Environmental Science & Technology

Article

Cite This: *Environ. Sci. Technol.* 2018, 52, 11359−11366

pubs.acs.org/est

Changes in Emissions of Ozone-Depleting Substances from China Due to Implementation of the Montreal Protocol

Xuekun Fang,[*,†,‡] A. R. Ravishankara,[*,§] Guus J. M. Velders,[∥,∇] Mario J. Molina,[⊥] Shenshen Su,[#,‡] Jianbo Zhang,[‡] Jianxin Hu,[*,‡] and Ronald G. Prinn[†]

[†]Center for Global Change Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States

[‡]State Key Joint Laboratory for Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China

[§]Department of Chemistry and Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado 80523, United States

[∥]National Institute for Public Health and the Environment (RIVM), P.O. Box 1, 3720 BA Bilthoven, The Netherlands

[∇]Institute for Marine and Atmospheric Research Utrecht (IMAU), Utrecht University, 3508 TC Utrecht, The Netherlands

[⊥]Department of Chemistry and Biochemistry, University of California, San Diego, La Jolla, California 92093, United States

[#]Electric Power Planning & Engineering Institute, Beijing 100120, China

Supporting Information

ABSTRACT: The ozone layer depletion and its recovery, as well as the climate influence of ozone-depleting substances (ODSs) and their substitutes that influence climate, are of interest to both the scientific community and the public. Here we report on the emissions of ODSs and their substitute from China, which is currently the largest consumer (and emitter) of these substances. We provide, for the first time, comprehensive information on ODSs and replacement hydrofluorocarbon (HFC) emissions in China starting from 1980 based on reported production and usage. We also assess the impacts (and costs) of controls on ODS consumption and emissions on the ozone layer (in terms of CFC-11-equivalent) and climate (in CO_2-equivalent). In addition, we show that while China's future ODS emissions are likely to be defined as long as there is full compliance with the Montreal Protocol; its HFC emissions through 2050 are very uncertain. Our findings imply that HFC controls over the next decades that are more stringent than those under the Kigali Amendment to the Montreal Protocol would be beneficial in mitigating global climate change.

INTRODUCTION

The Montreal Protocol, agreed to in 1987 and amended in subsequent years, aims to minimize depletion of the ozone layer by phasing out the production and consumption of ozone-depleting substances (ODSs),[1] e.g., chlorofluorocarbons (CFCs), carbon tetrachloride, methyl chloroform (1,1,1-trichloroethane), halons, methyl bromide (bromomethane), and hydrochlorofluorocarbons (HCFCs). CFCs were replaced initially by HCFCs which have smaller ozone-depleting potentials and/or by nonozone-depleting substances and technologies. Hydrofluorocarbons (HFCs) and/or other substances or technologies are now replacing HCFCs. HFCs essentially do not deplete the ozone layer, but many of them are potent greenhouse gases (GHGs).[2−4]

China, an Article-5 country under the Montreal Protocol, ratified the Protocol in 1991. As a consequence of this ratification, China was obligated to freeze production and consumption of CFCs and halons by 1999, followed by a complete (100%) phase out by 2010.[1] China was also obligated to freeze production and consumption of HCFCs by 2013 and achieve a complete phase out by 2040.[1] In addition, monetary help from the Multilateral Fund (MLF of the Montreal Protocol) enabled the transition and, since the early 1990s, the MLF-subsidized China's ODSs phase-out projects with a total of approximately 1.2 billion USD (2014 USD). Now, it is interesting to ask how ODS consumption/emission changed in China over the last three decades (before and after the Montreal Protocol was implemented in China). Note that China is currently the largest contributor to the global total ODS emissions.[3]

A few previous studies have presented bottom-up estimates of ODS emissions in China (for example, see refs 5−7). There are some top-down estimates based on in situ atmospheric

Received: March 8, 2018
Revised: August 20, 2018
Accepted: August 22, 2018
Published: August 22, 2018

DOI: 10.1021/acs.est.8b01280
Environ. Sci. Technol. 2018, 52, 11359−11366

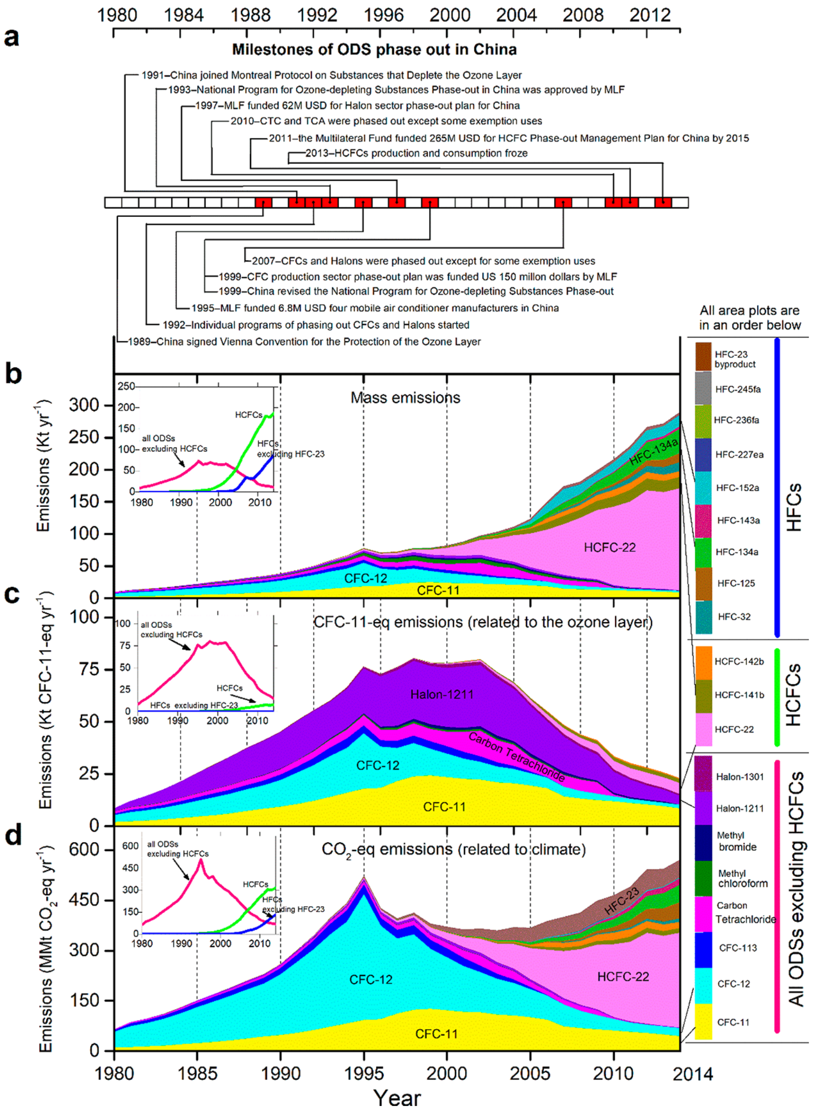

Figure 1. Historical (1980–2014) emissions of each ozone-depleting substance (ODS) and alternative hydrofluorocarbon (HFC) in China. (a) Milestones of ODS phase-out in China. (b) Emissions of each ODS and HFC. (c) CFC-11-eq emissions. (d) CO_2-eq emissions. Inserts show the contributions of all ODS combined excluding HCFCs (red line), HCFCs (green line), and HFCs combined excluding HFC-23 (blue line). Note that HFC-23 produced from HCFC-22 production for domestic dispersive use are included in this accounting.

measurements that provide estimates of ODS emissions for China for a few years.[8−11] However, all of these studies accounted for a few discrete years and a limited number of ODSs and HFCs. Therefore, a comprehensive assessment of the impacts of China's implementation of the Montreal Protocol was previously not possible.

Our study provides the most comprehensive knowledge of emission inventory of ODSs and HFCs from China for more than three decades between 1980 and 2014. This study also assesses the impact on the ozone layer and provision of climate protection by the implementation of the Montreal Protocol in China. This study also comments on the possible future control priorities on future ODS and HFC emissions through 2050.

■ METHOD

Estimating ODS and HFC Emissions at Sector and Compound Levels. In total, 11 ODSs (CFC-11, CFC-12, CFC-113, carbon tetrachloride, methyl chloroform, methyl bromide, Halon-1211, Halon-1301, HCFC-22, HCFC-141b, and HCFC-142b) and 9 HFCs (HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-245fa, HFC-152a, HFC-227ea, and HFC-236fa) were included in this study. ODSs were/are widely used in a total of 13 industrial (usage) sectors in China: 3 major sectors, consisting of foam blowing, industrial and commercial refrigeration, and room air conditioning, and 10 other smaller sectors. Figure S1 shows a flowchart of emission calculation steps used in this study. Application sectors (*i*) of each ODS and HFC (*j*) in China are shown in Table S1. Other substances (e.g., CFC-114, CFC-115, Halon-1202, Halon-2402, HCFC-123, and HCFC-124) were not included because their consumption and emissions are negligible in China.[5] Information on the chemical formula, lifetime, ODP, and GWP are shown in Table S2.

A detailed methodology for calculating ODS emissions is presented in the Supporting Information and described briefly here. Emissions from 13 different sectors were estimated: (1) refrigerators, (2) freezers, (3) room air conditioning, (4) mobile air conditioning, (5) industrial/commercial refrigeration, (6) foam blowing, (7) solvents, (8) tobacco industry,

(9) aerosol propellants, (10) chemical-processing agents, (11) firefighting, (12) methyl bromide usage, and (13) HCFC-22 production. ODS emissions from the first four sectors were derived from sales of products and the emission rates during installation, operation, maintenance, and disposal. ODS emissions from other sectors were derived from their consumption data using specific emission functions. The emission functions were derived primarily using the IPCC Guidelines for National Greenhouse Gas Inventories,[12] Wan et al.,[5] and Wang et al.[13] The equations and parameters for each sector and ODS are provided in the Supporting Information. Projections (2015−2050) of ODS and HFC consumption are assumed to follow the schedule of ODS phase out and HFC phase down for China required by the Montreal Protocol (listed in Table S3; linear interpolation was used for years not scheduled in the Montreal Protocol).

The emissions and consumptions for each chemical in each sector were summed on a yearly basis. This study presents annual ODS consumption for each sector (Figure S2a) and each ODS (Figure S3) and annual ODS emissions for each sector (Figure S2c) and each ODS (Figure 1b). Data are provided in a separate file in the Suporting Information.

HFC-23 emissions increased due to enhanced production of HCFC-22.[14,15] To assess the impact of the Montreal Protocol on China, this study calculated HFC-23 emissions only from the production of HCFC-22 used as a substitute in domestic sectors and not those from the production of HCFC-22 used as feedstock (see SI text).

Estimates of total ODS emissions in this study agree, within 0.1%, 0.4%, and 4.7%, with the top-down estimate based on atmospheric measurements made at Gosan Station[10] in terms of mass, CFC-11-eq, and CO_2-eq, respectively (Figure S4). Our estimate of total HFC emission agrees, within 6.4% and 3.2%, with the top-down estimate in terms of mass and CO_2-eq, respectively (Figure S5). These suggest that our bottom-up estimates are robust.

Assessing the impacts of the Montreal Protocol. To calculate projected emissions without the Montreal Protocol, actual emissions of CFCs, HCFCs, and HFCs in 2012 (before HCFC controls started in 2013) were converted to virtual "CFC emissions" in 2012 by using the CFC emission profile in 1995, i.e., before China started the conversion. Virtual emissions between 1996−2011 and 2013−2015 were interpolated and extrapolated linearly based on the known 1995 emissions and the expected 2012 (virtual) emission values, respectively. Note that this projection is not based on the emissions with an increasing trend in 1991−1995. The avoided emissions are equal to the difference between what would have been emitted without the Montreal Protocol and those actually emitted. Depletion of stratospheric ozone (a greenhouse gas) by the ODS partially offsets the effect of increased ODS acting as a greenhouse gas.[16,17] In this study, when accounting for the net actual avoided emissions, we used 20% of the difference between ODS CO_2-eq emissions under the projection scenario and under the actual pathway as ozone depletion offset.[18] Note that when assessing the reduction of emissions by the Montreal Protocol, this study excluded emissions of HCFC-22 and R-410A (R-410A is a blend of HFC-125 and HFC-32) from room air conditioners and HCFC-22/HCFC-142b from extruded polystyrene (XPS) foam. They were excluded because these two sectors did not switch from the use of CFCs to HCFCs, i.e., there were no control measures by the Montreal Protocol for these two sectors before 2013. It is important to note that the avoided emission estimate can be different if we were to use a different ODS use projection in China. Therefore, our calculated avoided emissions should be taken as a reasonable estimate and not as a hard number.

The mole fraction of specific ODS i in the year j was calculated from annual ODS emissions, its molecular weight and lifetime, the number of global atmospheric molecules, and other input data (see eqs 1−3).

$$\frac{dC_i}{dt} = F_i \times E_i - \frac{C_i}{\tau_i} \tag{1}$$

Integration of eq 1 yields

$$C_{i,j} = C_{i,j-1} \times \exp\left(-\frac{1}{\tau_i}\right) + F_i \times E_{i,j-1} \times \tau_i \times \left(1 - \exp\left(-\frac{1}{\tau_i}\right)\right) \tag{2}$$

Here $C_{i,j}$ and $C_{i,j-1}$ are the mole fraction (pmol mol^{-1}), $E_{i,j-1}$ is the annual ODS emissions (kg year^{-1}), τ_i is the ODS lifetime (years), and F_i (mol mol^{-1} kg^{-1}) is a factor that relates the mass emitted to the global mole fraction.

$$F_i = \left(\frac{N_A}{N_a}\right)\frac{F_{\text{surf}}}{M_i} = 5.68 \times 10^{-9}\frac{F_{\text{surf}}}{M_i} \tag{3}$$

Here M_i is the molecular weight of ODS i (kg mol^{-1}), N_a is the number of global atmospheric molecules, N_A is Avogadro's number, and F_{surf} is a factor relating the global mean surface mole fraction to the global mean atmospheric mole fraction, which was taken to be 1.07 for all ODSs.[19,20]

RESULTS AND DISCUSSION

Past Emissions of ODSs in China. Estimates of China's ODS emissions are shown in Figure 1 and Figure S2. Unlike previously published studies, our study covers almost all ODS and ODS-related sectors in China and is for a long period (1980−2014). The ODS emission estimates in this study agree well with the top-down estimates by Li et al.,[10] which used the interspecies correlation technique based on measured atmospheric ODS mole fractions at a ground observatory in East Asia (Figure S4), downwind of China. It is, therefore, suggested that estimates of ODS consumption and emissions in this study are likely the most robust to date.

The calculated total emission of ODSs was 9 Kt year^{-1} in 1980, increasing to 196 Kt year^{-1} by 2014 (Figure 1b). These emission numbers are smaller than the corresponding consumption in those years (e.g., 237 Kt year^{-1} in 2014) due to ODS banking, i.e., storage of ODS in equipment (e.g., refrigerators and air conditioners). The diminishing fractional consumption and emissions from firefighting, aerosol, solvent, and other sectors (Figure S2) show that China shifted from ODSs to non-ODS alternatives for such applications. This is consistent with the milestones of actions taken in China to implement the Montreal Protocol (see Figure 1a). For example, phase out of Halons started in the late 1990s after the MLF provided 62 million U.S. dollars to China in 1997. Subsequently, the consumption of Halon-1211 and Halon-1301 has decreased quickly.

Ozone depletion potential (ODP)-weighted emission, also referred to as CFC-11-eq emissions, is a metric used frequently to assess the protection of the ozone layer. This study shows that total CFC-11-eq emissions of all ODSs (latest ODP value for each ODS used here are shown in Table S2) in China increased from 8 Kt CFC-11-eq year^{-1} in 1980 to a peak of 80 Kt CFC-11-eq year^{-1} in 1998; since then the emissions have decreased to 22 Kt CFC-11-eq year^{-1} in 2014 (Figure 1c). The decrease in total CFC-11-eq consumption and emissions of all ODSs after the late 1990s shows that control measures taken comply with the Montreal Protocol succeeded in phasing out China's ODSs.

Global warming potential (GWP; 100-year time horizon) weighted emissions (also referred to as CO$_2$-eq emissions) is a metric for assessing climate impacts.[3] The total CO$_2$-eq emissions of ODSs from China increased from 64 million metric tonnes CO$_2$-eq per year (hereinafter MMt CO$_2$-eq year^{-1}) in 1980 to a maximum of 519 MMt CO$_2$-eq year^{-1} in 1995. Since then, the total CO$_2$-eq emissions of ODSs decreased to 307 MMt CO$_2$-eq year^{-1} in 2006. It is interesting to note that the total mass emissions of HCFCs (green line in the inset of Figure 1b) have surpassed those of all other ODSs combined since 2005 (red line in the inset of Figure 1b). However, because of the lower ODP and GWP of HCFCs relative to CFCs, the CFC-11-eq or CO$_2$-eq emissions of HCFCs (green lines in the insets of Figure 1c and 1d, respectively) were smaller than the corresponding emissions of all other ODSs combined (red lines in the insets of Figure 1c and 1d, respectively).

Significance of Past Emissions from Global and National Perspectives. The fraction of China's CFC-11-eq emissions of ODSs to global total CFC-11-eq emissions of ODSs (an update of Rigby et al.[21]) increased from 0.9% in 1980 to 21% in 2002 and then decreased to 8.3% in 2014 (Figure 2a). However, the fraction of China's total CO$_2$-eq emissions of ODSs and HFCs to global total emissions of ODSs and HFCs increased gradually from 0.9% in 1980 to 24% in 2014 (Figure 2b), which highlights the increasing importance of China's contribution to global climate impact of ODS and HFC emissions.

Fractions of China's total CO$_2$-eq emissions of ODSs and HFCs relative to its national CO$_2$ emissions increased from 4.6% in 1980 to 18% in 1995 and then decreased to 6.4% in 2014 (Figure 2c) showing that emissions of ODSs and substitute HFCs are still important parts of China's greenhouse gas emissions. A part of the reason for the decrease during the last decades, of course, is the continued increases in CO$_2$ emissions from China. Without the Montreal Protocol, the proportions presented in Figure 2c for the years following ~1995 would have been even larger (e.g., the proportion would be 19% in 2014 based on the projected emissions without the Montreal Protocol; see Methods). Proportions of China's total CO$_2$-eq emissions of ODSs and HFCs relative to global total CO$_2$ emissions increased from 0.4% in 1980 to 2.3% in 1995 (while CO$_2$ emissions were increasing), decreased to a lowest value of 1.4% in 2008, and then increased to 1.7% in 2014 (Figure 2d). This suggests that China's ODS and HFC emissions cannot be neglected in global greenhouse gas emission mitigation. Clearly, China's ODS and HFC emissions are still significant and worthy of note.

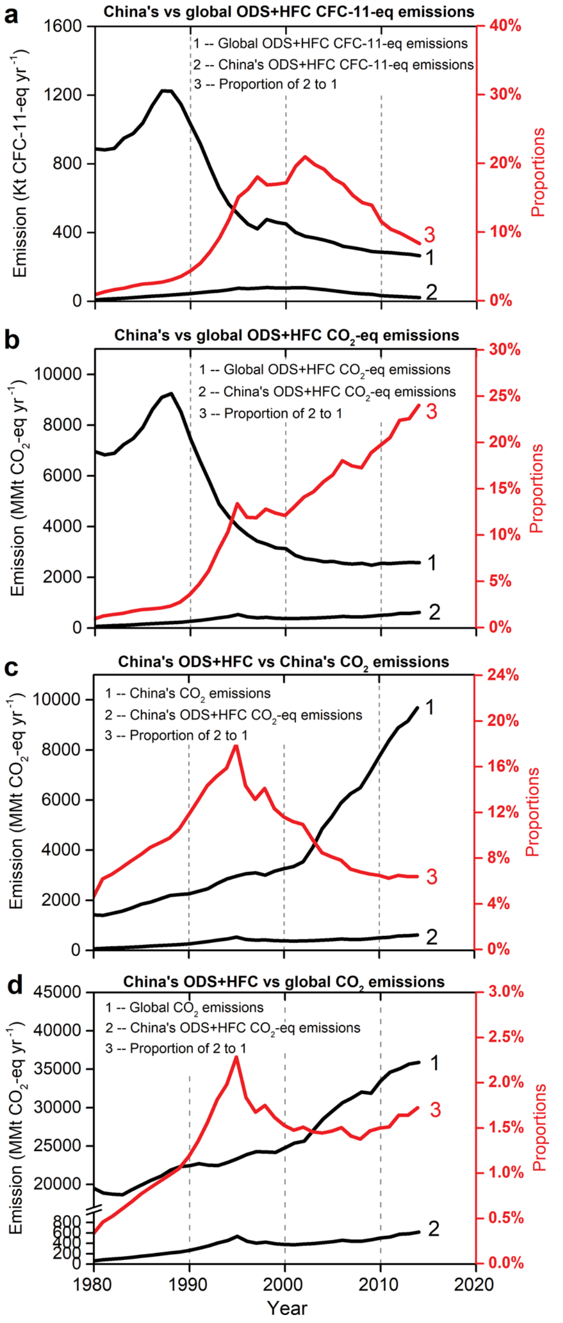

Figure 2. Historical emissions in national and global perspectives (1980−2014). Emissions of ODSs and HFCs in China are compared to global ODS and HFC CFC-11-eq emissions (a), global ODS and HFC CO$_2$-eq emissions (b), China's CO$_2$ emissions (c), and global CO$_2$ emissions (d). Global ODS and HFCs emissions were derived from an update of Rigby et al.[21] China's CO$_2$ emissions for1980−2013 and 2014 were derived from Liu et al.[26] and the Global Carbon Project estimate,[25] respectively. Global CO$_2$ emissions were derived from the Global Carbon Project estimate.[25] In all panels, the fractional contributions (red lines) are also shown (right axis).

China's Future ODS and HFC Emissions. Developments of China's future ODS emissions are of great interest to policymakers, researchers, and the public. Total ODS consumption by mass reached its peak value in 2012 and is expected to gradually decrease to zero by 2040, as required by the Montreal Protocol (Figure S2a). However, this study found that the peak year of the total ODS emissions by mass is 2017, being 214 Kt year^{-1} (Figure S2c). During 2015−2050, HCFC-22, HCFC-141b, and HCFC-142b will be the major compounds contributing to the total ODS emissions, respectively, of 72%, 20%, and 8% in terms of mass, but CFC-11 and CFC-12 will continue to be emitted. The room air-conditioning, industrial/commercial refrigeration, and foam-blowing sectors will each contribute approximately one-third of the total ODS consumption and emissions (Figure S2b,d). Thus, these three compounds and sectors are potential targets for future ODS emission mitigation in China. In the coming three decades, the ODS consumption (mainly HCFCs) in China will be limited by the Montreal Protocol phase-out schedules. The ODS emissions will therefore be determined by the adopted phase-out schedules and release from banks. On the basis of these considerations, China's future ODS emissions are likely defined as long as the country fully complies with the Montreal Protocol.

A recent paper found the emissions of CFC-11 (calculated from global monitoring) to remain roughly constant over the period from around 2002 to 2014 with a further increase by 13 ± 5 Gg year^{-1} (25 ± 13%) during 2014−2016 above the 2002−2012 mean.[22] This finding is in contrast to the expectation that CFC-11 emissions continue to decrease because its production was to have ceased. The authors suggest that this continued larger emissions (beyond what is expected from banks) is likely due to unreported production in East Asia. They do not report such enhanced emissions for other major ODSs (e.g., CFC-12).

It is noted again that our paper deals with reported/scheduled production and usage; such reporting will not be able to discover illegal production/use, which a country may not know and cannot report on. The findings of Montzka et al. highlight the need for continued monitoring, reporting, and verification, steps that are essential for any successful treaty. The high-accuracy measurements of Montzka et al. have uncovered potential unreported emissions before they became large or sustained for long periods of time. If these East Asia emissions are indeed from China, the calculated CFC-11 emissions in this study would be smaller than the actual CFC-11 emissions in China. However, it is to be noted that the unreported emissions detected by Montzka et al. of about 13 Gg year^{-1} since 2012 constitute a fraction of the global ODS emissions of ~280 Gg year^{-1} of CFC-11-eq emissions in 2014 (see global totals in Figure 2a); also, it is a small fraction of the maximum CFC-11-eq emissions of ~1200 Gg year^{-1} at the peak in the late 1980s.

China's future HFCs emissions are very uncertain and highly dependent on the demand for refrigeration, air conditioning, and other applications as well as possible enhancements in HFC regulations in China. HFCs are widely used as substitutes for CFCs and HCFCs. If there were no HFC regulation (line 1 in Figure 3; cited from Fang et al.[23]), the use of HFC in China increases concurrently with HCFC phase out. Then HFC emissions in China are projected to increase from 49 CO_2-eq MMt CO_2-eq year^{-1} in 2010 to 2000−2800 MMt CO_2-eq year^{-1} in 2050,[23] which is much larger than the peak value of historical total CFC and HCFC emissions (520 MMt CO_2-eq year^{-1} in 1995). A "2024 phase down" scenario, line 2 in Figure 3, is close to that agreed to in the HFC Amendment to the Montreal Protocol in Kigali, Rwanda, October 10−14, 2016.[24] This scenario is also cited from Fang et al.,[23] which assumes that HFC consumption in China will be frozen in 2024 at the level of consumption in the previous year and will then decrease gradually by schedule. Under this scenario, HFC emissions from China are projected to reach a peak of 1000−1200 MMt CO_2-eq year^{-1} in 2030,[23] which is also far higher than the peak value of historical total CFC and HCFC emissions (520 MMt CO_2-eq year^{-1} in 1995). A stricter HFC phase-down schedule, which is more stringent than agreed to in the Kigali Amendment, is exemplified by the "2013 North American Proposal" that was put forth before the Amendment (Line 3 in Figure 3; also cited from Fang et al.[23]). This is used merely to illustrate a pathway to further reduce HFC emission and show that there are possible ways to reduce HFC emissions beyond those agreed to in the Kigali Amendment. Even under this hypothetical more ambitious phase-down schedule, HFC emissions will surpass the peak value of historical total ODS emissions in terms of their CO_2-eq.

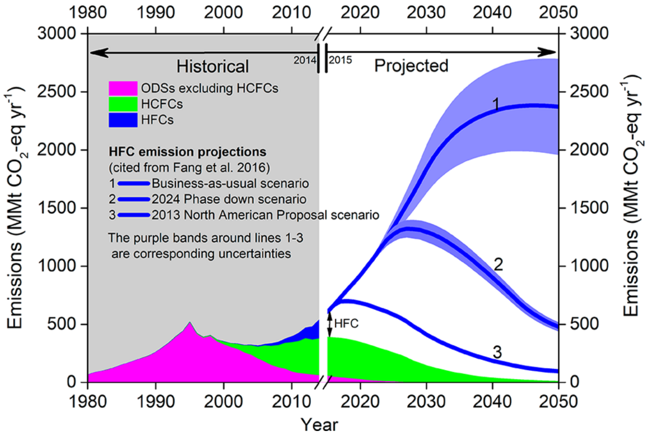

Figure 3. Historical (1980−2014) and projected (2015−2050) emissions of ODSs and HFCs in China. Projections of HFC emissions are cited from Fang et al.[23] The blue bands around lines 1−3 (HFC emission projections) are uncertainties for each projection (also cited from Fang et al.[23]). Projected line 3 is a hypothetical path that is more stringent HFC phase down schedule akin to the "2013 North American Proposal" that was put forth before the Kigali Agreement was adopted. "2024 phase-down scenario", line 2, is close to that of the Kigali Amendment.

Impacts and Costs of Controlling ODSs in China. Without the implementation of the Montreal Protocol and the financial support from MLF, it is likely that emissions of CFCs and other ODSs (excluding HCFCs) in China would have increased substantially. This is evident from the increased consumption of their replacements (e.g., HCFCs and HFCs) during 1995−2014 (Figure S2). This study shows the actual emissions of ODSs and HFCs from China and what the emissions would have been without the Montreal Protocol (Figure 4; see Methods), termed virtual emissions. If the Montreal Protocol had not been implemented in China, the global atmospheric ODS abundances would have continued to increase (red line in Figure S6) and enhanced ozone layer depletion; it would have also delayed the expected ozone layer recovery. Now, clearly, the emissions of ODSs are decreasing for most chemicals as shown by the observed tropospheric abundances of substances controlled under the Montreal Protocol.

This study quantified the impact of implementation of the Montreal Protocol in China. Compared to the emissions of 77 Kt CFC-11-eq year^{-1} in 1995, the emissions were reduced by 58 Kt CFC-11-eq year^{-1} in 2014 (Figure 4a). The avoided emissions (the difference between virtual and actual CFC-11-eq emissions) are even greater; they were 185 Kt CFC-11-eq year^{-1} in 2014, equivalent to ~70% of real global total ODS CFC-11-eq emissions in 2014. The cumulative avoided emissions during 1995−2014 (Table 1) are estimated to reach 1700 CFC-11-eq Kt. Of course, the exact estimates of

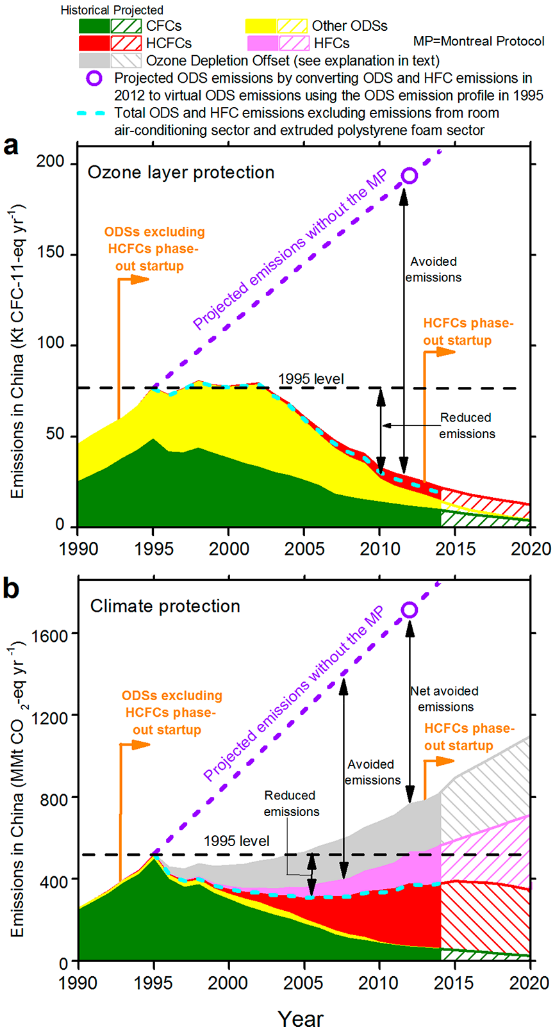

Figure 4. Benefits of the China's adoption of the Montreal Protocol for protecting the ozone layer (a) and climate (b). Reduced emissions, avoided emissions and net avoided emissions measure the benefits of the Montreal Protocol in China. The estimated emissions were historical before 2014 and projected after 2015. Note that the projection of ODS emissions without the Montreal Protocol (purple dashed lines) is not based on the emissions with an increasing trend in 1991−1995 (see Methods).

Table 1. Benefits to the Ozone Layer (kilo tonnes CFC-11-eq) and Climate (million tonnes CO$_2$-eq) Due to Emission Reductions in China in Accordance with the Montreal Protocol

	benefit to the ozone layer		benefit to climate	
	reduced emissions[a]	avoided emissions	reduced emissions[a]	avoided emissions[b]
2000	0	33	206	395
2005	18	85	258	646
2010	46	147	203	784
2014	58	185	133	850
1995−2014	420	1700	3760	11 000

[a] Reduction in emissions compared to the year 1995. [b] The ozone depletion offset is considered since the increase in atmospheric ODSs has an indirect negative (cooling) potential on Earth's climate response due to the associated depletion of stratospheric ozone (see main text).

the benefits of avoided emissions are somewhat uncertain since we do know exactly the course that would have been taken by China (or any other country). Yet, it is evident that China's actions directly benefited the protecting the ozone layer, as did the actions of other countries that signed on to the Montreal Protocol.

The climate cobenefits of ODS controls in China were also investigated (Figure 4b). The maximum CO$_2$-eq emission reduction compared to emissions in 1995 was 258 MMt CO$_2$-eq year^{-1} in 2005. The net avoided emissions were 850 MMt CO$_2$-eq year^{-1} in 2014, the last year of our available data. This is equivalent to ∼9% of China's national fossil fuel CO$_2$ emissions. The cumulative net avoided emissions during the 1995−2014 period were 11 000 MMt CO$_2$-eq, which is larger than China's total 2014 CO$_2$ emissions of 9680 MMt,[25,26] i.e., China avoided more than 1 year of CO$_2$ emissions during the two decades of adhering the Montreal Protocol.

As of 2011, China's ODS phase-out activities had received approximately 1.2 billion USD (2014 USD) in financial support from the MLF. Cumulative reduced and avoided CO$_2$-eq emissions up to 2011 were estimated to be about 2880 and 8550 MMt CO$_2$-eq, respectively. Thus, the cost per tonne of avoided and reduced CO$_2$-eq emissions for the donor organization was 0.14 and 0.42 USD, respectively. These numbers are much lower than the CO$_2$ price of 2.9−37.8 USD per tonne between April 2008 and December 2014 under the European Union Emission Trading Scheme.[27] Thus, it is clear that the MLF approach was effective in reducing emissions and very likely highly cost effective for the donor nations.

In the coming three decades, the ODS consumption (mainly HCFCs) in China will be strongly limited by the Montreal Protocol HCFCs phase-out schedule. Thus, it will extend the benefit of the protocol for the ozone layer that has been achieved in the last two decades. However, the benefit to climate will be at risk due to the increasing use of HFCs. Even under the HFC-control emission scenario ("2024 phase-down" scenario; line 2 in Figure 3), HFC emissions (e.g., 1150 MMt CO$_2$-eq year^{-1} in 2030) would surpass the climate benefit achieved by reducing ODS emissions. To preserve this climate cobenefit, HFC usage in China would need to be more stringent than that agreed to in the Kigali Amendment to the Montreal Protocol.

Implications. The above analysis for China's ODS emission changes, based solely on reported production and usage, appear to be in compliance with the Montreal Protocol. This reduction suggests that future phase down of HFCs could similarly benefit from the successful mechanisms of ODS phase out achieved under the Montreal Protocol. Further, if similar HFC phase-down controls of potentially large HFC emissions are enacted and adhered to by other countries with increasing emissions, e.g., India, there would be substantial contribution of HFC phase down to mitigate global climate change. Furthermore, the methodology used in this study could be applied to study other countries with substantial ODS and HFC emissions, especially developing countries where comprehensive assessments of the implementation of the Montreal Protocol are lacking.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications Web site at The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b01280.

Data that support the findings of this study (XLSX)

Detailed methodologies for calculating ODS emissions in each sector for each ODS; ODP, GWP, lifetime of each ODS, ODS phase-out schedule, parameters used in the emission estimation, estimated consumption and emissions, and other parameters (PDF)

AUTHOR INFORMATION

Corresponding Authors

*E-mail:fangxk@mit.edu.
*E-mail: A.R.Ravishankara@colostate.edu.
*E-mail: jianxin@pku.edu.cn.

ORCID

Xuekun Fang: 0000-0002-7055-0644
A. R. Ravishankara: 0000-0001-9059-8437
Jianbo Zhang: 0000-0001-8937-0953

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported in part by a National Aeronautics and Space Administration (NASA) grant NNX11AF17G awarded to the Massachusetts Institute of Technology (MIT). We are also thankful for the support from the Collaborative Innovation Center for Regional Environmental Quality of China. Work by A.R.R. was supported by Colorado State University. We thank Jooil Kim, Shanlan Li, Pengju Bie, Zhifang Li, and Ziyuan Wang for comments and suggestions on the manuscript. We thank Matt Rigby at the University of Bristol, UK, for providing estimates of global emissions of each ODS and HFC, which is an update of Rigby et al.[21] We thank Martin Wolf from the Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, for his edits to the paper. The views presented here are those of the authors and do not necessarily represent the views of the organizations where they are employed.

REFERENCES

(1) *Handbook for the Montreal Protocol on Substances That Deplete the Ozone Layer*, 7th ed.; United Nations Environment Programme: Nairobi, Kenya, 2009; http://ozone.unep.org/Publications/MP_Handbook/MP-Handbook-2009.pdf.

(2) Hurwitz, M. M.; Fleming, E. L.; Newman, P. A.; Li, F.; Mlawer, E.; Cady-Pereira, K.; Bailey, R. Ozone depletion by hydrofluorocarbons. *Geophys. Res. Lett.* **2015**, *42* (20), 8686−8692.

(3) *Assessment for Decision-Makers: Scientific Assessment of Ozone Depletion: 2014. Global Ozone Research and Monitoring Project, Report No. 56*; World Meteorological Organization: Geneva, Switzerland, 2014.

(4) Ravishankara, A. R.; Turnipseed, A. A.; Jensen, N. R.; Barone, S.; Mills, M.; Howard, C. J.; Solomon, S. Do Hydrofluorocarbons Destroy Stratospheric Ozone. *Science* **1994**, *263* (5143), 71−75.

(5) Wan, D.; Xu, J. H.; Zhang, J. B.; Tong, X. C.; Hu, J. X. Historical and projected emissions of major halocarbons in China. *Atmos. Environ.* **2009**, *43* (36), 5822−5829.

(6) Zhao, X. Y.; Duan, H. B.; Li, J. H. An evaluation on the environmental consequences of residual CFCs from obsolete household refrigerators in China. *Waste Manage.* **2011**, *31* (3), 555−560.

(7) *Emission Database for Global Atmospheric Research (EDGAR), release version 4.2*; European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL), 2011; http://edgar.jrc.ec.europa.eu (accessed Mar 22, 2012).

(8) Vollmer, M. K.; Zhou, L. X.; Greally, B. R.; Henne, S.; Yao, B.; Reimann, S.; Stordal, F.; Cunnold, D. M.; Zhang, X. C.; Maione, M.; Zhang, F.; Huang, J.; Simmonds, P. G. Emissions of ozone-depleting halocarbons from China. *Geophys. Res. Lett.* **2009**, *36*, L15823.

(9) Stohl, A.; Kim, J.; Li, S.; O'Doherty, S.; Mühle, J.; Salameh, P. K.; Saito, T.; Vollmer, M. K.; Wan, D.; Weiss, R. F.; Yao, B.; Yokouchi, Y.; Zhou, L. X. Hydrochlorofluorocarbon and hydrofluorocarbon emissions in East Asia determined by inverse modeling. *Atmos. Chem. Phys.* **2010**, *10* (8), 3545−3560.

(10) Li, S.; Kim, J.; Kim, K. R.; Mühle, J.; Kim, S. K.; Park, M. K.; Stohl, A.; Kang, D. J.; Arnold, T.; Harth, C. M.; Salameh, P. K.; Weiss, R. F. Emissions of Halogenated Compounds in East Asia Determined from Measurements at Jeju Island, Korea. *Environ. Sci. Technol.* **2011**, *45* (13), 5668−5675.

(11) Kim, J.; Li, S.; Kim, K. R.; Stohl, A.; Mühle, J.; Kim, S. K.; Park, M. K.; Kang, D. J.; Lee, G.; Harth, C. M.; Salameh, P. K.; Weiss, R. F. Regional atmospheric emissions determined from measurements at Jeju Island, Korea: Halogenated compounds from China. *Geophys. Res. Lett.* **2010**, *37* (12), L12801.

(12) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Intergovernmental Panel on Climate Change: Japan, 2006; Vol. 3 (Industrial process and product use).

(13) Wang, F.; Zhang, J.; Feng, J.; Liu, D. Estimated historical and future emissions of CFC-11 and CFC-12 in China (in Chinese with English abstract). *Acta Sci. Circumstantiae* **2010**, *30* (9), 1758−1765.

(14) Fang, X.; Thompson, R. L.; Saito, T.; Yokouchi, Y.; Kim, J.; Li, S.; Kim, K. R.; Park, S.; Graziosi, F.; Stohl, A. Sulfur hexafluoride (SF6) emissions in East Asia determined by inverse modeling. *Atmos. Chem. Phys.* **2014**, *14* (9), 4779−4791.

(15) Simmonds, P. G.; Rigby, M.; McCulloch, A.; Vollmer, M. K.; Henne, S.; Mühle, J.; O'Doherty, S.; Manning, A. J.; Krummel, P. B.; Fraser, P. J.; Young, D.; Weiss, R. F.; Salameh, P. K.; Harth, C. M.; Reimann, S.; Trudinger, C. M.; Steele, P.; Wang, R. H. J.; Ivy, D. J.; Prinn, R. G.; Mitrevski, B.; Etheridge, D. M. Recent increases in the atmospheric growth rate and emissions of HFC-23 (CHF3) and the link to HCFC-22 (CHClF2) production. *Atmos. Chem. Phys. Discuss.* **2017**, *2017*, 1−31.

(16) Shindell, D.; Faluvegi, G.; Nazarenko, L.; Bowman, K.; Lamarque, J.-F.; Voulgarakis, A.; Schmidt, G. A.; Pechony, O.; Ruedy, R. Attribution of historical ozone forcing to anthropogenic emissions. *Nat. Clim. Change* **2013**, *3*, 567.

(17) Ramaswamy, V.; Schwarzkopf, M. D.; Shine, K. P. Radiative forcing of climate from halocarbon-induced global stratospheric ozone loss. *Nature* **1992**, *355* (6363), 810−812.

(18) Velders, G. J. M.; Andersen, S. O.; Daniel, J. S.; Fahey, D. W.; McFarland, M. The importance of the Montreal Protocol in protecting climate. *Proc. Natl. Acad. Sci. U. S. A.* **2007**, *104* (12), 4814−4819.

(19) *Scientific assessment of ozone depletion: 2010. Global Ozone Research and Monitoring Project, Report No. 52*; World Meteorological Organization: Geneva, Switzerland, 2011; http://ozone.unep.org/Assessment_Panels/SAP/Scientific_Assessment_2010/index.shtml (accessed Jan 1, 2012).

(20) Velders, G. J. M.; Daniel, J. S. Uncertainty analysis of projections of ozone-depleting substances: mixing ratios, EESC, ODPs, and GWPs. *Atmos. Chem. Phys.* **2014**, *14* (6), 2757−2776.

(21) Rigby, M.; Prinn, R. G.; O'Doherty, S.; Miller, B. R.; Ivy, D.; Mühle, J.; Harth, C. M.; Salameh, P. K.; Arnold, T.; Weiss, R. F.; Krummel, P. B.; Steele, L. P.; Fraser, P. J.; Young, D.; Simmonds, P. G. Recent and future trends in synthetic greenhouse gas radiative forcing. *Geophys. Res. Lett.* **2014**, *41* (7), 2623−2630.

(22) Montzka, S. A.; Dutton, G. S.; Yu, P.; Ray, E.; Portmann, R. W.; Daniel, J. S.; Kuijpers, L.; Hall, B. D.; Mondeel, D.; Siso, C.; Nance, J. D.; Rigby, M.; Manning, A. J.; Hu, L.; Moore, F.; Miller, B. R.; Elkins, J. W. An unexpected and persistent increase in global emissions of ozone-depleting. *Nature* **2018**, *557* (7705), 413−417.

(23) Fang, X.; Velders, G. J. M.; Ravishankara, A. R.; Molina, M. J.; Hu, J.; Prinn, R. G. Hydrofluorocarbon (HFC) Emissions in China: An Inventory for 2005−2013 and Projections to 2050. *Environ. Sci. Technol.* **2016**, *50* (4), 2027−2034.

(24) *The Kigali Amendment to the Montreal Protocol: HFC Phase-down*; United Nations Environment Programme, 2016; http://www.unep.org/ozonaction/Portals/105/documents/7809-e-Factsheet_Kigali_Amendment_to_MP.pdf.

(25) Le Quéré, C.; Moriarty, R.; Andrew, R. M.; Peters, G. P.; Ciais, P.; Friedlingstein, P.; Jones, S. D.; Sitch, S.; Tans, P.; Arneth, A.; Boden, T. A.; Bopp, L.; Bozec, Y.; Canadell, J. G.; Chini, L. P.; Chevallier, F.; Cosca, C. E.; Harris, I.; Hoppema, M.; Houghton, R. A.; House, J. I.; Jain, A. K.; Johannessen, T.; Kato, E.; Keeling, R. F.; Kitidis, V.; Klein Goldewijk, K.; Koven, C.; Landa, C. S.; Landschützer, P.; Lenton, A.; Lima, I. D.; Marland, G.; Mathis, J. T.; Metzl, N.; Nojiri, Y.; Olsen, A.; Ono, T.; Peng, S.; Peters, W.; Pfeil, B.; Poulter, B.; Raupach, M. R.; Regnier, P.; Rödenbeck, C.; Saito, S.; Salisbury, J. E.; Schuster, U.; Schwinger, J.; Séférian, R.; Segschneider, J.; Steinhoff, T.; Stocker, B. D.; Sutton, A. J.; Takahashi, T.; Tilbrook, B.; van der Werf, G. R.; Viovy, N.; Wang, Y. P.; Wanninkhof, R.; Wiltshire, A.; Zeng, N. Global carbon budget 2014. *Earth Syst. Sci. Data* **2015**, 7 (1), 47−85.

(26) Liu, Z.; Guan, D.; Wei, W.; Davis, S. J.; Ciais, P.; Bai, J.; Peng, S.; Zhang, Q.; Hubacek, K.; Marland, G.; Andres, R. J.; Crawford-Brown, D.; Lin, J.; Zhao, H.; Hong, C.; Boden, T. A.; Feng, K.; Peters, G. P.; Xi, F.; Liu, J.; Li, Y.; Zhao, Y.; Zeng, N.; He, K. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* **2015**, *524* (7565), 335−338.

(27) ECX EUA Futures; https://www.quandl.com/data/ICE/CZ2014-ECX-EUA-Futures-December-2014-CZ2014.