

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 GtCO₂-eq of cumulative emission be avoided from 2020 to 2050, but an additional bank of
31 about 39-64 GtCO₂-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

ozone, and now increasingly with HFCs, which do not deplete ozone at all. The contributions of emissions of HCFCs and HFCs to climate change depend upon their atmospheric lifetimes and radiative efficiencies and thereby on their Global Warming Potentials (GWP_s), as well as the total emission and hence the abundance. The GWP is an index comparing the integrated radiative forcing of an emission of a greenhouse gas, integrated over typically one hundred years, relative to that of emitting the same mass of carbon dioxide (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 years) and GWPs 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 (see Section 7). HCFCs are now scheduled to be phased out globally in 2040, and are already being replaced by HFCs (as well as by 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 in concentrations implies a growing contribution of HFCs to radiative forcing of climate change, which could become substantial in comparison to carbon dioxide under some circumstances (Gschat et al., 2011; Velders et al., 2009; Velders et al., 2012).

CFCs used in rapid-release applications, like spray cans and solvents, were largely replaced with not-in-kind alternatives right away after environmental concerns were recognized. Because of these same concerns, HCFCs and HFCs were always only used in limited amounts for rapid-release applications. Figure 1 shows that the substitution of CFCs with HCFCs and HFCs 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. In several previous HFC scenario studies (Velders et al., 2009; Velders et al., 2012; Gschrey et al., 2011; IPCC/TEAP, 2005; Meinshausen et al., 2011; UNEP, 2009a) banks have been considered in the modelling approach, but the focus in discussing climate change effects was only on emissions and radiative forcing, and the fact that the time lag between production and emissions results in a bank and associated hidden 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 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 CO₂-equivalent (CO₂-eq) production, emissions, and bank sizes, using
218 GWPs with a 100-yr time horizon. CO₂-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 CO₂-
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 CO₂-eq
223 emissions, the shorter lifetimes of HFCs (compared with the atmospheric residence time of
224 CO₂) 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 CO₂ 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 GtCO₂-eq around 1990, while the HFC banks are
239 projected to have the potential to reach more than twice this size, about 50-80 GtCO₂-eq, at
240 the end of the 21th 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 CO₂ emissions.
249 The CFC annual GWP-weighted emissions were about 40% of the annual CO₂ emissions in
250 1988, while the CFC bank in that year was slightly larger than the annual CO₂ emissions,
251 implying that another year's worth of CO₂-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 CO₂
253 emissions (RCP8.5) in 2050 and 75% for the CO₂ scenario with strong mitigation (RCP3PD).
254 In these scenarios, the HFC bank grows to 39-64 GtCO₂-eq compared with an annual CO₂
255 emission of 12-74 GtCO₂-eq yr⁻¹ 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 CO₂-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 GtCO₂-eq from 2020 to 2050, while a bank of about 39-64 GtCO₂-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 underestimate 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 GtCO₂-eq of avoided production, of which 50-80
275 GtCO₂-eq is manifested in avoided emission and 10-16 GtCO₂-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 21th century, and may reach
284 values of more than 0.5 W m⁻².

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⁻² in 2054 to 0.07-0.11
291 W m⁻² in 2100. However, this is still more than 0.4 W/m² 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 CO₂ 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⁻² yr⁻¹ in 2050, which
298 is about half the rate of increase in CO₂ forcing of 0.025-0.035 W m⁻² yr⁻¹ 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⁻² (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 GtCO₂-eq in our baseline
314 scenarios. If destroyed instantaneously in 2050, the radiative forcing is reduced by 0.09-0.14
315 W m⁻² around 2060 and 0.03-0.05 W m⁻² 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 $0.15\text{-}0.24 \text{ W m}^{-2}$, with equal contributions from the production
326 phaseout and bank destruction. By 2100, the radiative forcing reduces to $0.04\text{-}0.06 \text{ W m}^{-2}$,
327 with the production phaseout contributing most of the change, about $0.19\text{-}0.29 \text{ W m}^{-2}$, and the
328 bank destruction only $0.03\text{-}0.05 \text{ W m}^{-2}$. 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 CO₂ 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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463 **Tables**

464

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

Applications	CFCs	HCFCs	HFCs
Short banking times (< 1 y)			
Aerosol propellant	CFC-11		HFC-134a
	CFC-12		HFC-152a
	CFC-113		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 y)			
Refrigeration and stationary air conditioning	CFC-11 CFC-12 CFC-114 CFC-115	HCFC-22	HFC-23 ^{1,2} HFC-32 ¹ HFC-125 ¹ HFC-134a ¹ HFC-143a ¹
Mobile air conditioning	CFC-12		HFC-134a
Fire extinguishing		HCFC-123	HFC-23 HFC-125 HFC-227ea
Long Banking times (> 10 y)			
Closed cell foam blowing	CFC-11 CFC-12 HCFC-22	HCFC-141b HCFC-142b HFC-365mfc	HFC-134a HFC-245fa 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 CO₂.

		Halocarbons ¹			
	Year (x)	Emission (GtCO ₂ -eq yr ⁻¹)	Cumulative emission (1950 to x) (GtCO ₂ -eq)	Bank (GtCO ₂ -eq)	CO ₂ emission ² (GtCO ₂ -eq yr ⁻¹)
CFCs	1988 ³	8.8	154 ⁴	24.6	22
HCFCs	2014 ³	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 CO₂ 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 GtCO₂-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 CO₂
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

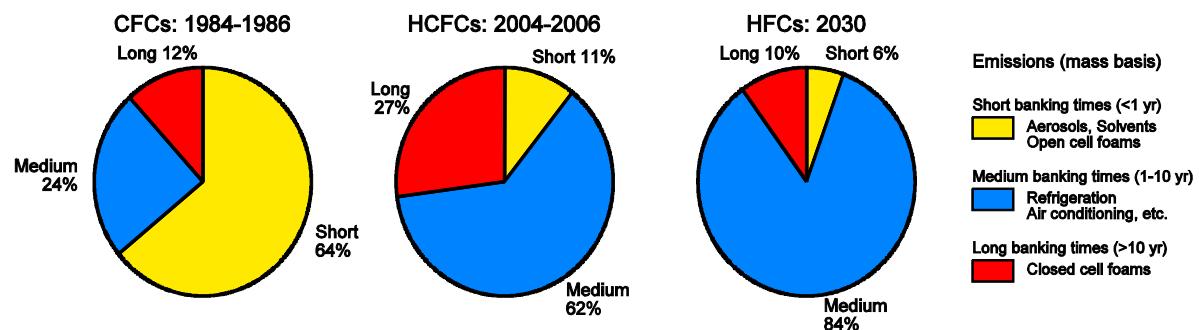
506 production phaseout of HFCs in 2020, 2030, 2040, or 2050, as in Figure 2. No bank
507 destruction is assumed. For CO₂ the radiative increases relative to 2000 are shown for the four
508 RCP scenarios (Meinshausen et al., 2011). The radiative forcing values for the halocarbons
509 represent net changes 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).

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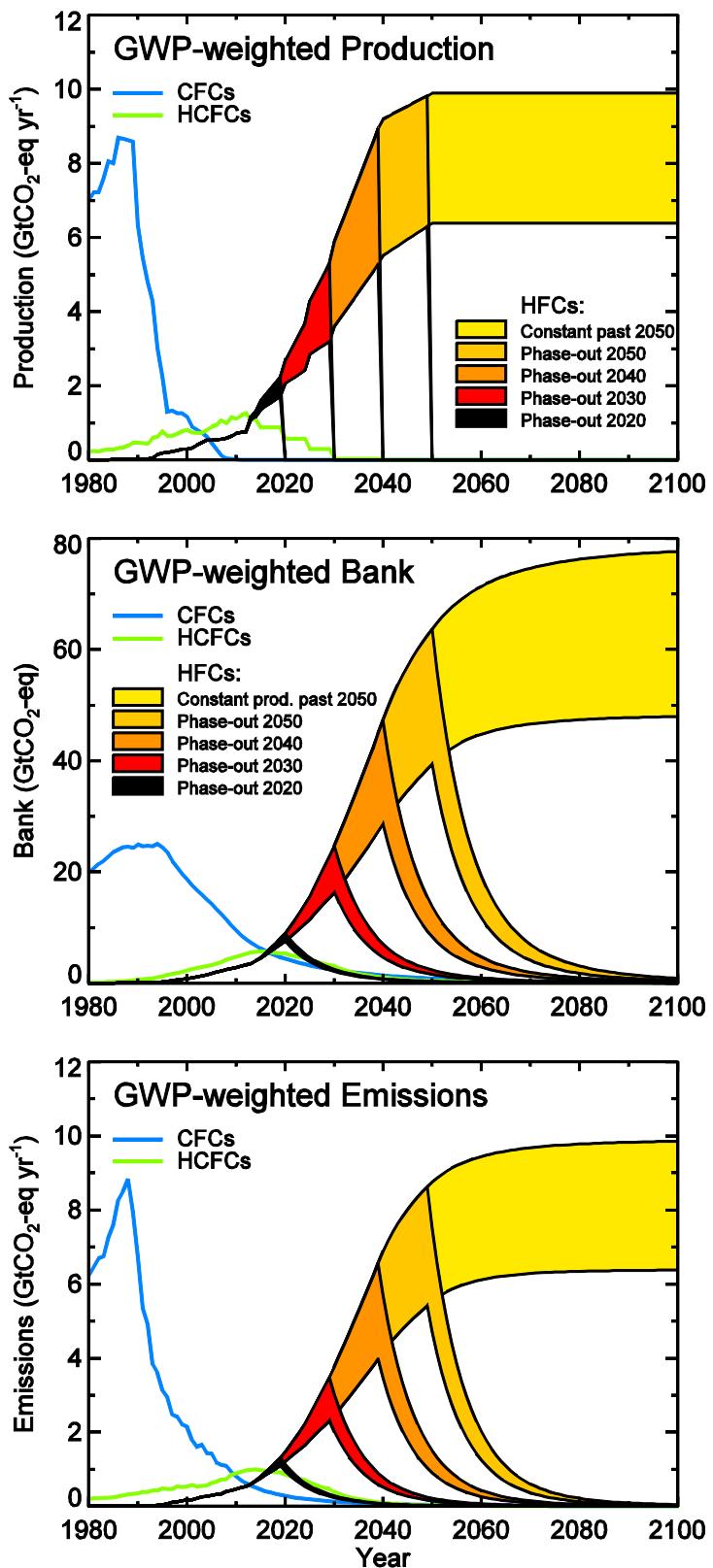
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520 Figure 1

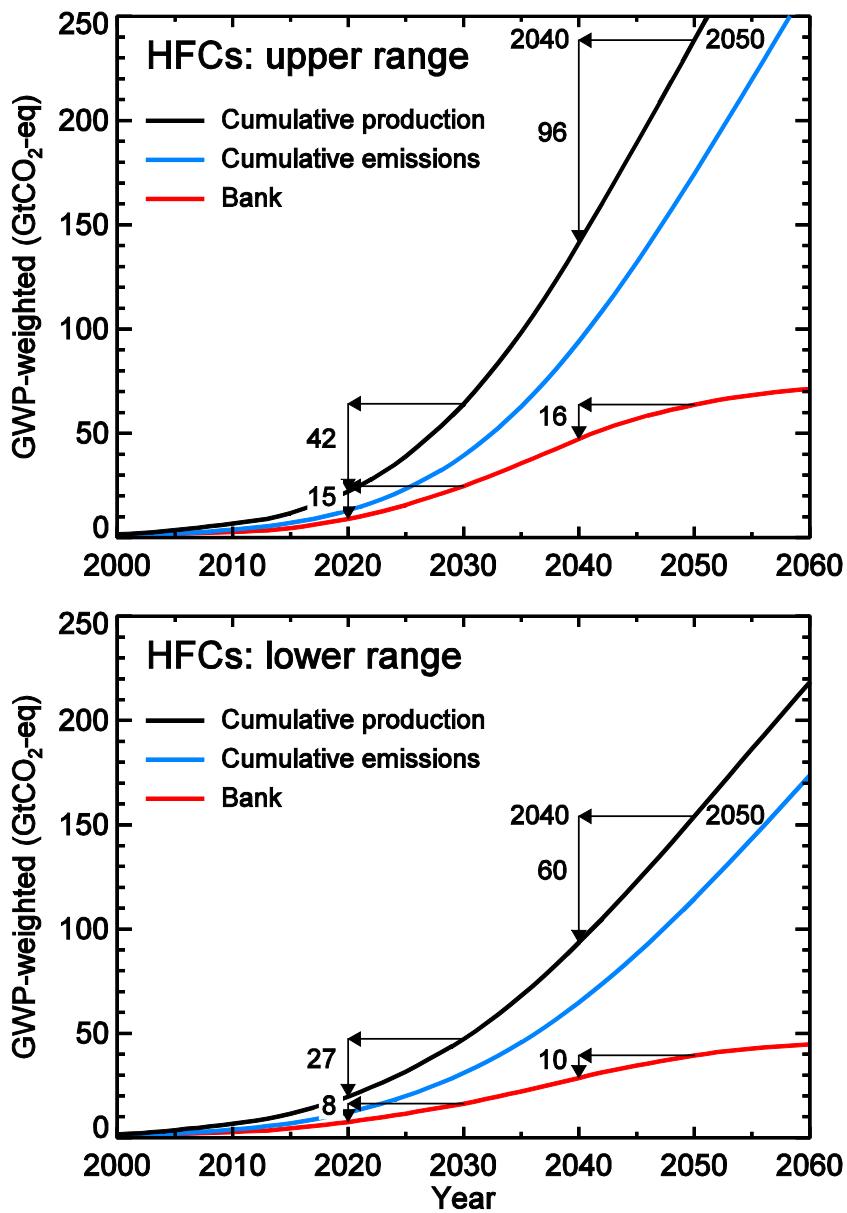
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523 Figure 2

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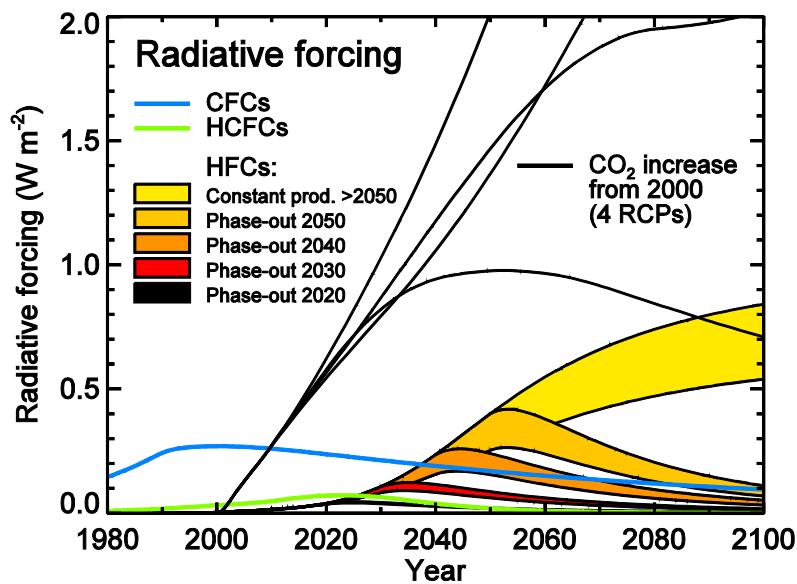


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526 Figure 3

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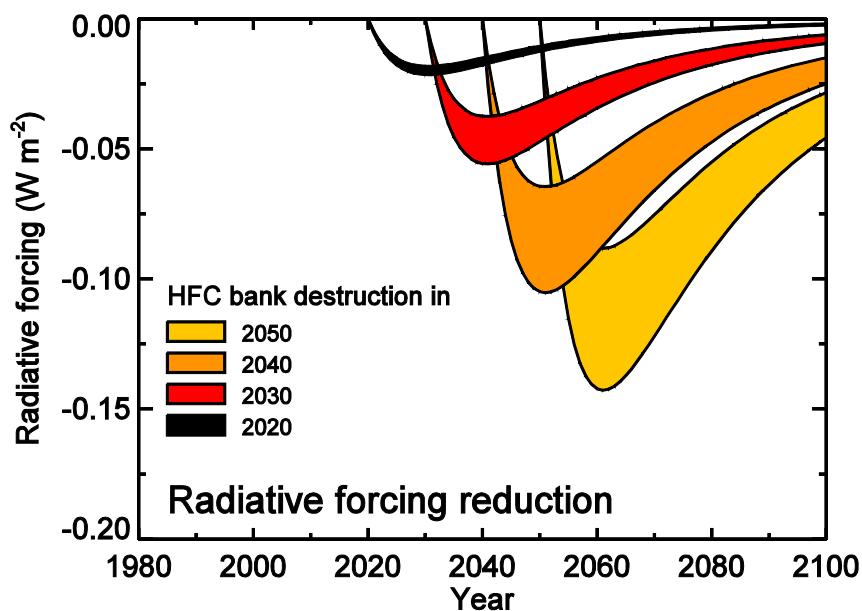


529

530 Figure 4

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532



533

534 Figure 5

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