <sup>4</sup>	24.6	22
HCFCs	2014 <sup>3</sup>	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

471 1) The CFC and HCFC emissions and banks are from the baseline scenarios (WMO, 2011). The HFC emissions and banks are the upper and  
472 lower ranges of the scenarios of Velders et al. (2009).

473 2) The CO<sub>2</sub> emissions are from fossil and industrial uses. The ranges are from the upper and lower RCP scenarios (Meinshausen et al., 2011).

474 3) Years with maximum emissions in the baseline scenario.

475 4) The cumulative CFC emissions from 1950 to 2014 are 226 GtCO<sub>2</sub>-eq.

476



477 **Figure Captions**

478

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

485

486 Figure 2 GWP-weighted production, bank, and emissions of halocarbons for the period 1980  
487 to 2100. Calculated direct GWP-weighted data (100-yr time horizon) are shown for the  
488 baseline scenarios of the CFCs and HCFCs (WMO, 2011) and the upper and lower ranges of  
489 the HFC scenarios from Velders et al. (2009). In these scenarios the HFC production past  
490 2050 is constant at the 2050 level. Four additional scenarios are shown in which there is a  
491 global phaseout in production of HFCs in 2020, 2030, 2040, or 2050. The GWPs used here  
492 are those used in the reference scenarios, i.e. of WMO (2011) for the CFCs and HCFCs, and  
493 IPCC (2007) for the HFCs.

494

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

500

501 Figure 4 Radiative forcing of halocarbons for the period 1980 to 2100 and increase in CO<sub>2</sub>  
502 radiative forcing from 2000. The radiative forcings of halocarbons are shown for the baseline  
503 scenarios of the CFCs and HCFCs from WMO (2011) and the upper and lower ranges of the  
504 HFC scenarios from Velders et al. (2009). In these scenarios the HFC production past 2050 is  
505 constant at the 2050 level. Four additional scenarios are shown in which there is a global

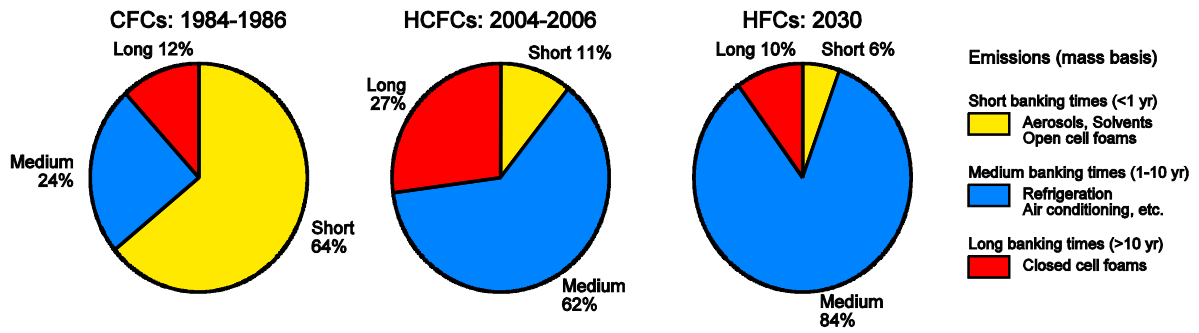
506 production phaseout of HFCs in 2020, 2030, 2040, or 2050, as in Figure 2. No bank  
507 destruction is assumed. For CO<sub>2</sub> the radiative increases relative to 2000 are shown for the four  
508 RCP scenarios (Meinshausen et al., 2011). The radiative forcing values for the halocarbons  
509 represent net changes from the start of the industrial era (ca. 1750) to present.

510

511 Figure 5 Reductions in radiative forcing from destruction of the HFC banks in 2020, 2030,  
512 2040, or 2050 relative to the case with only a production phaseout in that same year. This is  
513 equivalent to the radiative forcing contribution from the HFC bank post-2020, -2030, -2040,  
514 and -2050 in the production-phaseout scenarios. This reduction plus the production phaseout  
515 gives the maximum possible mitigation, i.e. the zero emissions scenario. The ranges  
516 correspond to the upper and lower HFC reference scenarios from Velders et al. (2009).

517

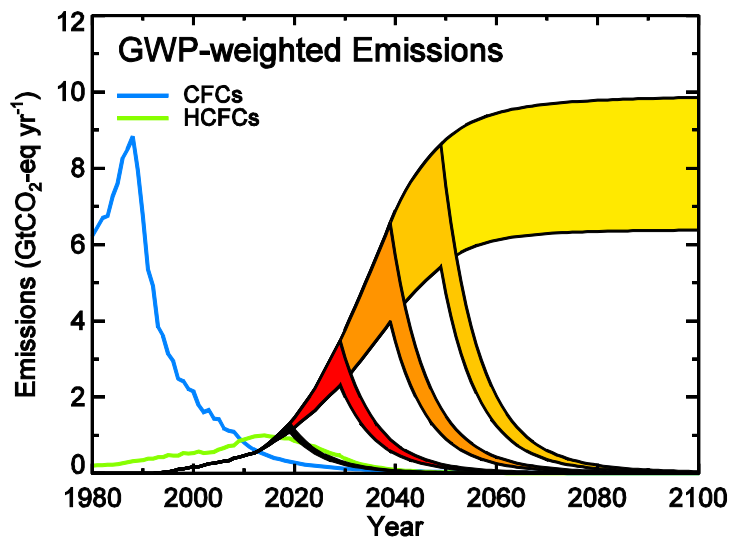
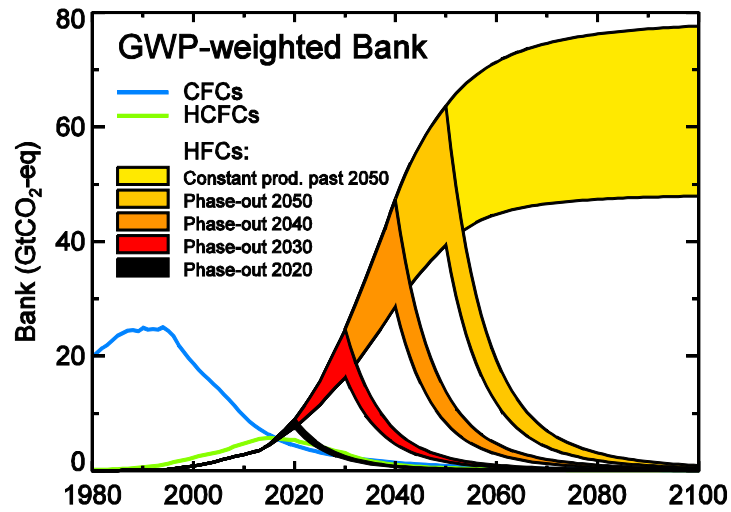
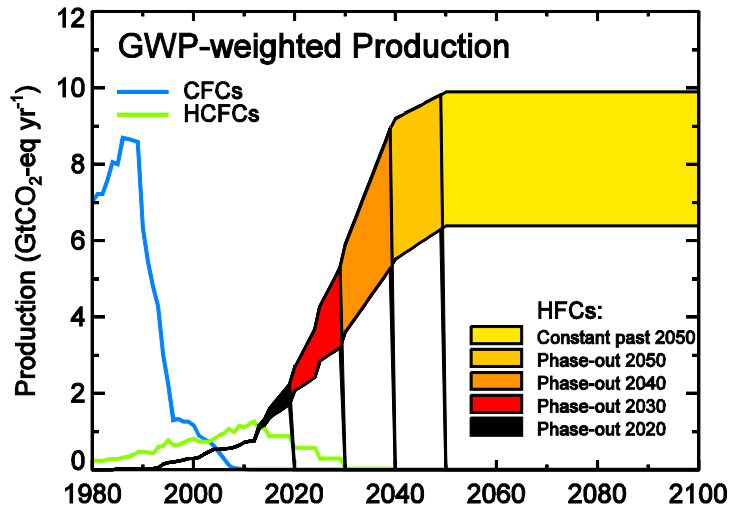
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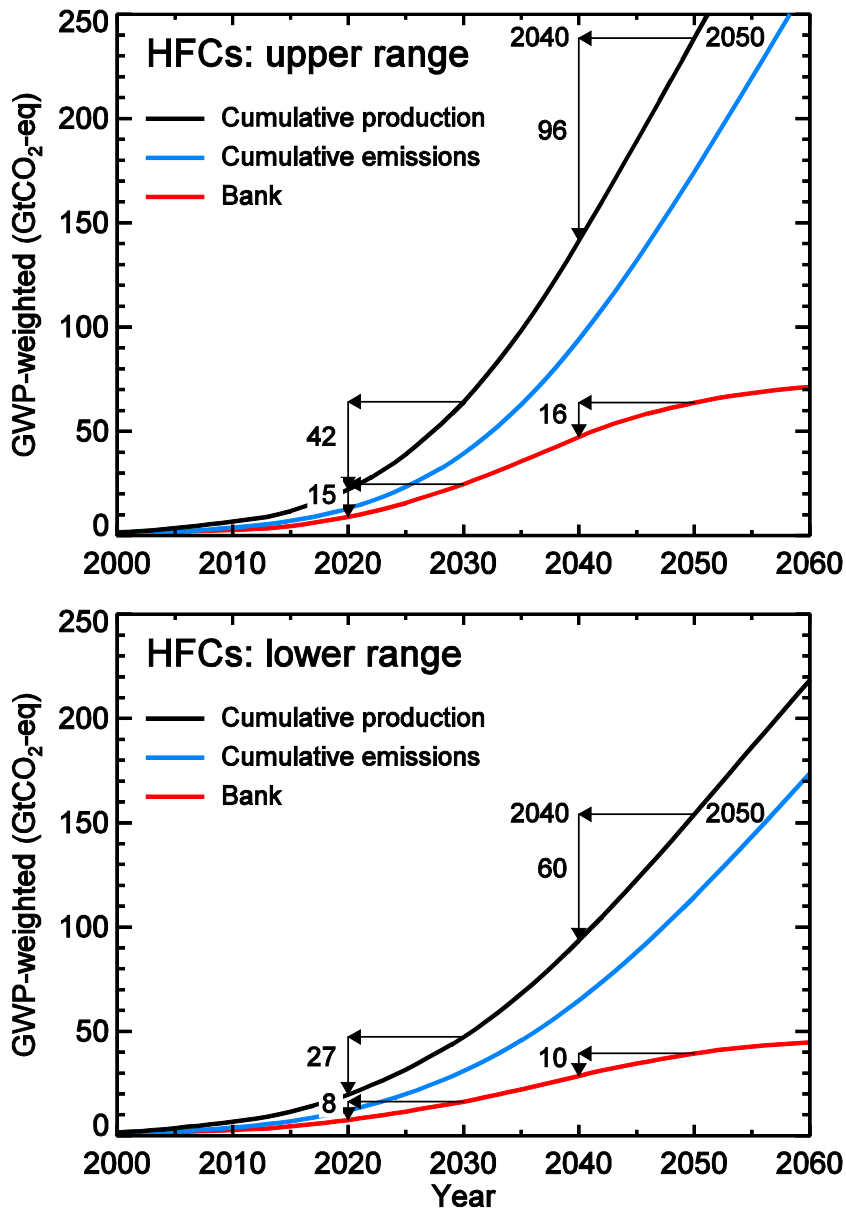
520 Figure 1

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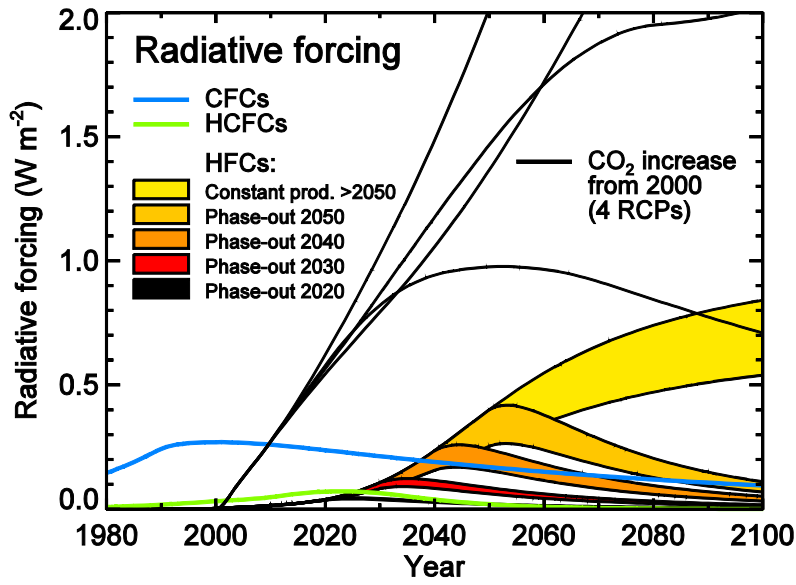
523 Figure 2



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526 Figure 3

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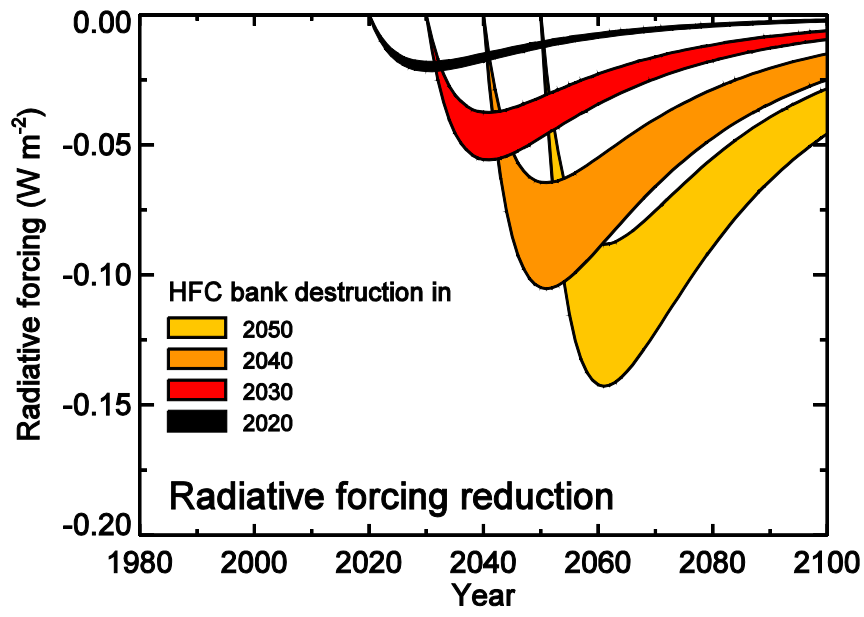


529

530 Figure 4

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532



533

534 Figure 5

535