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Hydrofluorocarbon (HFC) Emissions in China: An Inventory for 2005–2013 and Projections to 2050

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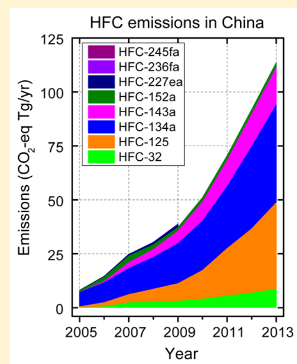
Supporting Information

ABSTRACT: Many hydrofluorocarbons (HFCs) that are widely used as substitutes for ozone-depleting substances (now regulated under the Montreal Protocol) are very potent greenhouse gases (GHGs). China's past and future HFC emissions are of great interest because China has emerged as a major producer and consumer of HFCs. Here, we present for the first time a comprehensive inventory estimate of China's HFC emissions during 2005–2013. Results show a rapid increase in HFC production, consumption, and emissions in China during the period and that the emissions of HFC with a relatively high global warming potential (GWP) grew faster than those with a relatively low GWP. The proportions of China's historical HFC CO_2-equivalent emissions to China's CO_2 emissions or global HFC CO_2-equivalent emissions increased rapidly during 2005–2013. Using the "business-as-usual" (BAU) scenario, in which HFCs are used to replace a significant fraction of hydrochlorofluorocarbons (HCFCs) in China (to date, there are no regulations on HFC uses in China), emissions of HFCs are projected to be significant components of China's and global future GHG emissions. However, potentials do exist for minimizing China's HFC emissions (for example, if regulations on HFC uses are established in China). Our findings on China's historical and projected HFC emission trajectories could also apply to other developing countries, with important implications for mitigating global GHG emissions.



INTRODUCTION

To address the challenge of the ozone-layer depletion, the parties to the Montreal Protocol agreed in 1987 to phase out the production and consumption of ozone-depleting substances (ODSs): initially, it was mainly focused on chlorofluorocarbons (CFCs) and halons; hydrochlorofluorocarbons (HCFCs) were later targeted via a phase-out agreement.[1,2] Hydrofluorocarbons (HFCs) were and are widely used as substitutes for CFCs and HCFCs.[3] Most HFCs are potent greenhouse gases (GHGs) with high global warming potentials (GWPs) and are included under the Kyoto Protocol.[4] Atmospheric abundances of HFCs are rapidly increasing. For example, HFC-134a has increased by ∼7.6% in 2011–2012, and other major HFCs have increased similarly or even more in recent years.[5] Global HFC CO_2-equivalent emissions have strongly increased by about a factor of 6 since the 1990s,[6] and in baseline scenarios, are projected to account for 9–19% of projected global CO_2 emissions by 2050[1] and up to 75% by 2050 in a CO_2 scenario with strong mitigation.[7] Indeed, HFC emissions, if left unabated could offset the CO_2 mitigation measures. Thus, HFC emissions are of great interest to international policy makers and policy negotiators as well as domestic policy makers and managers.[2] Debates on controlling HFCs globally are underway; HFCs are being discussed even under the Montreal Protocol regime.

In China, as a result of the phase-out of CFCs and HCFCs in compliance with the Montreal Protocol, HFC consumption has increased in the past. In some sectors, HFCs have been used as a substitute for CFCs since the 1990s. For example, since 2000, all new mobile air conditioners in China have used HFC-134a instead of CFC-12.[8] HFCs are now used as substitutes for HCFCs, whose consumption was frozen in 2013, and will be phased out in the coming decades. For example, R-410A (a blend of HFC-32 and HFC-125) has been increasingly used as the refrigerant in new room air conditioners,[9] in which HCFC-22 had been predominantly used in the past.

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HFC emissions from China have been estimated using bottom-up methods,[10,11] ratio methods,[12−15] and the inverse-modeling methods.[16,17] The Emission Database for Global Atmospheric Research (EDGAR) v4.2 provides information on only HFC-134a and, even for that compound, for only through 2008.[10] Su et al. provides estimates of emissions for HFC-134a through 2010.[11] Thus, bottom-up information for HFC-134a emissions after 2010 and emission estimates for other HFCs for all years are lacking. Top-down studies (the ratio and inverse modeling methods) only provide emission estimates for a certain period (e.g., the year 2008 in Stohl et al.[9]). Thus, a full picture of historical HFC emissions in China cannot be obtained on the basis of these available studies.

This study provides a comprehensive inventory of China's HFC consumption and emissions during 2005−2013 and projects HFC consumption and emissions according to the HCFC phase-out schedule in compliance with the Montreal Protocol and potential HFC regulations in China.

■ MATERIALS AND METHODS

In this study, we include HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-245fa, HFC-227ea, and HFC-236fa (Table S1 shows detailed information on each HFC). HFC-23 was not considered because it has few intentional uses, and its emissions mainly originate as a by-product of the production of HCFC-22. The historical and projected emissions of HFC-23 in China have been described in detail in Fang et al.[18]

Estimation of Historical HFC Consumption during 2005−2013. Consumption data for each HFCs during 2005−2009 were derived from survey of China's HFC industry[19] that were also used by Zhang et al.[20] For 2010−2013, annual consumption data for HFCs are not available. However, data for the annual production of each HFC are provided in an industrial production database Web site (because the Web site is not easily accessible, we have given the numbers in Table S2). The ratio of total consumption to total production for each HFC during 2005−2009[19] was used to estimate annual HFC consumption based on the annual HFC production in 2010−2013 (see detailed estimation in Table S2). Discussion on the variation of ratio of consumption to production is provided in the Supporting Information text and Table S3. China is a main producer of HFCs in the world and produces almost all kinds of HFCs. The amount of HFCs produced in China is larger than the amount consumed in China. Thus, no or minor HFCs were supposed to be imported into China. Regarding the HFC export, the amount of HFC accounted under HFC consumption is that in exported equipment (e.g., room air conditioners). Exports of HFC as raw materials are not included under "consumption" numbers reported in our study. In our study, HFC-32 and HFC-125 in exported equipment (e.g., room air conditioners) were excluded from consumption numbers before calculating emissions. Consumption of all HFCs for the years before 2005, except HFC-134a, was assumed to be zero because their annual consumption prior to this date was very small (e.g., total consumption of HFCs excluding HFC-134a was 10 Gg/year in 2005, which accounted for only 6% of consumption of these HFCs in 2013). Annual HFC-134a consumption for the period 1995−2002 was obtained from Hu et al.,[8] whereas annual consumption for 2003 and 2004 was interpolated linearly from the 2002 and 2005 consumption.

Projection of HFC Consumption under a Non-HFC-Regulation Scenario. Our "business-as-usual" (BAU) scenario (also referred to as non-HFC-regulation scenario) assumes that HFC use increases concurrently with HCFC phase-out and that there are no specific HFC regulations in China. HCFC consumption data for 2008−2010 were reported by Zhang et al.[20] Under the BAU scenario, the HCFC consumption in China during 2011−2050 is assumed to grow in proportion to the gross domestic product (GDP) scenarios from Shared Socioeconomic Pathways (SSP) projections.[21] The high and low ends of the range for GDP growth follow the SSP5 and SSP3 scenarios (the five data sets (SSP1 to SSP5) quantified by the OECD as illustrative SSPs),[21] respectively. Due to the Montreal Protocol, HCFC consumption in China was frozen in 2013 at the baseline of an average of the 2009−2010 level and will be reduced by 10% in 2015, 35% in 2020, 67.5% in 2025, and 97.5% by 2030.[22] We assume that the HFCs and not-in-kind replacements (the replacement pattern is shown in Table S4) make up for the differences between the HCFC demand and the lower HCFC consumption to comply with the Montreal Protocol. HFCs were used even before the start of the HCFC phase-out (see the section above); we assume that those uses during 2014−2050 will grow in proportion to the SSP GDP scenario.[23] Therefore, the total annual HFC consumption is the sum of HFC growth due to its continued current uses and that for replacing HCFC as it is phased out. In our calculations, after the year 2030, the HFC demand changes in proportion to population rather than GDP, assuming the use of HFCs is saturated by 2030. The year 2030 is used because it is estimated that by then the HFC usage per capita in China would have caught up with the current levels used in developed countries. Thus, the projection for China's HFC consumption is reasonable because before 2030, the HFC usage per capita in China is still smaller than that in developed countries. The China's population is projected to decrease slightly during 2030−2050 in the SSP projections.[21] The SSP projections of GDP and population in China for the period 2010−2050 are shown in Figure S1. Using the GDP and population projections from Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES), we obtained a similar estimate of projected HFC consumption, e.g., ∼ 2500 CO_2-eq Tg/year in 2050.

Projection of HFC Consumption under Mitigation Scenarios. Currently, proposals on controlling HFC usages are under discussions, e.g., the United States, Canada, and Mexico together submitted proposals to phase down production and consumption of HFCs under the Montreal Protocol. The 2013 North American proposal suggests that HFC consumption in Article 5 countries be frozen at 100% of the baseline consumption in 2018, followed by a 25% reduction by 2025, 60% reduction by 2030, and 85% reduction by 2043 (Table S5).[24] According to the methodology for baseline consumption proposed in the 2013 North American proposal, China's HFC consumption baseline is estimated to be 401 CO_2-eq Tg/year in 2018 (398 CO_2-eq Tg/year using the GWP values proposed in the 2013 North American proposal). Annual HFC consumption is assumed to be reduced linearly between the above phase-down steps. We also assume that annual HFC consumption will follow the BAU scenario through 2016 and then decrease linearly to the HFC consumption cap in 2018. In 2014 and 2015 new proposals have been submitted by the North American countries, as well as other countries. The 2015 North American proposal is only slightly different from the one submitted in 2013 and does not significantly affect the HFC emissions toward 2050. The methodology for assessing the

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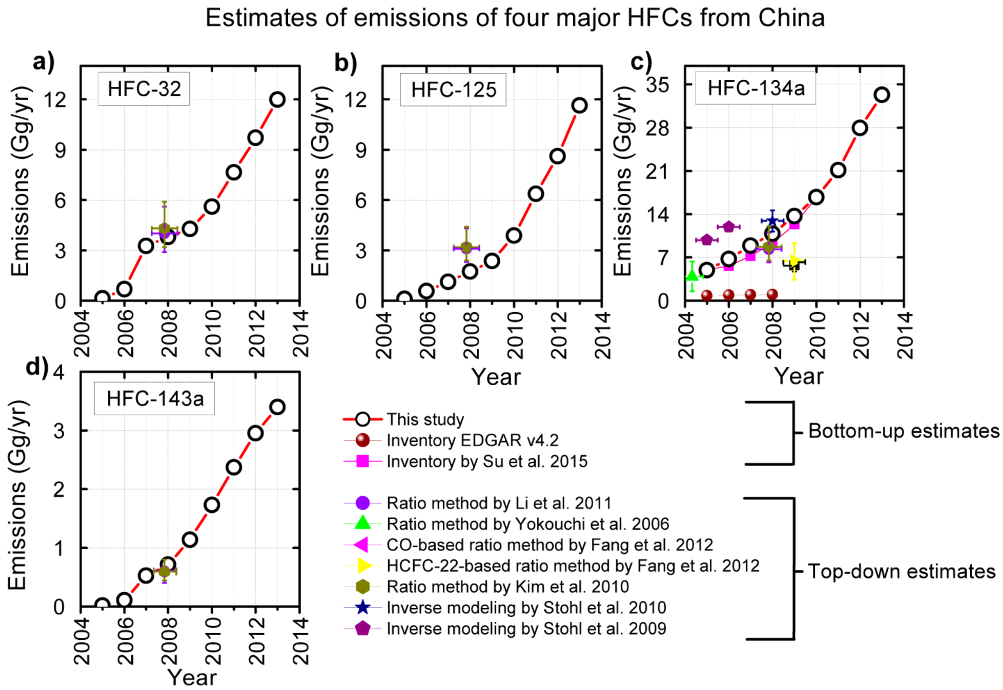

Figure 1. HFC emission estimates in this study and other published estimates.[10−17] X-error bar in the plot denotes the span of the target period in the respective study (for example, the 12 months from May 2004 to May 2005 in Yokouchi et al.[15] and the 14 months from November 2007 to December 2008 in Li et al).[14]

2013 proposal used in this study can be applied to analyze other similar proposals.

An alternative mitigation scenario (2024 "phase-down" scenario) is the same as the scenario for phasing down of HFCs in the global HFC projections described by Velders et al.[1] In this scenario, HFC consumption will be frozen in 2024 at the level of consumption in the previous year and will then decrease by 4% each year until 20% of the baseline level, in 2044, and remain constant through 2050. HFC consumption growth during 2014−2023 will be the same as in the BAU scenario. Note that others could come up with different scenarios, but such scenarios can also be analyzed.

Estimation of Emissions from Consumption. Emissions are calculated as constant fractions of HFCs released annually from identified banks.[1] The annual bank of HFCs is equal to the sum of the bank and consumption in the previous year, minus the emissions in the previous year. The methodology is shown in Equations 1 and 2. The emission factors are taken from Velders et al.,[3] as shown in Table S6. It is hard to quantify the uncertainty of estimated emissions partly because there are no reported uncertainties in production and consumption number and partly because there are no cogent ways to estimate uncertainties in such reports.

$$E_t = f \times (B_t + C_t) \tag{1}$$

$$B_t = B_{t-1} + C_{t-1} - E_{t-1} \tag{2}$$

Here, B_t and B_{t-1} represent the HFC banks in the year t and t-1, respectively, C_t and C_{t-1} are HFC consumption in the year t and t-1, respectively, E_t and E_{t-1} are HFC emissions in the year t and t-1, respectively, and f is emission factor for each HFC.

Estimation of mixing ratio and radiative forcing. The surface global mean mixing ratio of specific HFC i in year j was calculated from global annual HFC emissions, its lifetime and molecular weight, number of molecules in the global atmosphere, and other input data (see equations 3−5). Atmospheric surface global mean mixing ratios of HFC were multiplied by their radiative efficiency values (Table S1) to obtain radiative forcing (eqs 4).

$$\frac{dC_i}{dt} = F_i \times E_i - \frac{C_i}{\tau_i} \tag{3}$$

Integrate the equation yields

$$C_{i,j} = C_{i,j-1} \times \exp\left(-\frac{1}{\tau_i}\right) + F_i \times E_{i,j-1} \times \tau_i \times \left(1 - \exp\left(-\frac{1}{\tau_i}\right)\right) \tag{4}$$

Here $C_{i,j}$ and $C_{i,j-1}$ are the mean surface mixing ratios (ppt), τ_i is the lifetime (years), $E_{i,j-1}$ is the global annual emissions (kg yr^{-1}), and F_i (ppt kg^{-1}) is a factor that relates the mass emitted to the global mean surface mixing ratios.

$$F_i = \left(\frac{N_A}{Na}\right)\frac{F_{surf}}{M_i} = 5.68 \times 10^{-9}\frac{F_{surf}}{M_i} \tag{5}$$

Here M_i is the molecular weight (kg mol^{-1}), N_A is the Avogadro constant, N_a is the number of molecules in the global atmosphere, and F_{surf} is a factor relating the global mean surface mixing ratio to the global mean atmospheric mixing ratio. F_{surf} was taken to be 1.07 for all HFCs.[25,26]

$$RF_{i,j} = C_{i,j} \times RE_i/1000 \tag{6}$$

Here $RF_{i,j}$ (W m^{-2}) is the radiative forcing, and RE_i is the radiative efficiency (W m^{-2} ppb^{-1}; listed in Table S1).

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RESULTS AND DISCUSSION

China's Historical HFC Production, Consumption, and Emissions. Our study has compiled a comprehensive inventory of China's HFC production, consumption, and emissions during 2005−2013 (values are tabulated in Table S2). Our results show that HFC-134a contributes about 40% to the total HFC production and consumption by mass, followed by HFC-125, HFC-32, and HFC-152a. Productions of HFC-143a, HFC-227ea, HFC-236fa, and HFC-245fa are small, indicating limited current applications in China. Overall, consumption accounted for about half the production by mass. The difference between production and consumption is due to the export or feedstock use of HFCs, e.g., some of produced HFC-152a is used as feedstock for producing HCFC-142b, and some of produced HFC-125 is exported as refrigerant to other countries. As for emissions, the estimated HFC-134a emissions were 33 Gg/year for 2013, which contributed ∼40% of the total 2013 HFC emissions by mass. HFC-152a, HFC-32, and HFC-125 emissions were close behind, at ∼12 Gg/year in 2013. Results show a rapid increase in HFC production, consumption, and emissions during 2005−2013.

Figure 1 shows emission estimates of four major HFCs in this study and other available estimates using either bottom-up or top-down approaches. The plots show that many years were not covered by previous studies. For example, HFC-143a emissions were only investigated during the period from November 2007 to December 2008 by Kim et al.[12] and Li et al.[14] This study extends the coverage to a full period of 2005−2013 for the major HFCs. This study also provides a coverage period of 2005−2009 for HFC-227ea, HFC-236fa, and HFC-245fa, whereas there are no previous estimates for these three compounds. Therefore, considering the temporal coverage and compound coverage, this study made a breakthrough in understanding the evolution of HFC emissions in China. Figure 1 shows that the EDGAR estimates for HFC-134a emissions are much lower than other estimates. Our estimates for HFC-134a emissions are consistent with the estimates by Su et al.[11] Our HFC-134a emission estimates are lower than the inverse-modeling estimates by Stohl et al.[8] Overall, estimates in this study agree with previous estimates for the four major HFCs. We suggest that more bottom-up and top-down estimates are needed to better constrain the rapidly changing HFC emissions in China. It is also worth noting that the differences between the various emissions estimates from China could be larger than the emissions from some of the smaller emitters.

High-GWP HFCs and Low-GWP HFCs. Figure 2 shows the HFC GWP-weighted (also referred to as CO_2-eq) consumption and emissions in China during 2005−2013. The HFC CO_2-eq consumption and emissions were obtained using the consumption and emissions of each HFC multiplied by their latest assessed 100 year GWPs (GWP_{100}),[3] respectively. The total HFC CO_2-eq emissions increased from 8.1 CO_2-eq Tg/year in 2005 to 113 CO_2-eq Tg/year in 2013. Of note is that relatively high-GWP HFC-143a (GWP_{100} = 5080) and HFC-125 (GWP_{100} = 3450) CO_2-eq emissions have been growing with average growth rates of 100% and 83% per year, respectively, which are higher than the growth rates of 77% per year for the lower-GWP HFC-32 (GWP_{100} = 704) and 27% per year for HFC-134a (GWP_{100} = 1360). Thus, among these four major HFCs, the emissions of those with a relatively high GWP grew faster than those with a relatively low GWP during 2005−2013. The consumption pattern also shows that high-GWP HFCs grew faster than low-GWP HFCs. Therefore, special attention should be paid to controlling the higher-GWP HFCs to mitigate HFC CO_2-eq emissions.

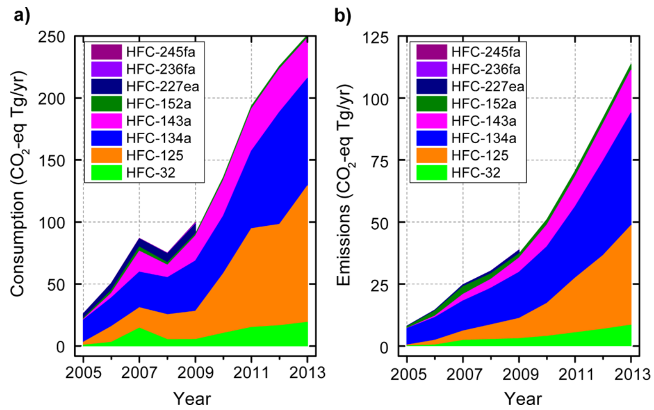

Figure 2. CO_2-equivalent HFC (a) consumption and (b) emissions in China during 2005−2013. The CO_2-equivalent values were obtained using emissions of each HFC, multiplied by their 100 year GWP.[3] Consumption and emission data for HFC-227ea, HFC-236fa, and HFC-245fa between 2010 and 2013 were not available and are plotted in these two figures.

Historical Emissions in National and Global Perspectives. Annual China's ODS CO_2-eq emissions stabilized at ∼300 CO_2-eq Tg/yr during the 2005−2013 period[27] (Figure S2), while the proportion of China's HFC CO_2-eq emissions to China's ODS CO_2-eq emissions increased from 3% in 2005 to 34% in 2013 (Figure 3a), which reveals the shift from ODS to HFC emissions in China due to the increasing usage of HFCs during the phase-out of ODSs in compliance with the Montreal Protocol. China's national CO_2 emissions from fossil fuel combustion and cement production increased from 5341 Tg/year in 2005 to 9151 Tg/year,[28] with an absolute increase about 35 times larger than that of HFC CO_2-eq emissions. Nevertheless, the proportion of China's HFC CO_2-eq emissions to China's national CO_2 emissions increased from 0.15% in 2005 to 1.24% in 2013 (Figure 3b), which suggests the increasing importance of HFC emissions in China's GHG emissions. In a global perspective, the proportion of China's HFC CO_2-eq emissions to global HFC CO_2-eq emissions increased to 17% in 2012 (Figure 3c), although the global HFC CO_2-eq emissions increased by 70% during this period.[6] The proportions of China's HFC CO_2-eq emissions to global CO_2 emissions were smaller than 0.32%, with an increasing trend during 2005−2013 (Figure 3d). Overall, in national and global perspectives, the importance of China's historical HFC CO_2-eq emissions increased during 2005−2013, and it would definitely continue increasing after 2013 because HFCs is a main option, if there are no regulations on HFCs, for replacing HCFCs whose consumption is an order of magnitude higher than that of HFC in China in 2013.

HFC Emissions under a Non-HFC-Regulation Scenario. Figure 4 shows the projected consumption and emissions under the BAU scenario (compound-specific HFC data are in Table S7). Our calculations show that HFC CO_2-eq consumption (Figure 4a) will increase from 134 CO_2-eq Tg/year in 2010 to 2200−3000 Tg/year in 2030 and then decrease to 1900−2800 CO_2-eq Tg/year (the range represents estimates based on projected low and high growth rates of GDP before 2030 and

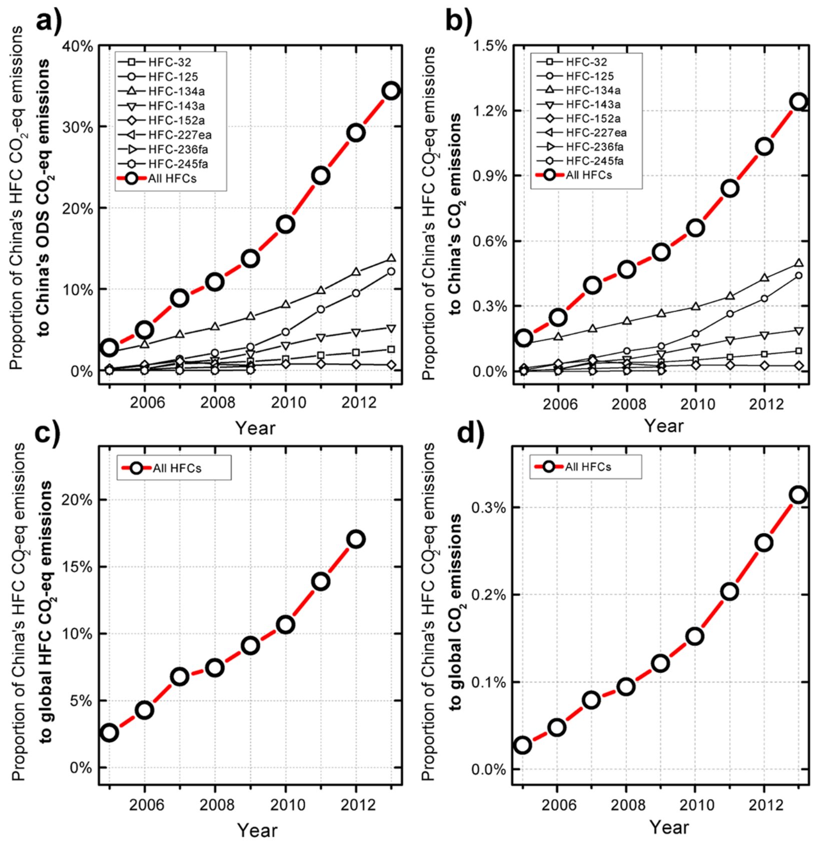

Figure 3. Historical HFC CO_2-eq emissions from national and global perspectives. Plots (a)−(d) show proportions of China's HFC CO_2-eq emissions to China's ODS CO_2-eq emissions,[27] China's CO_2 emissions,[28] global HFC CO_2-eq emissions,[6] and global CO_2 emissions,[33] respectively. China's emissions for HFC-227ea, HFC-236fa, and HFC-245fa were not estimated for 2010−2013.

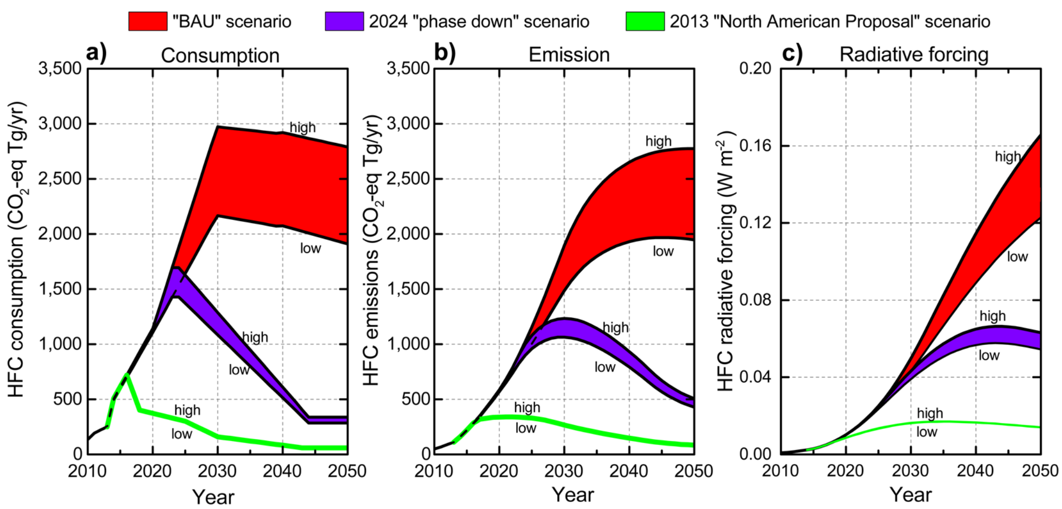

Figure 4. Projected China's HFC CO_2-eq (a) consumption, (b) emissions, and (c) radiative forcing under the "BAU" scenario, the 2024 "phase-down" scenario, and the 2013 "North American proposal" scenario. The range of high and low results from the projected low and high growth rates of HFC uses (e.g., before the HFC freeze goes in to effect in 2024 and 2018 under these two HFC mitigation scenarios, respectively).

decrease rates of population after 2030) in 2050. The HFC CO_2-eq emissions (Figure 4b) are projected to increase from 49 CO_2-eq Tg/yr in 2010 to 2000−2800 CO_2-eq Tg/year in 2050. The projected radiative forcing from China's HFCs monotonically increases throughout the BAU scenario to 0.12−0.17 W m^{-2} (Figure 4c). Thus, China's HFC consumption and emissions are projected to increase under the BAU scenario. The increases in HFC projections depends on, among other factors, the projected growth rates in GDP and population and on the year (about 2030) the consumption in China is assumed to be saturated. Earlier or later saturation results in smaller or larger HFC emissions after 2030.[29] The decrease in global ODS emissions since the late 1980s, due to the Montreal Protocol, is estimated to have resulted in ∼10 000 Tg of avoided CO_2-eq emissions in 2010,[1,3] which represents the global climate benefit of the Montreal Protocol. If HFC growth continues on

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the BAU trajectory in China, the increase in China's HFC emissions (cumulative emissions for 2014−2050 are 59 000 (51 000−67 000) CO_2-eq Tg; see Table 1) is projected to offset the global climate benefit of the Montreal Protocol in the year 2010 by a factor of 5 to 7.

Table 1. Cumulative Consumption and Emissions under the BAU Scenario and Two Mitigation Scenarios (CO_2-eq Tg) during 2014−2050[a]

	cumulative consumption	cumulative emissions
"BAU" scenario	74 000 (63 000−85 000)	59 000 (51 000−67 000)
2024 "phase-down" scenario	31 000 (29 000−34 000)	29 000 (27 000−31 000)
2013 "North American proposal" scenario	8100 (8000−8100)	8200 (8100−8200)

[a]The range in parentheses results from the projected low and high growth rates of HFC uses.

HFC Emissions under Mitigation Scenarios. Figure 4 shows HFC CO_2-eq consumption and emissions under 2024 "phase-down" schedule and the North American proposal of 2013 (compound-specific data are in Table S8 and S9). Under the 2024 "phase-down" scenario, HFC CO_2-eq emissions are projected to peak in 2030 at 1000−1200 CO_2-eq Tg/year and then decrease gradually to 430−510 CO_2-eq Tg/year in 2050. This scenario is consistent with China's recently announced commitment to peak CO_2 emissions around 2030.[30] Compared to the "BAU" scenario, cumulative avoided emissions for 2014−2050 under this scenario are 30 000 (24 000−36 000) CO_2-eq Tg. The projected radiative forcing from China's HFCs under this scenario increases to 0.05−0.06 W m^{-2} in 2050 (Figure 4c).

Under the North American Proposal scenario, HFC CO_2-eq emissions will reach about 340 CO_2-eq Tg/yr in 2021 and will then decrease to about 84 CO_2-eq Tg/yr in 2050, which is only ∼3% of projected HFC emissions under the BAU scenario. Compared to the BAU scenario, cumulative avoided emissions for 2014−2050 under this scenario are 51 000 (43 000−59 000) CO_2-eq Tg. The projected radiative forcing from China's HFCs under this scenario will be about 0.01 W m^{-2} in 2050 (Figure 4c), which is much lower than other two scenarios. The substantial avoidance of HFC emissions under the two mitigation scenarios could be achieved if regulations on HFC uses are to be established in China. Low-climate-impact substitutes and technologies are already commercially available in many consuming sectors.[2,31] For example, HCFC-22 could be replaced by R-290 (Propane, GWP_{100} = 0) rather than R-410A (GWP_{100} = 2077) in the room air-conditioning sector; HFC-1234yf ($CF_3CF{=}CH_2$, GWP_{100} < 5) could replace HFC-134a (GWP_{100} = 1360) in the mobile air-conditioning sector.

In national and global perspectives, China's projected HFC CO_2-eq emissions could be important. Under the HFC BAU scenario, the proportions of China's HFC CO_2-eq emissions to China's CO_2 emissions (Figure S3a) were estimated to increase from less than 1% in 2010 to more than 15% in 2050, revealing the possible significance of future China's HFC emissions to China's total GHG emissions. Under the HFC mitigation scenarios, the proportions could be reduced to less than 1%. Under the HFC BAU scenario, the proportions of China's HFC CO_2-eq emissions to global HFC CO_2-eq emissions (Figure S3b) and global CO_2 emissions (Figure S3c) could increase to more than 23% and 3%, respectively, in 2050, revealing that China's HFC CO_2-eq emissions could be of great global importance. However, under the HFC mitigation scenarios, the proportions could be less than 2% and 0.1%, respectively. Thus, China's HFC CO_2-eq emissions could be either important for the future GHG emissions (under the BAU scenario) or negligible (under the mitigation scenario).

There are both opportunities and challenges for mitigations of HFC consumption and emissions in China. The opportunities are as follows: first, applications using HFCs, except HFC-134a, are currently still at an early stage in China (HFC consumption is smaller by an order of magnitude than HCFC consumption). Second, in many consuming sectors, low-GWP or zero-GWP substitutes and technologies are already commercially available.[2,31] Third, China has joined the United States and other countries in discussions targeted at curbing HFC emissions. However, several challenges stand in the way of controlling HFCs in China. First, there is no single solution for replacing HCFCs.[2] It is worth noting that the situation was similar when multiple substitutes were needed to phase out a given CFC. Second, there are currently no domestic regulations on HFCs in China. Regulations and guidelines are urgently needed to be established in China if it is to control HFCs in the near future. Third, technical and financial incentives to ramp down use of HFCs by the industry have not been determined in detail, and it may also hinder switching to non-HFCs.

An analysis of HFC emissions in this study are not meant to detract from the essential need to mitigate CO_2 emissions. The global community and China have to not only deal with CO_2 but also address HFCs before it becomes a large contributor in the future.

Implications for Other Developing Countries. A comparison between the HFC emissions for non-Annex I countries (mainly developing countries) for 2010−2012[32] and those from China estimated in this study shows that China's HFC CO_2-eq emissions account for ∼35% of total emissions in non-Annex I countries in 2010−2012. In other words, significant HFC emissions are indeed coming from developing countries other than China. By comparing estimates for the two periods 2007−2009 and 2010−2012, we find that HFC CO_2-eq emissions from other developing countries have increased by ∼30%.

In the coming decades, in the absence of an HFC phase-down schedule, HFC consumption and emissions from other developing countries will probably also increase as dramatically because HFCs will be used in place of the phase-out of HCFCs (as done under the BAU scenario in China). Thus, the HFC historical estimations, projections, opportunities, and challenges, discussed in relation to China, could apply to other developing countries. Reducing future HFC emissions from China and other developing countries provides an important opportunity for mitigating global GHG emissions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b04376.

Additional material including a consistency check for HFC-32 and HFC-125 and estimation of mixing ratio and radiative forcing. Tables showing information on HFCs; compound-specific HFC production, consumption, and emissions in China during 2005–2013; discussion on the variation of ratio of consumption to production; replacement pattern of HCFC consumption by HFC consumption; HFC phase-down steps from the 2013 North American HFC amendment proposal; emissions factors; and projected HFC consumption and emissions under three scenarios. Figures showing SSP projections of GDP and population in China for the period 2010–2050; historical and projected CO_2-eq emissions of China's HFCs, respectively, in national and global perspectives; ratios of annual HFC-125 and HFC-32 consumption. (PDF)

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Notes

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