Article

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Historical emissions of HFC-23 (CHF_3) in China and projections upon policy options by 2050

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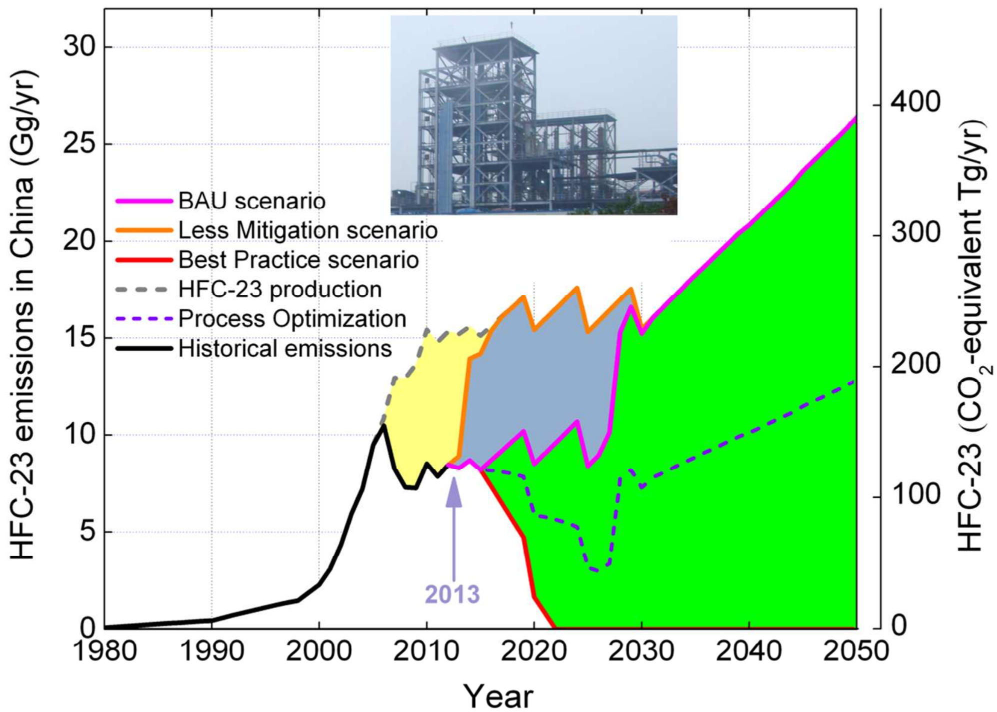
BAU scenario
Less Mitigation scenario
Best Practice scenario
HFC-23 production
Process Optimization
Historical emissions
2013
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HFC-23 (CO_2-equivalent Tg/yr)
Year
0
5
10
15
20
25
30
100
200
300
400
1980
1990
2000
2010
2020
2030
2040
2050

Abstract:

Trifluoromethane (CHF_3, HFC-23) is one of the hydrofluorocarbons (HFCs) regulated under the Kyoto Protocol with a global warming potential (GWP) of 14800 (100-year). China's past, present and future HFC-23 emissions are of considerable interest to researchers and policymakers involved in climate change. In this study, we compiled a comprehensive historical inventory (1980–2012) and a projection (2013–2050) of HFC-23 production, abatements and emissions in China. Results show that HFC-23 production in China increased from 0.08 ± 0.05 Gg/yr in 1980 to 15.4 ± 2.1 Gg/yr (228 ± 31 Tg/yr CO_2-eq) in 2012, while actual HFC-23 emissions reached a peak of 10.5 ± 1.8 Gg/yr (155 ± 27 Tg/yr CO_2-eq) in 2006, and decreased to a minimum of 7.3 ± 1.3 Gg/yr (108 ± 19 Tg/yr CO_2-eq) in 2008 and 2009. Under the examined business-as-usual (BAU) scenario, the cumulative emissions of HFC-23 in China over the period 2013–2050 are projected to be 609 Gg (9015 Tg CO_2-eq which approximates China's 2012 CO_2 emissions). Currently, China's annual HFC-23 emissions are much higher than those from the developed countries, while it is estimated that by year 2027, China's historic contribution to the global atmospheric burden of HFC-23 will have surpassed that of the developed nations under the BAU scenario.

Introduction

Trifluoromethane (CHF_3, HFC-23) is a potent greenhouse gas (GHG) regulated under the Kyoto Protocol with a global warming potential (GWP) of 14800 over a 100 year time horizon and an atmospheric lifetime of 270 years.[1] HFC-23 is an unavoidable by-product in the production of chlorodifluoromethane ($CHClF_2$, HCFC-22) which is applied widely in air conditioning, commercial refrigeration, extruded polystyrene (XPS) foams (termed “dispersive production”), and also used as a feedstock in Pentafluoroethane (CF_3CHF_2, HFC-125) production[2] and fluoropolymer manufacture[3] (termed “feedstock production”). Bottom-up estimates show that before 2001 developed countries dominated in HFC-23 production, while thereafter developing countries took over the leading role due to a substantial increase of HCFC-22 production since the 1990s. Due to the lack of market for the by-product HFC-23, it has historically been directly emitted to the atmosphere from the HCFC-22 production facilities, and this practice continues to a significant extent today.[4]

In 2007, the Montreal Protocol Parties reached an agreement with an accelerated phase-out schedule for production and consumption of HCFCs for dispersive applications in developed and developing countries.[5] Dispersive production of HCFCs in developing countries including China, will be subject to a phase-out beginning with a freeze in 2013 at the baseline level of the average of 2009 and 2010 ODP-weighted production, followed by a 10% reduction with respect to that by 2015, a 35% reduction by 2020, a 67.5% reduction by 2025 and a 97.5% reduction by 2030.[6]

However, the production of HCFC-22 for use as feedstock is unrestricted currently and for the foreseeable future. Therefore, future HFC-23 production is anticipated to be controlled by the increase of HCFC-22 feedstock production versus the decrease of HCFC-22 dispersive production.

Abatement of HFC-23 emissions is an important factor contributing to the difference between HFC-23 production and its actual emission. Since 2006, destruction (incineration) of HFC-23 has been implemented in China under the United Nations Framework Convention on Climate Change's (UNFCCC) Clean Development Mechanism (CDM). There are a total of 19 CDM projects globally, with 11 of these located in China. Four Chinese CDM projects started in 2006, followed by five starting in 2007, another starting in 2008 and a final project starting in 2009.[7] When expiration of the first seven-year crediting period of CDM projects in China starts in 2013, whether the abatement measures continue or not will certainly have an impact on future HFC-23 emissions in China and globally.

HFC-23 emissions from China are suspected to have made the biggest contribution to the recent annual global emissions, especially to the increase of HFC-23 emissions in developing countries.[4] Li et al. revealed the significance of HFC-23 emissions in China for the period Nov-2007 to Dec-2008, which were estimated to contribute 74% to global HFC-23 emissions and 95% to total East Asian HFC-23 emissions.[8] A number of other studies have estimated HFC-23 emissions from China. The earliest of these used a tagged-tracer simulation in a 3D transport model and a tracer-ratio technique and estimated the emission to be 10 ± 4.6 Gg/yr for the period Apr-2004 to

May-2005.[9] More recent studies show a discrepancy among estimates, e.g., top-down estimates 6.2±0.7 Gg/yr for 2008,[10] 12 (8.6–15) Gg/yr for the period Nov-2007–Dec-2008,[11] 10 (7.2–13) Gg/yr for the period Nov-2007–Dec-2008,[8] and a bottom-up estimate 13.0 Gg/yr for 2008.[12]

While these recent studies do provide insight into annual emissions for specific years, in order to understand the driving forces behind Chinese HFC-23 emissions, there is the need for a long-term assessment of Chinese HFC-23 production, abatement and emission. In this study, we first compile comprehensive inventories of historical HFC-23 production, abatement and emission in China for the period 1980–2012, and gain some insight into the factors governing these processes. We then project these factors forward through the year 2050 to illustrate their influence on future HFC-23 emissions. Finally, we quantify past, current and future contributions from China, from the developing countries excluding China and from the developed countries to the atmospheric abundance of HFC-23.

Estimating historical emissions

HCFC-22 production

Only total HCFC (not individual HCFC) production data are available from the data center of United Nations Environment Programme.[13] Even if we assume that HCFC-22 makes up 100% of the total production (indeed HCFC-22 is the largest contributor), we could not calculate the total HCFC-22 production values because the feedstock production information is not obligatory to the public and not shown in this data set. Therefore, we could not use this data set. Fortunately, information from other sources for some years is available. Annual production for HCFC-22 was obtained in some nation-wide production surveys,[14] as well as specific information of components of HCFC-22 production from 2000 onwards including domestic dispersive and feedstock production and exported dispersive and feedstock production. The data reveal that HCFC-22 production increased from 70 Gg/yr in 2000 to 549 Gg/yr in 2010. Production data for 2011 and 2012 are available from industry market websites (http://www.chinaiol.com/). After summing up the monthly reported production, annual total production was estimated to be 530 in 2011 and 543 Gg/yr in 2012.

Production data for the period 1980-1999 are sparse. In the late 1950s, trial production of HCFC-22 started in China, and by the end of the 1970s, HCFC-22 production amounted to less than 2 Gg/yr. Thereafter, due to the expansion of freezers, air conditioners, and fluoropolymer industrial sector, the demand for HCFC-22 increased rapidly. The production in the year 1990 was estimated to be 12 Gg/yr. For 1997, HCFC-22 total production was officially reported in the document of National Program for Ozone-depleting Substances Phase-out in China to be 40 Gg/yr.[15] HCFC-22 production in 1998 was estimated to be 44 Gg/yr.[16] Production data for other missing years in the 1980s and 1990s were interpolated linearly between the values stated above. The total production in these two decades were really small, about one fiftieth of production in 2010, therefore, errors in the values for these decades will not strongly influence the total production from 1980 to 2012.

Co-production ratio of HFC-23/HCFC-22

Co-production ratio of HFC-23/HCFC-22 (mass ratio) is a crucial parameter for calculating the HFC-23 production and subsequent emissions. In order to produce Certified Emission Reduction (CER) credits from HFC-23 incineration, CDM plants continuously monitored HFC-23 and HCFC-22 production. This information is well documented in the submitted CDM project monitoring reports, which typically span 2–6 months of production. Co-production ratios for the period 2006–2013 are available in these monitoring reports, which can be downloaded from the CDM project database.[7] For the years 2002–2004, Project Design Documents (PDD) provide the more "historical" co-production ratios. Individual ratios from 264 monitoring reports (accessed as of 1st July 2013) and 11 PDD for 11 projects in China are shown in supporting information (SI) Fig. S1, as well as values from CDM HFC-23 projects in other countries (Project 0807 in Argentina was excluded due to incomplete information in the monitoring reports). Independent-samples t-tests show that there is no significant difference between co-production ratios in China and in other countries (2-tailed).

The red hollow circles in Fig. S1 show the annual mean co-production ratios weighted by the HCFC-22 production in each plant. Note that for estimating the annual mean co-production ratio for each year, production of HFC-23 and HCFC-22 in some monitoring reports were divided into two parts weighted by the number of days inside or outside of that year if that monitoring period crossed over two years. The calculated annual mean co-production ratios reveal a slight decrease over time, from 3.31% in 2002 to 2.83% in 2012. The annual relative standard deviations of the co-production ratios from 11 facilities were highest in 2003 (29%) and lowest in 2012 (11%). Ratio data for the years 2006 and 2007 were excluded in this comparison since most projects had not been launched yet in these two years. For estimating the co-production ratio prior to 2002 and in 2005, 2006 and 2007, a linear extrapolation of the 2002–2004 and 2008–2012 ratio data was used.

Based on the total HCFC-22 production from the CDM monitoring reports and the estimated HCFC-22 total production from Section 0, we attribute 48 ± 2% of total annual Chinese HCFC-22 production to the CDM projects during 2009–2012. Considering CDM projects cover almost half of total HCFC-22 production in China, we made the simple assumption that the mean co-production ratios of HFC-23/HCFC-22 in these CDM projects represent the mean values from all HCFC-22 production plants in China.

Incineration of HFC-23 from HCFC-22 production

Annual amounts of HFC-23 involved in CDM projects in China are shown in Fig. S2. Eleven projects have produced HFC-23 emission reductions of 32 Gg eligible for CER credits between 2006 and 2012 (shown as the left bar for each year in Fig. S2). However, CER-eligible emission reductions are smaller than the real HFC-23 emission reductions, since some of the HFC-23 incinerations are not eligible for CER credits (for instance, if the waste gas generation ratio or HCFC-22 production exceeded the plant's historic values as documented in the Project Design Document).

Each project monitoring report accounted for actual HFC-23 production, incineration, sales, storage and releases, and annual 'non-release' amounts were determined (shown as the right bar for each year in Fig. S2), which appear on average to be about 20% (10%–24%) higher than the annual amounts eligible for CER credits (left bars). Therefore, a total of about 38 Gg HFC-23 was actually prevented from being released to the atmosphere during 2006–2012 compared to the 32 Gg CER-eligible reductions. Since all CDM projects in China were in operation by 2009, the annual amount eligible for CER credits and "non-release" amounts have been relatively constant thereafter.

Assembling an inventory of HFC-23 emissions

Annual total production of HFC-23 is calculated as the sum of annual domestic HCFC-22 production for feedstock and dispersive uses and exported HCFC-22 production for feedstock and dispersive uses (compiled in Sect. 0), multiplied by the mean annual co-production ratios of HFC-23/HCFC-22 (Sect. 0). Then Eq. 1 was used for estimating emissions of HFC-23. HFC-23 may be used as feedstock in the production of Halon-1301, as a fire extinguishing agent or as an etching agent in the semiconductor industry. The application of HFC-23 in these industrial sectors was assumed negligible, according to the assumption made for the global estimate as described by Miller et al.[4] The overall uncertainties of annual total HFC-23 emissions were estimated based on uncertainties assigned to the individual components (see Table S1). The assigned uncertainties for earlier time are larger than those for later time, e.g., the uncertainties of HCFC-22 production during 1980–1996 and 1999 are 50%, while the uncertainties of HCFC-22 production during 2000 – 2010 are 5%.

$$E = P - A - \sum C_i + \sum E_i \qquad (1)$$

Here E is annual total emission (Gg/yr), P is annual total production (Gg/yr), A is annual non-release amount (Gg/yr) by abatement measures (e.g., CDM projects), C_i is consumed amount in application sector *i* (Gg/yr), and E_i is emission from application sector *i* (Gg/yr). Second National Communication on Climate Change of The People's Republic of China shows that emissions of HFC-23 in semiconductor sector in 2005 was 0.0044 Gg/yr, which is about 1/200 of the estimated total HFC-23 emissions[17]. Thus $\sum C_i$ and $\sum E_i$ (in Eq. 1) were assigned to zero.

Historical emissions in China: 1980–2012

Historical HFC-23 emissions

Estimates of the annual HFC-23 production and emission in China for the period 1980–2012 are plotted in Fig. 1. The HFC-23 production increased from 0.08 ± 0.05 Gg/yr in 1980 to 15.4 ± 2.1 Gg/yr in 2012. Note that the growth rate started to accelerate in the mid-1990s. For the period 1980–1990, the annual growth rate was estimated to be 0.04 Gg/yr, while for the period 1990−2000, the growth rate increased to 0.18 Gg/yr. After 2000, the annual growth rate was 1.1 Gg/yr. During 2000–2010, all three HFC-23 production components were found to increase, including HCFC-22 domestic dispersive production, feedstock production and exported production.

Contribution from domestic dispersive production to national totals was about 60% at the beginning of 2000s and declined to about 40% in 2010, while contributions from domestic feedstock production increased from 25% to 35% during this period. Contributions from exported production are about 25%.

The annual national total HFC-23 emissions were equal to the HFC-23 production until 2006 when CDM projects were launched to abate HFC-23 in China. Due to the emission reductions in 2006, the actual emissions of HFC-23 were 0.4 Gg/yr lower than the production. In 2006, HFC-23 emissions reached a peak of 10.5 ± 1.8 Gg/yr and then decreased to a minimum of 7.3 ± 1.3 Gg/yr in 2008 and 2009, followed by a slight increase to 8.5 ± 2.1 Gg/yr in 2012 when CDM projects abated about 45% of the HFC-23 produced. Of note is that since HCFC-22 production in non-CDM plants were started later than that of CDM plants, the co-production ratios of HFC-23/HCFC-22 in non-CDM plants may be lower than those in CDM plants due to technical improvement. This could lead to the result that the annual HFC-23 production and emissions in China in recent years are smaller than those estimated in this study. However, information about recent co-production ratios in non-CDM plants is currently very limited.

Comparison with other estimates

We compared our results with other published estimates using either bottom-up or top-down approaches (Fig. 2). Using observation data from Hateruma station, a tagged simulation from three-dimensional transport model and a tracer-ratio technique, the HFC-23 emissions from China for May-2004 to May-2005 were estimated to 10 ± 4.6 Gg/yr.[9] Based on observation data from three East Asian stations and inverse modeling, the HFC-23 emissions in 2008 were determined to be 6.2 ± 0.7 Gg/yr.[10] Our estimates are close to these two estimates. However, larger differences are found when compared to estimates of Li et al.[8] and Kim et al.[11] who used observation data at the Gosan station and a tracer ratio method. It seems that the estimate in Kim et al.[11] is identical to the global emissions which is derived from 2-D 12-box model inversions of AGAGE observations.[4] Emissions for the period May-2010 to May-2011 estimated using observation data at Shangdianzi station in Yao et al.[18] are significantly lower than our estimates. HFC-23 is mostly emitted from point sources (HCFC-22 production plants), while sources of reference species carbon monoxide (CO) adopted by Yao et al.[18] and HCFC-22 adopted by Li et al.[8] and Kim et al.[11] are widely spread. Therefore, the assumption of co-location of target species and reference species in the tracer-ratio method used in three studies above is not fully valid.

Comparisons were made with other bottom-up estimates (Fig. 2). Our estimates agree well with the officially reported value of 9 Gg/yr for 2005 in Second National Communication from China to UNFCCC[17]. EDGAR v4.2 provides a time series of bottom-up estimates of HFC-23 emissions in China until 2008, which appears close to our estimates within 1990–2000 but becomes higher (40% on average for the period 2001–2008) than our estimates thereafter. Note that the EDGAR v4.2 estimates for China are even larger than the global emissions in 2007 and 2008. Our estimate agrees with the estimates for 2000–2008[14] and for 2000–2010[19], even though there are some minor differences in parameters used in these three studies. e.g. a constant co-production ratio of 2.85% for all years was used by Cui et al.[19] while different annual mean co-production ratios were used in this study. Relatively big differences occurred in 2006 and 2007 among these three bottom-up estimates. Difference between HFC-23 production and emissions in 2006 is estimated as 3.5 Gg/yr in Feng et al.[14], larger than the other estimates, which is likely due to being unaware of the difference between the designed reduction capacity and the actually achieved destruction of HFC-23 in that year.

National and Global perspective

Relatively complete information of other HFC emissions is available from Li et al.[8] for 2008. After comparing HFC-23 emissions estimated in this study with other HFC emissions in Li et al.[8], we found that HFC-23 emissions rank second after HFC-134a in the contribution to national total HFC emissions (Fig. 3, lower left). However, in terms of the100-year GWP,[1] the contribution pattern becomes vastly different. GWP-weighted HFC-23 emissions were calculated to be 108 ± 20 Tg/yr CO_2-eq in 2008 and emissions of other HFCs were calculated to be 29 ± 8 Tg/yr CO_2-eq. This shows that HFC-23 emissions constituted 79 ± 6% of the national total GWP-weighted HFC emissions, revealing a dominant role of HFC-23 in the GWP-weighted HFC emissions in the year 2008 in China.

The contribution of HFC-23 emissions from China to the global total is also plotted in Fig. 3 (top panel). Global emissions for the period 1980–2009 were derived from top-down inversions in Miller et al.[4] The calculated contributions from Chinese emissions to global emissions displayed a gradual increase from 2 ± 1% in 1980 to 20 ± 6% in 2000 followed by a sharp increase to 77 ± 23% in 2005. The growth rate of contribution after 2000 is much higher than before 2000, which is consistent with the accelerated growth rate of HFC-23 production in China after 2000.

Projecting emissions in China: 2013–2035

Policy options and emission scenarios

First, we defined our business-as-usual (BAU) scenario. There are four components of HCFC-22 production in China. The first one is domestic dispersive production, which will be subject to Montreal Protocol phase out schedule of a 10% reduction by 2015 compared to the baseline of the average of 2009 and 2010 production, a 35% reduction by 2020, a 67.5% reduction by 2025 and a 97.5% reduction by 2030 that is averaged over the next 10 years. The second one is domestic feedstock production, which is extrapolated based on GDP growth of China provided by the EIA[20]. Tests show that the standardized domestic HCFC-22 feedstock production is significantly correlated with the standardized GDP during the period 2000–2012 ($P<0.05$), and that the slope for this correlation is close to "1" (see Fig. S3). We also chose the GDP Reference Case based on purchasing power parity out of three GDP projections offered in the report, which is the same input as used in the global HFC-23 emission projections by Miller and Kuijpers[21]. The relative growth rate of GDP in this case is estimated to be 8.12% during 2007–2015 and will decrease afterwards to 3.49% during 2030–2035. The third HCFC-22 production component is exported dispersive production, which is assumed to follow the Montreal Protocol phase out schedule as well since dispersive production is mainly exported to developing countries. The last component is exported feedstock production, which is extrapolated based on GDP growth of the whole world excluding China. EIA (2010) only provided GDP projection to 2035, thus we linearly extroplated GDP to 2050 based on values in 2030–2035. The average of the annual mean co-production ratio of HFC-23/HCFC-22 during 2008–2012 in China, 2.82%, was used for the projection calculation. In this BAU scenario, it was assumed that the CDM projects in China are approved for a total of three consecutive crediting periods ending between 2027 and 2030.

Second, we defined a Less Mitigation (LM) scenario, in which the abatement of HFC-23 in CDM projects will cease after the first crediting period and no abatement will exist in China thereafter. The CDM projects in China will end their first crediting period during 2013–2016 after 7 years of operation. The European Commission decided that the EU would cease the purchase of CER credits derived from emission mitigation of HFC-23 and N_2O produced in industrial processes after May 2013,[22] leading to loss of the purchasers of CER credits. So Chinese CDM projects are at risk of being stopped, even though all of them were registered as projects with renewable crediting periods, which will lead to less mitigation of HFC-23 emissions.

Finally, we defined a Best Practice (BP) scenario which represents that maximum effort will be made to tackle HFC-23 emissions, namely installing incineration facilities in all plants. We assumed that emission reductions from the new incineration facilities will start in 2016, which would be linearly increased to full reduction of produced HFC-23 after 6 years' capacity construction by 2022. Miller and Kuijpers (2011) have indicated that the effort of process optimization of co-production ratio of HFC-23/HCFC-22 would not be an ideal solution, since only 44% of global emissions projected in their reference scenario can be reduced if process optimization is adopted as reduction measures. We also tested projecting emissions if implementing process optimization in Chinese plants with the co-production ratio decreasing linearly from 2.82% in 2016 to 1.37% in 2030 which was achieved by one of the facilities in the developed world.[23] Results show the emission reduction would be 31% in 2020, 52% in 2030 and 51% in 2050 compared to BAU scenario (See Fig. 4 bottom panel). Significant emissions remain even after implementing documented process optimizations; therefore, process optimizations were not considered as the measures in BP scenario.

Projected emissions and identifying driving forces

Figure 4 shows the projected HFC-23 production, abatement and emission in China for the period 2013–2035 under the BAU scenario. The projected emissions show a "plateau" with a growth rate of only 0.15 Gg/yr during 2008–2027, which is a result of compensation of HFC-23 production increase from HCFC-22 feedstock production and decrease from HCFC-22 dispersive production, either domestic or exported. During this period, CDM projects were assumed to generate constant amounts of

HFC-23 emission abatement. Even without CDM projects, the emissions will be relatively constant in the 2013–2027 period, but at a plateau which is 6.9 Gg/yr higher. Since the dispersive production of HCFC-22 for domestic use or export is strictly regulated by the phase out schedule of the Montreal Protocol, the total HFC-23 emissions (and production) are greatly dependent on the extent of increase of HCFC-22 feedstock production, which means that if the actual growth rate of HCFC-22 feedstock production is greater or less than the assumed growth rate in our BAU scenario, the plateau will be upward or downward, respectively.

After a gradual annual increase of 0.15 Gg/yr during 2008–2027, there is a steep increase of 1.5 Gg/yr HFC-23 emissions up to 2031. At the end of 2027, six CDM projects are expected to expire after three crediting periods, followed by expirations of three projects in 2028, one project in 2029 and the last one in 2030. Therefore, changes in HFC-23 emissions in this stage are mostly driven by the CDM projects. After 2031, the HCFC-22 feedstock production becomes the sole driving forcing to the HFC-23 emissions since dispersive production reaches the minimum level required by the Montreal Protocol in 2030. In 2050, the total HFC-23 emissions (and production) in China will reach 26.4 Gg/yr, equal to 391 Tg/yr CO_2 emissions.

If the CDM projects are not renewed after the first crediting period as assumed in the LM scenario and no other abatement measures take place, the steep upturn of HFC-23 emissions could occur in the period 2013–2016 (Fig. 4, lower panel). On the other hand, if besides CDM projects, new incineration facilities start to be installed at all plants and full incineration is commenced in 2022 (BP scenario), the projected

HFC-23 emissions will decrease to approximately zero. By this point, the major factor controlling the annual dynamics of Chinese HFC-23 emissions for the next decade (2013–2022) becomes competition between closing existing abatement facilities and increasing new abatement facilities.

Over the period 2013–2050, cumulative emissions of HFC-23 in China under BAU scenario are estimated to be 609 Gg (9015 Tg CO_2-eq), which approximates the China's whole-year emissions of 9864 Tg CO_2 in 2012.[24] Velders et al. concluded that the projected global HFC emissions in 2050 could be equivalent to 9–19% of projected global CO_2 emissions, but HFC-23 was not included in the emission projection of the major HFCs.[25] Cumulative emissions of HFC-23 in China estimated in this study would amount to 5.3%–8.2% the total high and low estimates of CO_2 equivalents from HFCs over the period 2013–2050. Compared to BAU scenario, cumulative emissions of HFC-23 under LM scenario will be 97 Gg higher (1436 Tg CO_2-eq), while cumulative HFC-23 emission reductions of 557 Gg (8249 Tg CO_2-eq) can be achieved under BP scenario.

Simulating atmospheric abundance and quantifying contributions

Atmospheric abundance of HFC-23 was simulated using historical and projected emissions and a simple 1-box model (Fig. 5). As input to the model, we used a HFC-23 atmospheric lifetime of 222 years[26] and 5.136×10^{21}g for the mass of the atmosphere[27]. For China, historical emissions for 1980–2012 derived from the bottom-up estimates and emissions for 2013–2050 derived from BAU scenario projection were used in this simulation. For developing countries excluding China and developed countries, emissions for 1980–2008, 2009–2035 and for 2036–2050 are derived from bottom-up estimates by Miller et al.[4], projections by Miller and Kuijpers[21] and extrapolation based on the projections, respectively.

Fig. 5 shows that the simulated HFC-23 atmospheric abundance for the period 1980–2009 driven by the estimated historical emissions agrees well with the historical measurements from the Advanced Global Atmospheric Gases Experiment (AGAGE) network (the data were derived from Miller et al.[4]), which suggests that it is adequate to project future atmospheric abundance using this simple model. By the year 2050, the simulated atmospheric abundance of HFC-23 is 82 ppt, an increase of 233% relative to its 2012 value. This yields a radiative forcing of 16 mWm^{-2} in 2050 assuming radiative efficiencies taken from IPCC (2007).[28] Accelerated growth of HFC-23 atmospheric abundance during 2013–2050 was found, which is caused by the sustained increase of projected HFC-23 emissions from China and other developing countries. If the HFC-23 emissions in China are subject to LM scenario, the simulated HFC-23 atmospheric abundance will reach 89 ppt by the year 2050, while if the HFC-23 emissions in China are subject to the BP scenario, HFC-23 atmospheric abundance will reach only 41 ppt (see Fig. 5). This reveals that if the measures (incineration) in BP scenario are implemented in China, HFC-23 atmospheric abundance in middle of 21st century could be cut to half of abundance simulated in BAU scenario.

We also quantified contributions from China, developing countries excluding China and developed countries to the atmospheric abundance (Fig. 5, lower panel), which are compared with the contributions to annual global emissions giving 1980, 1995, 2013, 2025 and 2035 as examples (Fig. 5, upper and middle panels). Note that contributions from emissions before 1980 (dash line in the plot) were attributed to developed countries since almost 100% of global emissions then were from developed countries revealed by Miller et al.[4] The upper panel of Fig. 5 shows contribution of Chinese annual emissions to global emissions is 2% in 1980, which increased to 68% in 2013 and 76% in 2050, while the middle panel of Fig. 5 shows that the accumulated contributions of emissions from China to the annual global atmospheric abundance were significantly delayed compared to the annual emission contributions to global emissions, e.g. accumulated Chinese emissions only contribute 32% of atmospheric abundance in 2013 compared to annual Chinese emissions' contribution to 68% of global emissions. In this sense, historical emissions from developed countries accounted for most of atmospheric burden up to now (e.g., 61% in 2013), even though now China is contributing more than 60% to current annual global emissions. We estimated that in circa 2027, China will surpass the developed countries with respect to the accumulated contributions to the global atmospheric abundance. This delay is of course due to the long atmospheric lifetime of HFC-23.

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manuscript.

Supporting Information Available

Uncertainties of components in assembling an inventory of HFC-23 emissions are shown in Table S1. Individual co-production ratios of HFC-23/HCFC-22 in China and other countries are presented in Figure S1. Annual amounts of HFC-23 involved in the CDM HFC-23 emission abatement projects are provided in Figure S2. The correlation between the standardized domestic HCFC-22 feedstock production and the standardized GDP in China are shown in Figure S3. This information is available free of charge via the Internet at http://pubs.acs.org/.

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Figure Captions

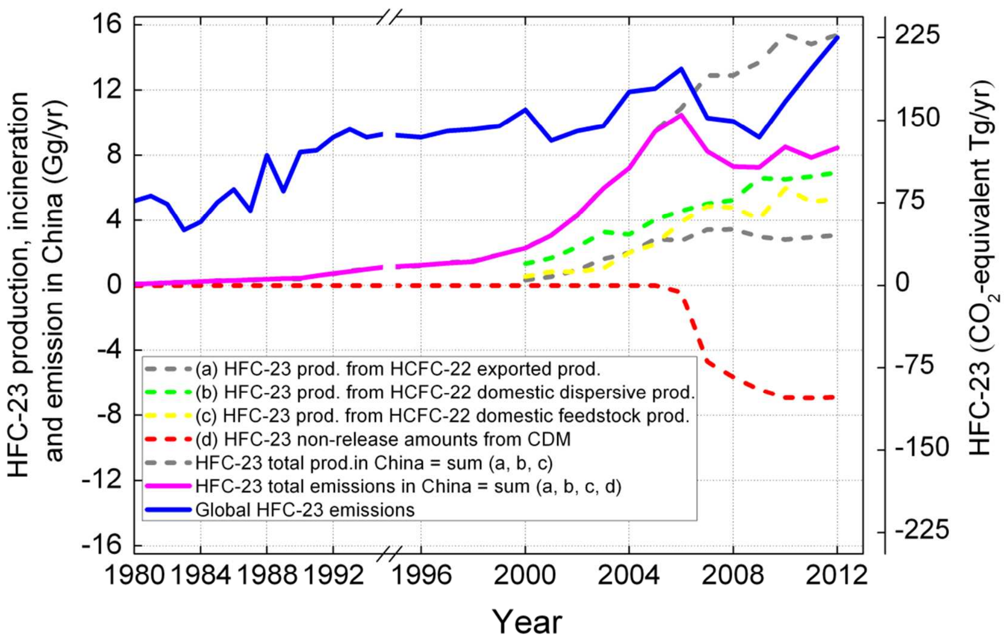

Fig. 1. Bottom-up estimates of annual HFC-23 production and emission in China for the period 1980–2012. The global HFC-23 emissions were derived from top-down estimates for 1980–1989 and bottom-up estimates for 1990–2008[4] and from projections for 2009–2012 [21]. Note that the period 1980–1995 on the X-axis is compressed to show the changes during 1995–2012 more clearly.

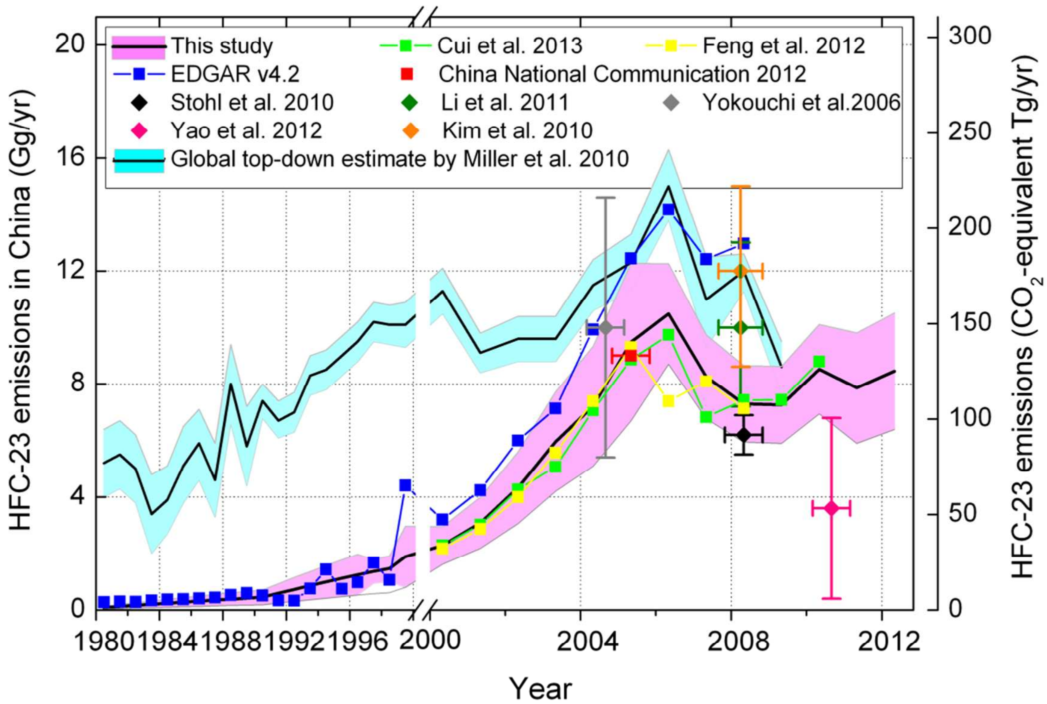

Fig. 2. Comparison with other published estimates of HFC-23 emissions in China, as specified in the legend at the top. Square symbols denote bottom-up estimates and diamond symbols denote top-down estimates. Note that since target time periods in most of the studies are after 2000, the period 1980–2000 on X-axis is compressed to show the comparisons for 2000–2012 more clearly. X-error bar in the plot represents the span of the target period in the respective study, for example 14 months of Nov-2007–Dec-2008 in Li et al.[8] while 12 months of Jan-2008–Dec-2008 in Stohl et al.[10]

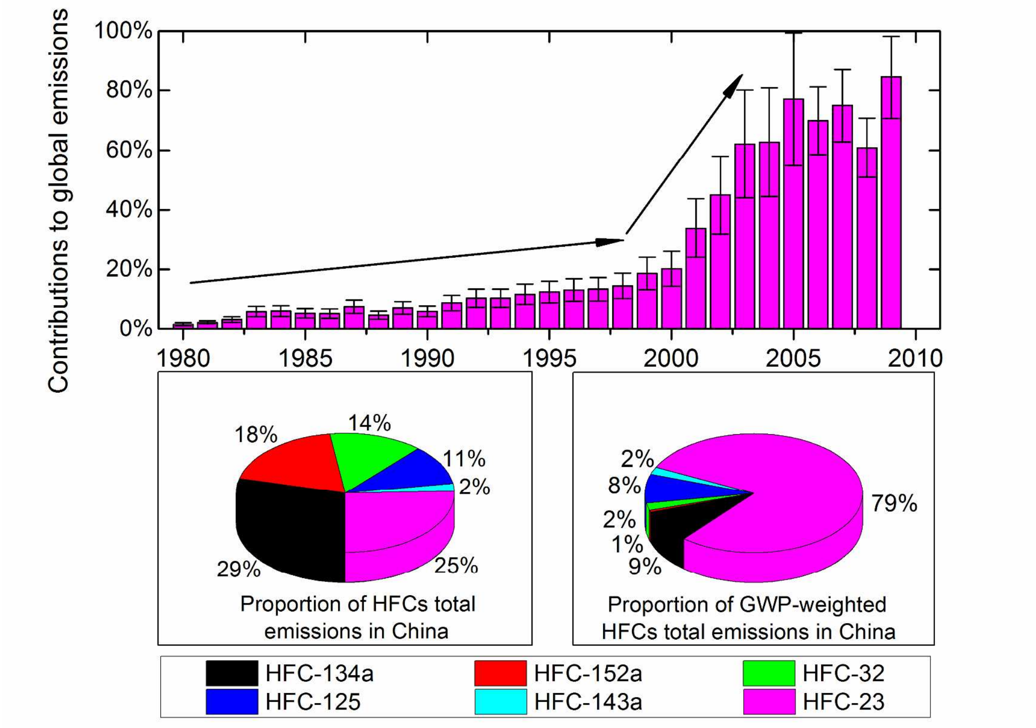

Fig. 3. Annual contributions of HFC-23 emissions from China to global total emissions (upper panel) and proportions of HFC-23 to the total, or GWP-weighted total, HFC emissions in China in 2008. Global emissions for the period 1980–2009 were derived from top-down inversions in Miller et al.[4] Emissions of HFC-23 are from this study, while emissions for other HFC emissions were derived from Li et al.[8] GWP values were taken from Forster et al.[1]

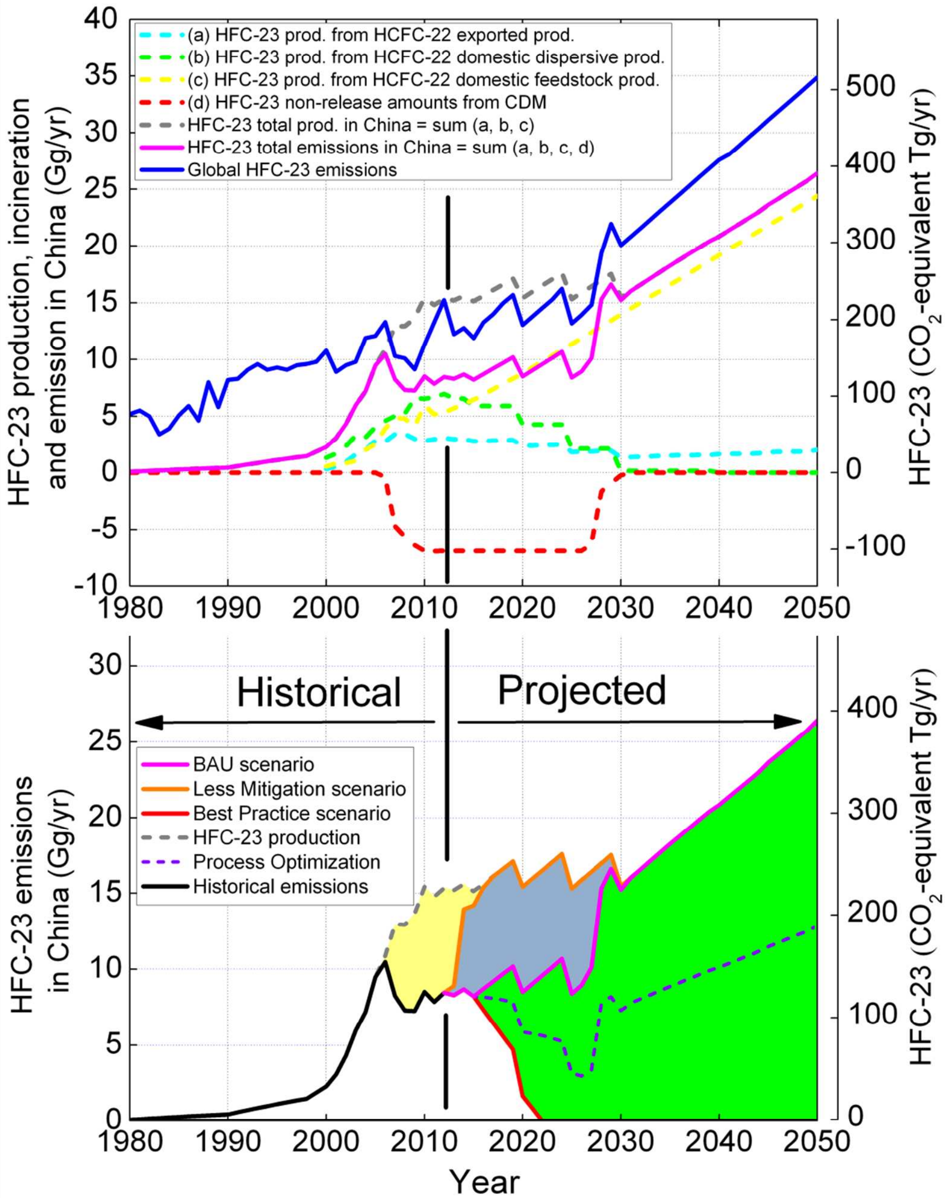

Fig. 4. Projected HFC-23 production, incineration and emissions in China for the period 2013–2050 under the BAU scenario (upper panel) and projections of annual HFC-23 emissions in China under three scenarios (lower panel). The historical emissions for the period 1980–2012 are also shown for a full depiction of HFC-23 emission evolution in China. Global HFC-23 emissions for 2036–2050 were linearly extrapolated based on HFC-23 emission components for the period 2031–2035 in the projection by Miller and Kuijpers (2011).

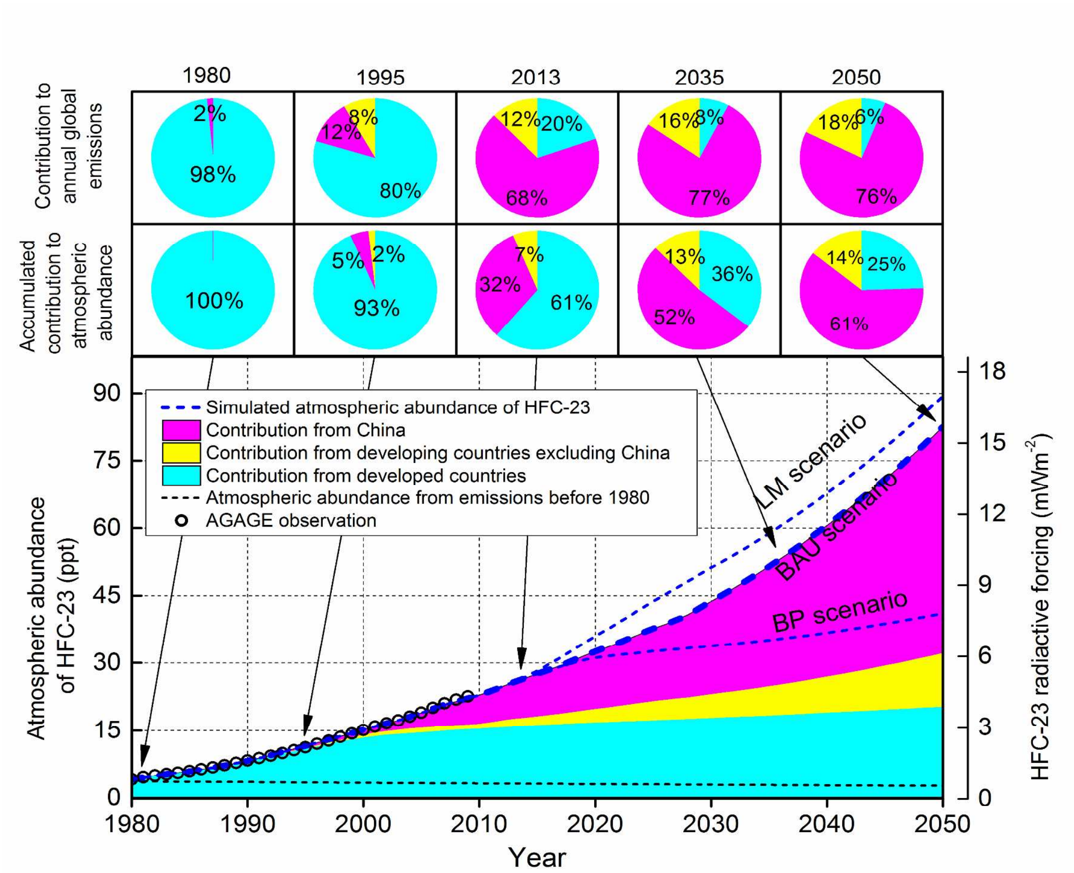

Fig. 5. Simulation of HFC-23 atmospheric abundance and quantification of contributions from China, developing countries excluding China and developed countries, as well as the annual observed HFC-23 atmospheric abundance from AGAGE network. The upper panel shows contributions of emissions from these three country categories to the annual global total emissions, giving 1980, 1995, 2013, 2035 and 2050 as examples. The middle panel shows accumulated contributions of emissions from these three country categories to the global atmospheric abundance in the respective year. The lower panel shows the simulated HFC-23 atmospheric abundance (left axis) using historical and projected emissions (Chinese emissions vary under BAU, LM or BP scenarios) and a simple 1-box model, and the corresponding radiative forcing (right axis). The dashed line represents the HFC-23 atmospheric abundance caused by emissions before 1980, which decreases with time.