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Atmospheric Chemistry and Physics Discussions



# Avoiding HFC growth is critical for keeping global warming below 2 °C during the 21st century

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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 end of the century, therefore 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]), 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. The potent stratospheric ozone depleting effects of CFCs were identified in 1974 (Molina and Rowland, 1974). This was followed, within a year, by the discovery of the potent greenhouse effect of the halocarbons CFC-11 and CFC-12 (Ramanathan, 1975). The Ramanathan study showed that the addition of one molecule of CFC-11 and CFC-12 has the same surface warming effect as the addition of more than 10 000 molecules of $CO_2$ to the atmosphere. This finding 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; Ramanathan et al., 1985a). The first international assessment (sponsored by WMO/NASA/NOAA/FAA and others) of the climate effects of non-$CO_2$ gases was conducted in 1985 (Ramanathan et al.,



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1985b) and 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 studies by Ravishankara et al. (1993), Pinnock et al. (1995) and Forster et al. (2007).

HFCs, along with $CH_4$, $O_3$, and BC, have relatively short lifetimes in the atmosphere, 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, $CH_4$ is about 12 yr, and the global weighted average lifetime for the various HFCs now in commercial use is about 15 yr, with a range of 1 to 50 yr (Table 1). The lifetimes of the SLCPs are much shorter than that of $CO_2$, which remains in the atmosphere for centuries to millennia. The radiative forcing by SLCPs will therefore decrease significantly within weeks to a few decades after emissions are reduced. Motivated by modeling studies (e.g. Ramanathan and Xu, 2010; Shindell et al., 2012), policy makers are showing 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-dimenional 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 (± 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 above calculated that full implementation of SLCP measures can reduce the rate of global warming during the next several decades by nearly 50 %. Furthermore, Arctic warming can be reduced by





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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 mitigations. 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 newly developed projections of HFC emissions and give the 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 et al., 2002, 2007). With the phase-out of CFCs under the Montreal Protocol completed in 1996 in developed countries and in 2010 in developing countries (UNEP, 2010a), and with the scheduled phase-out of HCFCs by 2030 (UNEP, 2007), HFCs are increasingly being used in applications that traditionally used CFCs, HCFCs and other ODSs (Velders et al., 2009, 2012), 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 presence of HFCs (see Table 1 for a list) in the atmosphere results almost completely from their use as substitutes for ODSs. The atmospheric abundance of major HFCs used as ODS substitutes has increased 10 to 15 % per year in recent years and is projected to continue to increase in coming decades under BAU scenarios (Velders et al., 2009, 2012; WMO, 2011).





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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). Due to their increasing use as replacements for ODSs that are being phased-out under the Montreal Protocol, 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 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 also hold for developing countries (Velders et al., 2009).

### 2.2 Other emission projection

The future emissions scenarios of $CO_2$ are adopted from Representative Concentration Pathway (van Vuuren et al., 2011) database with RCP 2.6 as mitigation case and RCP 6.0 as BAU case. $CO_2$ emission in mitigation case will decline by half in mid-21st century, while the BAU $CO_2$ emission is projected to continue to increase till 2080. The peak $CO_2$ atmospheric concentration is 660 and 440 ppm under BAU and mitigation cases, respectively. The SLCPs projections, except for HFCs, are retained from RX10. Under BAU scenario, $CH_4$ emissions are predicted to rise 40 % in 2030, and BC emissions are projected to increase by 15 % by 2015 and then level off. The mitigation scenarios is following recommendation from the studies by International Institute for Applied Systems Analysis (IIASA) (Cofala et al., 2007) and the Royal Society (2006) 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.





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## 2.3 Models

The model used in RX10 is an Integrated Carbon and Radiant Energy Budget Climate Model. It adopts the Bern $CO_2$ geochemistry model (Joos et al., 1996), which estimates the atmospheric $CO_2$ concentration from emissions. The RX10 model links emissions of other pollutants with their atmospheric concentrations and the change in the radiative energy forcing. The carbon- geochemistry model is then coupled with an energy balance climate model with a 300-m ocean mixed layer to simulate the temporal evolution of global mean surface temperature. The model can account for historical variations in the radiative forcing to the system attributable to natural factors, GHGs and air pollutants (i.e. sulfate dioxide, nitrates, carbon monoxide, BC, 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 Discussion

## 3.1 Large increase of HFC forcing

The radiative forcing of HFCs in 2008 was 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 0.40 $W m^{-2}$ in 2050 (BAU high in Fig. 1), equal to nearly 20 % to 45 % of $CO_2$ forcing by 2050 (if $CO_2$ follows BAU and mitigation scenarios, respectively; see Sect. 2.2 for detailed scenario descriptions), or about the same forcing contributed by current $CO_2$ emissions from the transportation sector (IEA, 2011). The demand for HFCs for the period 2050 to 2100 is assumed in the scenarios discussed here to maintain at the 2050 levels, 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). Replacing those HFCs currently in use with low-GWP HFCs that have lifetimes of less than one month can potentially eliminate all of the future HFC forcing increase (Velders et al., 2012), and the total HFC radiative forcing in 2050 would be less than its current value (Mitigation in Fig. 1; Fig. A1 for total forcing from CFCs, HCFCs and HFCs).

### 3.2 Implication on 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 together the four 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 time scale 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 HFCs growth patterns of Velders et al. (2009) in their BAU scenarios. Mitigation of the potential growth of HFCs is shown to be critical for limiting the warming 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).

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 (Velders et al., 2012; 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 0.5 °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 baseline (i.e. reference/BAU) scenarios the climate models assume for HFCs in their simulations. Many climate models





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assume much smaller growth of HFC emission, because of the implicit assumption that HFC replacements will be adopted extensively during this century, an assumption that largely depends on technological and economic developments and the extent of policy interventions. Our study, however, shows that if current growth rate of HFCs continue, the additional warming from HFCs alone will be as much as 0.5 °C during this century. The potential temperature mitigation by 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 on from 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 (red dash line and black solid 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). These combined emission reductions provide the greatest chance of stabilizing global temperature rise below 2 °C by 2100.

## 4 Conclusions

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 by successfully phasing out nearly 100 similar chemicals (Velders, et al., 2009, 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. A2). Another option is to rely on the UNFCCC and its Kyoto Protocol, where HFC emissions are included in the basket of gases. It is also important to emphasize that the focus of this studies was on near-term warming over the next several decades to end of the century. For the longer term



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(century and beyond), mitigation of $CO_2$ would be essential for a significant reduction in the warming.

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**Table 1.** Main applications using HFCs.

| HFC | Main applications (UNEP and WMO, 2011) | Lifetime (WMO, 2011) | 100-yr GWP (WMO, 2011) |
|---|---|---|---|
| HFC-13 4a | Mobile air conditioning, refrigeration, stationary air conditioning; foams, medical aerosols | 13.4 | 1370 |
| HFC-32 | In blends for refrigeration and air conditioning equipment, fire protection | 5.2 | 716 |
| HFC-125 | In blends for refrigeration and air conditioning equipment | 28.2 | 3420 |
| HFC-143a | In blends for refrigeration and air conditioning equipment | 47.1 | 4180 |
| HFC-152a | Foams | 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 |

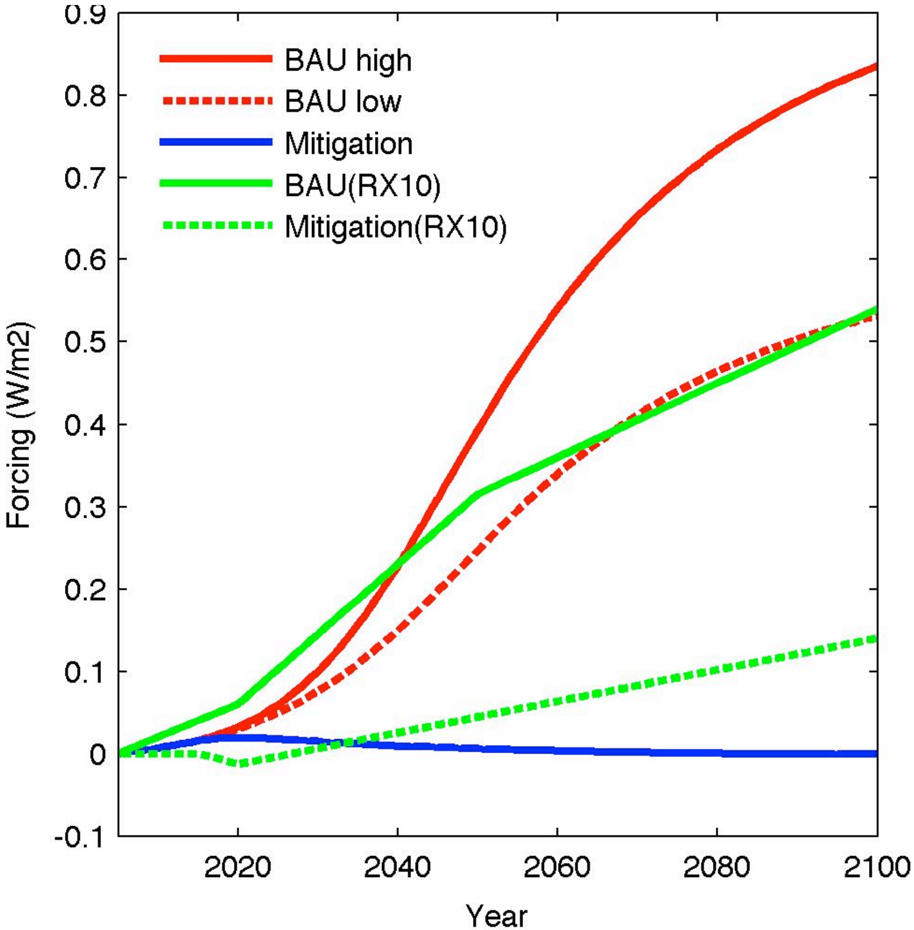


**Fig. 1.** HFC radiative forcing change since 2005. The scenarios previously adopted in RX10 is shown in green lines for reference.





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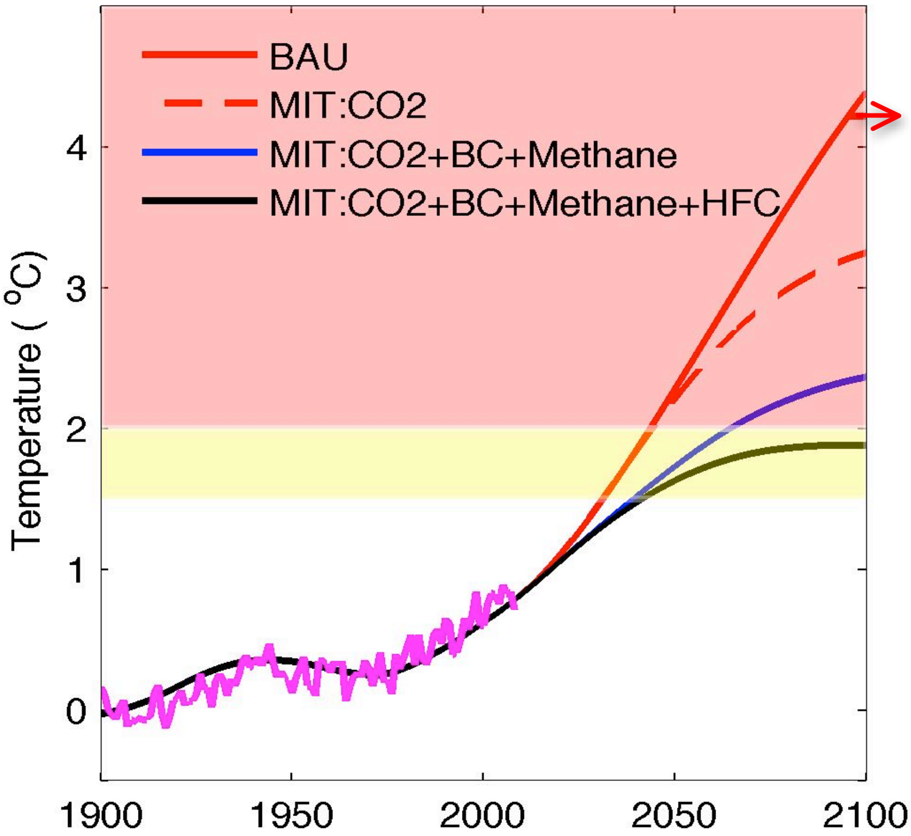


**Fig. 2.** Model simulated temperature change under various mitigation scenarios. BAU case (red solid line) considers higher estimates of future HFC growth (as red solid line in Fig. 1). BAU temperature at 2100 with lower estimates of future HFC growth (as red dash line in Fig. 1) is indicated by a red arrow on the right.





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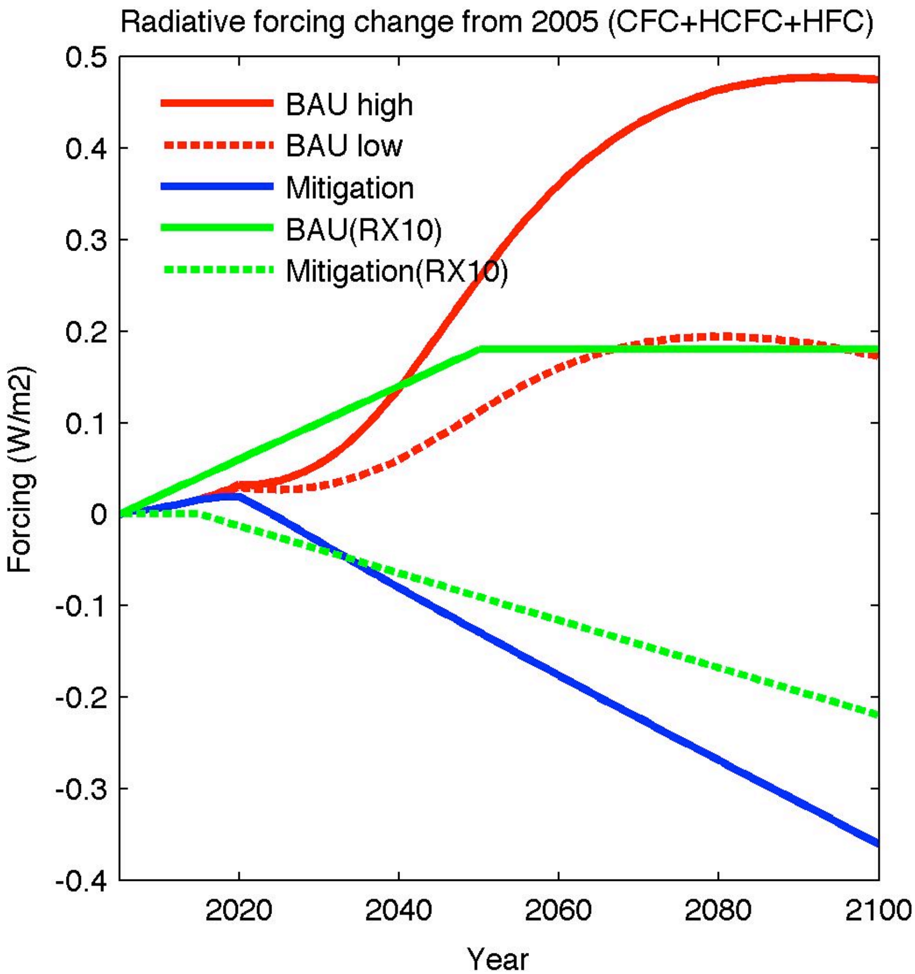


**Fig. A1.** Same as Fig. 1, but including forcing of CFCs and HCFCs.





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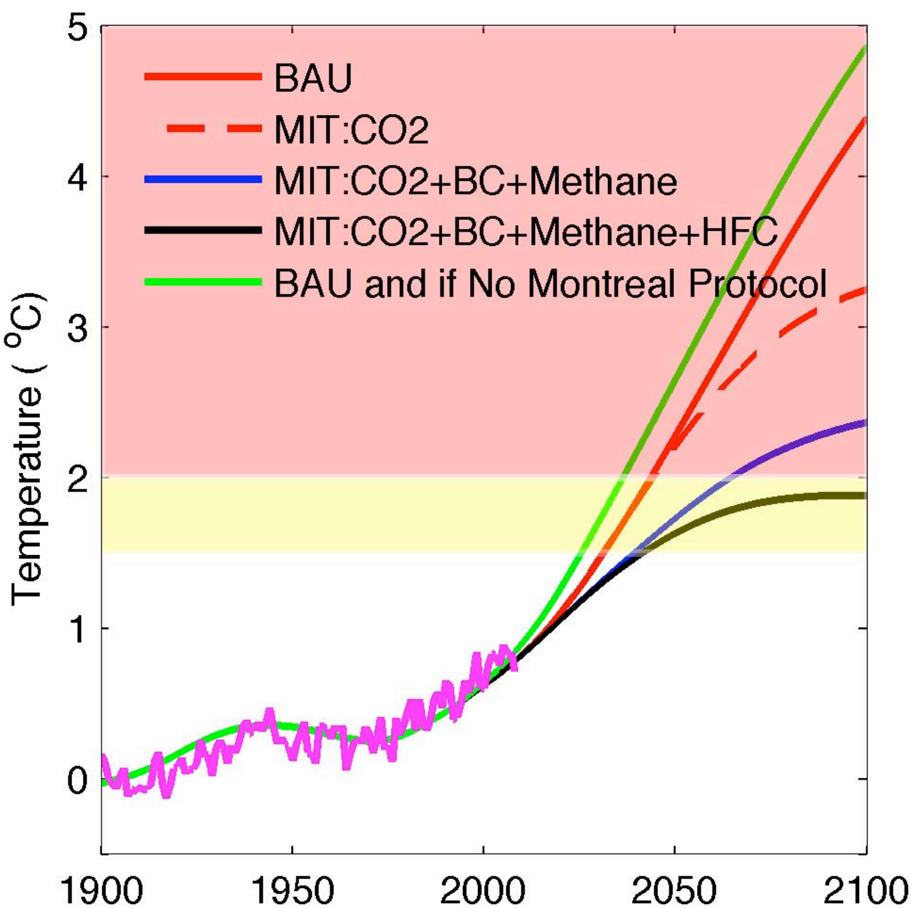


**Fig. A2.** Same as Fig. 2, except showing Montreal Protocol's implication on temperature (green line).





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