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The role of HFCs in mitigating 21st century climate change

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Abstract. There is growing international interest in mitigating climate change during the early part of this century by reducing emissions of short-lived climate pollutants (SLCPs), in addition to reducing emissions of CO_2. The SLCPs include methane (CH_4), black carbon aerosols (BC), tropospheric ozone (O_3) and hydrofluorocarbons (HFCs). Recent studies have estimated that by mitigating emissions of CH_4, BC, and O_3 using available technologies, about 0.5 to 0.6 °C warming can be avoided by mid-21st century. Here we show that avoiding production and use of high-GWP (global warming potential) HFCs by using technologically feasible low-GWP substitutes to meet the increasing global demand can avoid as much as another 0.5 °C warming by the end of the century. This combined mitigation of SLCPs would cut the cumulative warming since 2005 by 50 % at 2050 and by 60 % at 2100 from the CO_2-only mitigation scenarios, significantly reducing the rate of warming and lowering the probability of exceeding the 2 °C warming threshold during this century.

1 Introduction

The ozone depleting substances (ODSs) (e.g., chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs)), halons, and HFCs are part of a family of gases known as halocarbons. Halocarbons are used as refrigerants, propellants, cleaning and foam blowing agents, and fire extinguishers, etc. Molina and Rowland (1974) identified the potent stratospheric ozone depleting effects of CFCs. This was followed, within a year, by the discovery of the potent greenhouse effect of the halocarbons CFC-11 and CFC-12 (Ramanathan, 1975). Many studies confirmed this finding and estimated that the global warming potential (GWP) of CFC-11 and CFC-12 (using a 100 yr time horizon) at 4750 and 10 900 respectively, as summarized by the Intergovernmental Panel on Climate Change Fourth Assessment Report (Forster et al., 2007). Ramanathan (1975) set the stage for identifying numerous other non-CO_2 greenhouse gases (GHGs) in the atmosphere such as CH_4 and O_3 among others (see Wang et al., 1976 and Ramanathan et al., 1985a). The first international assessment of the climate effects of non-CO_2 gases was conducted in 1985 (Ramanathan et al., 1985b) and it concluded that CO_2 was the dominant contributor to greenhouse forcing until 1950s, and since the 1960s non-CO_2 gases have begun to contribute as much as CO_2. A more recent list of the non-CO_2 GHGs can be found in Pinnock et al. (1995) and Forster et al. (2007).

Most of HFCs now in use, along with CH_4, O_3, and BC (black carbon aerosols), have relatively short lifetimes in the atmosphere in comparison with long-lived GHGs, such as CO_2 and N_2O (nitrous oxide) (e.g., see Smith et al., 2012), and are therefore referred to as short-lived climate pollutants (SLCPs). The lifetime of BC is several days to weeks, tropospheric O_3 is a few months, and CH_4 is about 12 yr. The global average lifetime, weighted by the production of the various HFCs now in commercial use, is about 15 yr, with a range of 1 to 50 yr (Table 1). Because the lifetimes of the SLCPs are much shorter than that of CO_2, a significant portion of which remains in the atmosphere for centuries to millennia, the radiative forcing by SLCPs will decrease significantly within weeks to a few decades after their emissions are reduced.

Motivated by modeling studies (e.g., Ramanathan and Xu, 2010; Shindell et al., 2012), policy makers are showing

Table 1. Indicative applications using HFCs*.

HFC	Indicative applications UNEP and WMO (2011)	Lifetime WMO (2011)	100 yr GWP WMO (2011)
HFC-134a	Mobile and stationary air conditioning and refrigeration, foams, medical aerosols and cosmetic and convenience aerosol products	13.4	1370
HFC-32	In blends for refrigeration and air conditioning	5.2	716
HFC-125	In blends for refrigeration and air conditioning	28.2	3420
HFC-143a	In blends for refrigeration and air conditioning	47.1	4180
HFC-152a	Foams, aerosol products	1.5	133
HFC-227ea	Foams, medical aerosols, fire protection	38.9	3580
HFC-245fa	Foams	7.7	1050
HFC-365mfc	Foams	8.7	842
HFC-43-10mee	Solvents	16.1	1660

* HFC-23 is not included in the scenarios discussed here. Although it is currently the second most abundant HFC in the atmosphere, it is assumed that the majority of this chemical is produced as a byproduct of HCFC-22 production and not because of its use as a replacement for CFCs and HCFCs. Hence, the emissions of HFC-23 depend on a different set of assumptions than the other HFCs (Velders et al. 2009). Miller and Kuijpers (2011) estimated that HFC-23 emissions increase could contribute 0.014 W m^{-2} to radiative forcing in 2050. Therefore, the contributed warming due to potential HFC-23 will be only about 0.01 °C by our estimation.

increasing interest in fast-action climate mitigation strategies that target SLCPs (Wallack and Ramanathan, 2009; Molina et al., 2009). Ramanathan and Xu (2010) (hereafter RX10) concluded that as much as 0.6 °C warming can be avoided by mid-21st century using current technologies to reduce all four SLCPs, with mitigation of HFCs contributing about 20 % (0.1 °C) to the avoided warming by 2050. Furthermore, RX10 also showed that exceeding the 2 °C warming threshold can be delayed by three to five decades beyond 2050 by these efforts. Based on an international assessment commissioned by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) (UNEP and WMO, 2011), Shindell et al. (2012) used a 3-dimensional climate model to account for reductions in CH_4, O_3, and BC emissions (but not HFCs) using mitigation scenarios similar to those employed in RX10. UNEP and WMO (2011) as well as Shindell et al. (2012) calculated the avoided warming to be 0.5($\pm$ 0.05) °C by 2070. This estimate is consistent with RX10, which would also yield 0.5 °C avoided warming if only CH_4, O_3, and BC were mitigated. All three studies calculated that full implementation of mitigation measures for these three SLCPs can reduce the rate of global warming during the next several decades by nearly 50 %. Furthermore, Arctic warming can be reduced by two-thirds over the next 30 yr compared to business as usual (BAU) scenarios (UNEP and WMO, 2011).

However, with the exception of the RX10 study, HFCs have thus far not been included in analyses of the temperature mitigation benefit from SLCP mitigation. Even RX10 did not recognize the full potential of the radiative forcing increase, as shown recently by Velders et al. (2012), due to an unconstrained use of HFCs toward the end of this century. Therefore, what has been missing in the previous studies is the potentially large increase in HFC use. The present study builds upon RX10 to further account for the newly developed projections of HFC emissions and provides a detailed analysis of the implication of HFC mitigation on global temperature.

2 Methods

2.1 HFC emission projection

Because of their catalytic destruction of stratospheric ozone, production and consumption of CFCs, HCFCs and other ODSs are being phased out under the Montreal Protocol (Andersen and Sarma, 2002; Andersen et al., 2007). With the phase-out of CFCs under the Montreal Protocol completed in 1996 in developed countries and in 2010 in developing countries (UNEP, 2010), and with the scheduled phase-out of HCFCs by 2030 in developed countries, and 2040 in developing countries (UNEP, 2007), HFCs are increasingly being used as alternatives in applications that traditionally used CFCs, HCFCs and other ODSs to meet much of the demand for refrigeration, air conditioning, heating and thermal-insulating foam production (Velders et al., 2012). HFCs do not destroy the ozone layer (Ravishankara et al., 1994) but are potent GHGs (Velders et al., 2009).

The demand for HFCs is expected to increase in both developed and developing countries, especially in Asia, in the absence of regulations, as is the demand for HCFCs for feedstock (Velders et al., 2009). HFCs are the fastest growing GHGs in the US, where emissions grew nearly 9 % between 2009 and 2010 compared to 3.6 % for CO_2 (EPA, 2012). Globally, HFC emissions are growing 10 to 15 % per year and are expected to double by 2020 (WMO, 2011; Velders et al., 2012). The presence of HFCs in the atmosphere results almost completely from their use as substitutes for ODSs (Table 1).

The future HFC projection in this study is estimated using (1) the growth rates of gross domestic product (GDP) and populations from the Special Report on Emissions Scenarios (SRES) (IPCC, 2000), and (2) the replacement patterns of ODSs with HFCs and not-in-kind technologies as observed in the past years in Western countries. We assumed that these replacement patterns will stay constant and will hold for developing countries. The European Union regulation (842/2006) aimed at moving away from high-GWP HFCs is also included in the HFC projections used here. Readers are referred to Velders et al. (2009) for more details in HFC scenario development (e.g., emissions by substance, region and years). Because the projected forcing from HFC-23 is much smaller than that from intentionally produced HFCs, it is not included in this study. In spite of potential large increases in HFC-23 from the continued production of HCFC-22 for feedstock, the HFC-23 forcing in 2050 is 0.014 W m^{-2} (Miller and Kuijpers, 2011) and the associated warming is only about 0.01 °C.

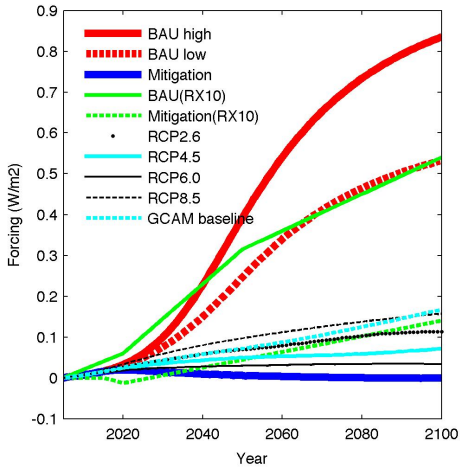

Fig. 1. HFC radiative forcing change (W m^{-2}) since the year of 2005. Note we include both upper (red solid line) and lower limits (red dash line) of HFC growth under BAU scenarios. The scenarios previously adopted in RX10 and from various other sources are shown for reference.

2.2 Other emission projection

The future emission scenarios of CO_2 are adopted from the Representative Concentration Pathway (RCP, van Vuuren et al., 2011) database. We take RCP 2.6 (van Vuuren et al., 2007) as mitigation case and RCP 6.0 (Hijioka et al., 2008) as BAU case for CO_2. CO_2 emissions in the mitigation case will decline by half in mid-21st century, while the BAU CO_2 emissions are projected to continue to increase until 2080. The peak CO_2 atmospheric concentration is 660 and 440 ppm under BAU and mitigation cases, respectively. We note that CO_2 scenarios under RCP 6.5 and 2.6 may have different assumptions with regard to emission sectors and therefore the difference between those two pathways may not directly represent the effect of mitigation efforts. The SLCP projections, except for HFCs, are retained from RX10. Under a BAU scenario, CH_4 emissions are predicted to rise by 40 % in 2030, and BC emissions are projected to increase by 15 % by 2015 and then level off. The mitigation scenarios follow recommendations from studies by the International Institute for Applied Systems Analysis (IIASA) (Cofala et al., 2007) and the Royal Society (2008) that maximum feasible reductions of air pollution regulations can result in reductions of 50 % in CO emissions and 30 % in CH_4 emissions by 2030, as well as reductions of 50 % in BC emissions by 2050.

2.3 Models

The model used in RX10 is an integrated carbon and radiant energy balance model. It adopts the Bern CO_2 geochemistry model (Joos et al., 1996) to estimate the atmospheric CO_2 concentration from emissions. The model links emissions of pollutants with their atmospheric concentrations and the change in the radiative forcing. The carbon-geochemistry model is then integrated with an energy balance climate model with a 300 m ocean mixed layer and a climate sensitivity of 0.8 (0.5 to 1.2) °C/(W m^{-2}) to simulate the temporal evolution of global mean surface temperature. The model also accounts for historical variations in the global mean radiative forcing to the system attributable to natural factors, GHGs and air pollutants including sulfates, nitrates, carbon monoxide, ozone, BC, and organic carbons. The model is capable of simulating the observed historical temperature variations (Fig. 2), as well as the historical CO_2 concentration and ocean heat content (Box 1 in RX10).

3 Results and discussions

3.1 Large increase of HFC forcing

The radiative forcing of HFCs in 2008 was small at less than 1 % of the total forcing from long-lived GHGs (WMO, 2011). However, without fast action to limit their growth, the radiative forcing of HFCs could increase from nearly 0.012 W m^{-2} in 2010 to up to 0.4 W m^{-2} in 2050 (BAU high in Fig. 1). The 0.4 W m^{-2} is equal to nearly 30 to 45 % of CO_2 forcing increase by 2050 (if CO_2 follows BAU and mitigation scenarios, respectively; see Sect. 2.2 for scenario descriptions), or about the same forcing contributed by current CO_2 emissions from the transportation sector (IEA, 2011). In the scenarios discussed here, the demand for HFCs for the period 2050 to 2100 is assumed to maintain at the 2050 levels (assuming complete market saturation), which results in increasing HFC abundances and radiative forcing past 2050, with HFC forcing possibly reaching as high as 0.8 W m^{-2} in 2100 (BAU high in Fig. 1).

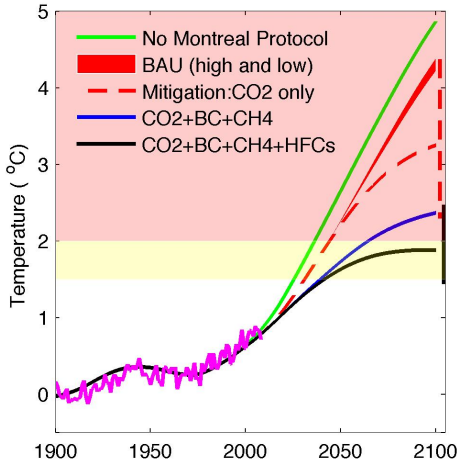

Fig. 2. Model simulated temperature change under various mitigation scenarios that include CO_2 and SLCPs (BC, CH_4, HFCs). BAU case (red solid line with spread) considers both high and low estimates of future HFC growths (as shown in red solid and dash lines in Fig. 1). Note this uncertainty of temperature projection related to HFC scenarios is around 0.15 °C at 2100. The vertical bars next to the curve show the uncertainty of temperature projection at 2100 due to climate sensitivity uncertainty. For simplicity, we only show the cases of CO_2 mitigation (red dash line) and full mitigation (black line).

We also calculate HFC forcing from emission data provided by the RCP database and compare them with our forcing projections. Similar comparisons of future emission and forcing are also shown in Fig. 5.5 of the WMO (2011) assessment. However, a direct comparison is difficult, because with the exception of RCP 8.0 (Riahi et al., 2007), the scenarios include various mitigation policies as assumptions and therefore cannot be considered as "BAU" scenarios. The Global Change Assessment Model (GCAM) group that produces RCP 4.5 (Wise et al., 2009; Thomson et al., 2011) does, however, make available a "BAU" scenario (GCAM baseline in Fig. 1), which does not include explicit mitigation actions (Smith et al., 2011). As a result, HFC forcing is two times larger in the GCAM baseline scenario than the associated RCP 4.5 scenario. The HFC BAU projections used in this study are substantially higher over the long-term than the projections of other studies, including RCP 8.0 and GCAM baseline. In the GCAM baseline, for example, HFC forcing increase from 2005 is less than 0.2 W m^{-2} in 2100, as compared to 0.5 to 0.8 W m^{-2} in our BAU scenarios.

There are several reasons for the discrepancies in HFC projections. (1) HFC scenarios have not received much attention in the development of the RCP database. Individual integrated assessment modeling groups have adopted various assumptions and techniques in developing those RCP projections and associated reference scenarios. However, detailed descriptions of HFC projection in RCPs and associated reference scenarios are not available in relevant papers, which are more focused on long-lived GHGs. (2) Most, if not all, of the RCP scenarios for HFCs were developed before 2007. Therefore, they did not take into account the accelerated HCFC phase-out in both developing and developed countries agreed by the parties at the 19th Meeting of the Parties to the Montreal Protocol in September 2007, which will lead to lower future HCFC emissions and higher HFC emissions (Meinshausen et al., 2011). (3) At least some RCP scenarios did not take into account the large observed growth in HFC use and atmospheric concentrations since 2000 (WMO, 2011). The linear growth in RCP scenarios (Fig. 1 and also see Fig. 3.22 of Clarke et al., 2007) is distinctly different from the assumptions of a growing market in developing countries, which was the basis of our HFC scenario. (4) Finally, another recent HFC scenario up to 2050 (Gschrey et al., 2011), which includes detailed market analysis, also shows emissions much higher than RCPs, but smaller than ours. The smaller emissions in Gschrey et al. (2011) compared to ours are the result of two assumptions: first, a larger fraction of non-fluorocarbon alternatives in several sectors; and second, and second, the market saturation in several sectors after about 2030, 10 yr earlier than in our scenarios, which considered consumption saturation for a few sectors at 2040 (Fig. 1b of Velders et al., 2009) and a complete saturation after 2050. Note that the emission of HFCs will continue increasing for a short time period after the market saturation at 2050, and the mixing ratio and forcing of HFC will further grow toward end of 21st century (Fig. 1). We acknowledge that some RCP models project HFC in a detailed method (e.g., by gas and sector based on the evolution of multiple drivers over time including vehicle demand, building air-conditioning use, etc.). Some RCP models and Gschrey et al. (2011) have also assumed some emission drivers do not scale with GDP over the long-term due to saturation effects (e.g., floor space of buildings), which could be even more important on a century timescale. The differences in considering saturation effects may be a reason that our projections yield larger emissions.

In conclusion, differences in HFC scenarios arise from large differences in their underlying assumptions and to the level they take into account recent information. HFC projections in some RCP scenarios do not use the more recent information as in Velders et al. (2009) and Gschrey et al. (2011). The scenarios in Velders et al. (2009) are based on assumptions similar to those of IPCC-SRES with respect to growth rates in GDP and population, but have incorporated new current information on (1) reported recent increases in consumption of HCFCs in Article 5 (developing) countries of about 20 % per year (through 2007), (2) replacement patterns of HCFCs by HFCs as reported in non-Article 5 (developed) countries, and (3) accelerated phase-out schedules of HCFCs in Article 5 and non-Article 5 countries (2007 Adjustment of the Montreal Protocol). We note that this HFC scenario is not necessarily a more accurate forecast of future HFC emissions than other scenarios, but a projection of what can happen if

developed countries continue current practices in replacing ODSs with HFCs and if developing countries follow this path as well.

In contrast to the large increase under BAU scenarios, replacing those HFCs currently in use with low-GWP HFC alternatives that have lifetimes of less than one month can eliminate future HFC forcing increase (Velders et al., 2012). Under the mitigation scenario, the total HFC radiative forcing in 2050 would be less than its current value (Mitigation in Fig. 1). Alternatives with no direct impact on climate, including ammonia, carbon dioxide, and hydrocarbons, as well as low-GWP HFCs and not-in-kind alternatives, are already in commercial use in a number of sectors. For other sectors, alternatives are being evaluated or further developed (UNEP, 2011). The calculation of climate mitigation assumes that the selected alternatives do not compromise energy efficiency, an assumption that appears reasonable in light of the historic trend of increased energy efficiency when chemicals are phased out under the Montreal Protocol (Andersen and Morehouse, 1997; Andersen and Sarma, 2002; Andersen et al., 2007).

3.2 Implication for global temperature

The simulated temperature trends (Fig. 2) agree with the earlier studies (Shindell et al., 2012; UNEP and WMO, 2011) that combined mitigation of CH_4, BC and O_3 can mitigate 0.5 °C of warming by the mid-century. It also agrees with RX10 that HFCs contribute about 0.1 °C to the avoided warming of 0.6 °C by 2050 and that SLCPs are critical for limiting the warming below 2 °C. CO_2 mitigation, although begun in 2015, has very little effect for the near-term (see difference between red solid line and red dash line in Fig. 2). Focusing on the longer timescale of the end of the century (Fig. 2), CO_2 mitigation plays a major role in reducing additional warming by as much as 1.1 °C by 2100. Next, the combined measures (CO_2, CH_4, BC and O_3) considered in UNEP and WMO (2011) and Shindell et al. (2012) are not sufficient to limit the warming below 2 °C (blue line in Fig. 2), had these studies included the updated projected HFC growth patterns of Velders et al. (2009) in their BAU scenarios. Mitigation of the potential growth of HFCs is shown to play a significant role in limiting the warming to below 2 °C and could contribute additional avoided warming of as much as 0.5 °C by 2100 (blue and black line in Fig. 2). Using the lower limits of BAU increase of HFC (red dash line in Fig. 1), 0.35 °C warming will be avoided.

The results are consistent with RX10 for the near-term, but the avoided warming from HFCs towards the end of the century is 100 % higher in this study, due to the updated forcing scenarios accounting for the high HFC growth rate (green lines in Fig. 1 for a comparison with RX10 forcing scenarios). Replacing HFCs with available low-GWP substitutes that have a lifetime of one month or less, or with other materials or technologies, can provide up to 0.35 to 0.5 °C of warming mitigation by 2100 in the scenarios used here. The important point to note is that assessing the role of HFCs in climate change depends on what BAU (i.e., reference/baseline) scenarios the climate models assume for HFCs in their simulations. Many climate models assume much smaller growth of HFC emission, because of the implicit assumption that replacements with low impact on climate for high-GWP HFCs will be adopted extensively during this century, an assumption that largely depends on the extent of policy interventions, as well as technological and economic developments. Our study, however, shows that if current growth rates of high-GWP HFCs continue, the additional warming from HFCs alone will be as much as 0.5 °C during this century. The potential temperature mitigation by the end of this century, from HFC replacement, is in addition to the 1 °C potential mitigation from other SLCP reductions (Fig. 2; also see RX10). When mitigation effort to reduce high-GWP HFCs is combined with that on BC and CH_4, 0.6 °C warming can be avoided by 2050 and 1.5 °C by 2100 (black solid line vs. red dash line in Fig. 2). This would cut the cumulative warming since 2005 by 50 % at 2050 and by 60 % at 2100 from the corresponding CO_2-only mitigation scenarios (red dash line in Fig. 2). Based on our high HFC growth scenarios, the contribution to the avoided warming at 2100 due to HFC emission control is about 40 % of that due to CO_2 emission control. Considering the near-term (2050) timescale, HFC emission is even more effective (140 % of CO_2 mitigation) in curbing the warming. Given the limited knowledge regarding climate sensitivity (0.5 to 1.2 °C/(W m^{-2})), the absolute value of projected temperature at the end of 21st century is also uncertain (vertical bars in Fig. 2), but the relative contribution of HFC to reducing the warming is still significant and less subject to such uncertainty.

4 Conclusions

The concept of "short-lived climate pollutants" highlights the shorter lifetime of those pollutants (including HFCs) as compared to long-lived GHGs (including CO_2 and CFCs). Our paper demonstrates the benefits of replacing high-GWP HFCs with low-GWP alternatives, so the overall forcing and associated warming due to HFC growth can be significantly reduced. The results presented here could strengthen the interest of policymakers in promoting fast-action strategies to reduce SLCPs, including HFCs, as a complement to immediate action to reduce CO_2 emissions. There are several policy options for limiting HFC growth, separate from those for BC and CH_4, including using the Montreal Protocol to phase down the production and consumption of HFCs (Molina et al., 2009; UNEP, 2012a, b), which would preserve the climate benefits the treaty has already achieved through its success in phasing out nearly 100 similar chemicals (Velders et al., 2007, 2012). Without the

Montreal Protocol, the projected radiative forcing by ODSs would have been roughly 0.65 W m^{-2} in 2010 (Velders et al., 2007), and the global temperature would have been higher (green line in Fig. 2). It is also important to emphasize that HFC mitigation should not be viewed as an "alternative" strategy for avoiding the 2 °C warming, but rather as a critical component of a strategy that also requires mitigation of CO_2 and the other SLCPs. The focus of this study is on near-term warming over the next several decades to end of the century. For the longer-term (century and beyond), mitigation of CO_2 would be essential for a significant reduction in the warming.

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