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HCFC-141b (CH_3CCl_2F) Emission Estimates for 2000–2050 in Eastern China

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ABSTRACT

HCFC-141b (CH_3CCl_2F) has dual environmental impacts on ozone depletion and climate change, with the ozone depletion potential of 0.11 and the global warming potential of 782, and its emissions has attracted international attention. Under the control of the Montreal Protocol, China should phase out the production and consumption of HCFC-141b by 2030. This study firstly estimated the HCFC-141b emissions in eastern China based on the bottom-up method during 2000-2019. The results show that the HCFC-141b emissions in eastern China increased from 0.4 Gg yr^{-1} in 2000 to 7.1 Gg yr^{-1} in 2019, and there was a bank of 253.6 Gg in PU foam products in 2019, which may have an impact on the future HCFC-141b emissions. In addition, the HCFC-141b emissions were predicted in eastern China from 2020–2050 under the baseline scenario (BAU), the Montreal Protocol scenario (MP), and the accelerated phase-out scenario (AP), and the emission potential was analyzed. The results show that the HCFC-141b emissions increased rapidly under the BAU scenario, with the cumulative emissions of 1162.6 Gg in 2020–2050. Under the MP and AP scenarios, the cumulative HCFC-141b emission reduction potential from 2020 to 2050 will be 1002.1 Gg (equivalent to 110.2 Gg CFC-11-eq and 783.6 Tg CO_2-eq) and 1034.8 Gg (equivalent to 113.8 Gg CFC-11-eq and 809.2 Tg CO_2-eq), respectively. Compared with the MP scenario, under the AP scenario, eastern China will get an additional emission reduction potential of 32.7 Gg (equivalent to 3.6 Gg CFC-11-eq and 25.5 Tg CO_2-eq) during 2020–2050, which will make greater contributions to protecting the ozone layer and mitigating climate change.

Keywords: HCFC-141b, Eastern China, Emission inventory, Ozone depleting substances, Greenhouse gases

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1 INTRODUCTION

Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) as typical halocarbons are regulated by Montreal Protocol (MP) because of their high Ozone depletion potential (ODP) (WMO, 2019) and global warming potential (GWP) (Steinbacher *et al.*, 2008). Under the MP controls, non-A5 and A5 countries (except refrigeration servicing) are requested to phase out HCFCs in 2020 and 2030, respectively. HCFC-141b (1-dichloro-1-fluoroethane, CH_3CCl_2F) is a transitional substitute for chlorofluorocarbons (CFCs) mainly applied in the PU foam (polyurethane foam) and solvent (solvent) sectors. From 1995 to 2014, the global HCFC-141b cumulative emissions were 1180.2 Gg, accounting for 13.2% of the global HCFC cumulative emissions, second only to HCFC-22 (73.4%) (Simmonds *et al.*, 2017). In addition, Western *et al.* (2022) found that the global HCFC-141b emissions increased from 8.0 Gg yr^{-1} in 2017 to 8.2 Gg yr^{-1} in 2020. Due to the global

HCFC-141b emissions accounted for a large proportion and continued to increase, which has attracted international attention.

The top-down or bottom-up method is used to estimate the HCFC-141b emissions at the global, national or regional scale. The top-down methods mainly include the box model, interspecies concentration correlation, and model inversion. The box model usually estimates the global-scale HCFC-141b emissions based on atmospheric background observation data from Advanced Global Atmospheric Gases Experiment (AGAGE) or National Oceanic and Atmospheric Administration (NOAA) (O'Doherty *et al.*, 2004; Montzka *et al.*, 2009; Rigby *et al.*, 2014; Simmonds *et al.*, 2017). The interspecies correlation and model inversion are generally used to estimate the national or regional-scale HCFC-141b emissions (Stohl *et al.*, 2010; Yi *et al.*, 2021). The bottom-up method is an emission factor approach based on production and consumption data (Wan *et al.*, 2009; Wang *et al.*, 2015; Fang *et al.*, 2018; Wu *et al.*, 2021).

As the largest producer and consumer of HCFCs in the world, China's emissions have attracted much attention at home and abroad, especially in eastern China, where emissions contribute the most (Wang *et al.*, 2015). At present, many studies have attempted to estimate the HCFC-141b emissions in China based on the national HCFC-141b consumption data by sector or observation data (Fang *et al.*, 2019; Yi *et al.*, 2021; Wu *et al.*, 2021), but there were few emission studies for eastern China. Western *et al.* (2022) estimated the HCFC-141b emissions of this region for 2008–2020 by using a top-down method based on atmospheric observation data. However, the HCFC-141b emission inventory covering most historical years has not been reported in this region based on a bottom-up method. In this study, we fully considered the characteristics of China's HCFC-141b emissions, used the latest localized emission factors, and firstly established a HCFC-141b emission inventory (2000–2050) in eastern China. In addition, the HCFC-141b emissions were predicted from 2020 to 2050 under the baseline scenario (BAU), the Montreal Protocol scenario (MP) and the accelerated phase-out scenario (AP), and the HCFC-141b emission reduction potential was also analyzed.

2 METHODS

2.1 Emission Estimation Method

In this study, it is identified that the HCFC-141b emission sources in eastern China are mainly polyurethane (PU) foam and solvent sector. Among them, PU foam can be divided into seven sub-sectors: vehicle polyurethane, water heater insulation, foam spray, sheet, pipeline insulation, refrigeration insulation, and unknown use, respectively. Generally, for the PU foam sector, HCFC-141b is emitted into the atmosphere in three stages: 1) the foaming process used as the foaming agent; 2) the usage process emitted through escape; 3) The disposal process emitted during landfill. For the PU foam sector, the HCFC-141b emission estimation method referred to that in the Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories (IPCC, 2006) and the HCFC-141b emission factors referred to those in the study of Wang *et al.* (2015) and IPCC guidelines (IPCC, 2006). The emission estimation equations are as follows:

$$E_{t,PU} = E_{t,foaming} + E_{t,usage} + E_{t,disposal} \quad (1)$$

$$E_{t,foaming} = EF_{foaming} \times C_t \quad (2)$$

$$E_{t,usage} = EF_{usage} \times Bank_t \quad (3)$$

$$E_{t,disposal} = EF_{Langfill} \times Bank_{t,landfill} \quad (4)$$

where $E_{t,PU}$ is the total HCFC-141b emissions (Gg yr^{-1}) from the PU foam sector in year t; $E_{t,foaming}$ is the emission (Gg yr^{-1}) from the foaming process in year t, $E_{t,usage}$ is the emission from the usage process (Gg yr^{-1}) in year t, $E_{t,disposal}$ is the emission (Gg yr^{-1}) from disposal process in year t; $EF_{foaming}$ is the emission factor from the foaming process (%), EF_{usage} is the emission factor from usage process (%), $EF_{Landfill}$ is the emission factor during landfill (%). The emission factors and the lifetimes of PU foam products are showed in Table 1. C_t is the consumption (Gg) of HCFC-141b in year t.

Table 1. The emission factor in PU foam sector and its sub-sector.

Number	Sub-sector	Lifetime (year)[a]	Emission factor (%)			
			Foaming process[a]	Usage process[a]	Disposal process[b]	
					Landfill	Incinerate
1	Refrigeration insulation	15	4.0	0.5	0.5	0.0
2	Water heater insulation	15	4.0	0.5	0.5	0.0
3	Pipeline insulation	30	10.0	1.0	1.0	0.0
4	Sheet	50	7.5	0.5	0.5	0.0
5	Foam spray	50	25.0	1.5	1.5	0.0
6	Vehicle polyurethane	12	95.0	0.4	0.4	0.0
7	Unknown use	20	10.0	4.5	4.5	0.0

[a] (Wang *et al.*, 2015); [b] (IPCC, 2006).

$Bank_t$ is the bank (Gg) of HCFC-141b in the PU foam products in use in year t, $Bank_{t,landfill}$ is the bank (Gg) of HCFC-141b in the PU foam products landfilled in year t.

For the solvent sector, the HCFC-141b emission estimation method mainly referred to IPCC (IPCC, 2006). The following formula is used:

$$E_{t,Solvent} = EF_{Solvent} \times S_t + (1 - EF_{Solvent}) \times S_{t\text{-}1} \quad (5)$$

where $E_{t,solvent}$ is the total HCFC-141b emission (Gg yr^{-1}) from the solvent sector in year t. S_t is the sale of solvent products in year t. $S_{t\text{-}1}$ is the sale of solvent products in year t-1. The emission from the solvent sector is regarded as the "prompt emission", 100% of the solvent is emitted within two years, thus $EF_{solvent}$ is 50%.

The HCFC-141b consumption data of each provincial sub-sector was calculated by the proxy parameter method based on the national HCFC-141b consumption data. Moreover, Monte Carlo simulation was used to quantify the uncertainty of the HCFC-141b emissions. In this study, we assumed that the uncertainty of consumption data and emission factors was 30% (IPCC, 2019), and that they all followed lognormal functions. The uncertainty range of the HCFC-141b emissions were expressed using the 10^{th} and 90^{th} confidence intervals, with 1,000,000 simulations.

2.2 HCFC-141b Consumption Projection Method

For the future HCFC-141b consumption, we set up three scenarios: (1) The Baseline scenario (BAU): HCFC-141b consumption will increase without the MP control. The consumption of HCFC-141b is predicted based on the specific driver factors selected by the Pearson correlation coefficient (PCC) method. (2) The Montreal Protocol scenario (MP): the HCFC-141b consumption in each sector will be reduced based on the phase-out schedule of MP. The baseline year was 2013, and the consumption will be completely phased out by 2030 (UNEP, 2020). (3) The accelerated phase-out scenario (AP): the HCFC-141b consumption in each sector will be rapidly reduced according to the Chinese latest accelerated phase-out schedule and be phased out by 2026. The phase-out schedule under MP and AP showed in Fig. 1.

3 RESULTS AND DISCUSSION

3.1 Historical HCFC-141b Consumption and Banks

The HCFC-141b consumption in eastern China increased at first, peaked in 2012 (29.1 Gg), and then declined to 16.3 Gg in 2019 (Fig. 2(a)). Among them, PU foam was always the main consumer sector in eastern China, ranging from 90.3%–93.3%. In 2019, the PU foam and solvent sectors accounted for 90.8% and 9.2% to the total HCFC-141b consumption, respectively.

From the cumulative consumption perspective (Fig. 2(a)), the PU foam and solvent sectors were 324.5 Gg (92.0%) and 28.4 Gg (8.0%) during 2000–2019, respectively. For the PU foam sector, the main consumer sub-sectors were water heater insulation, sheet and foam spray sub-sectors, with

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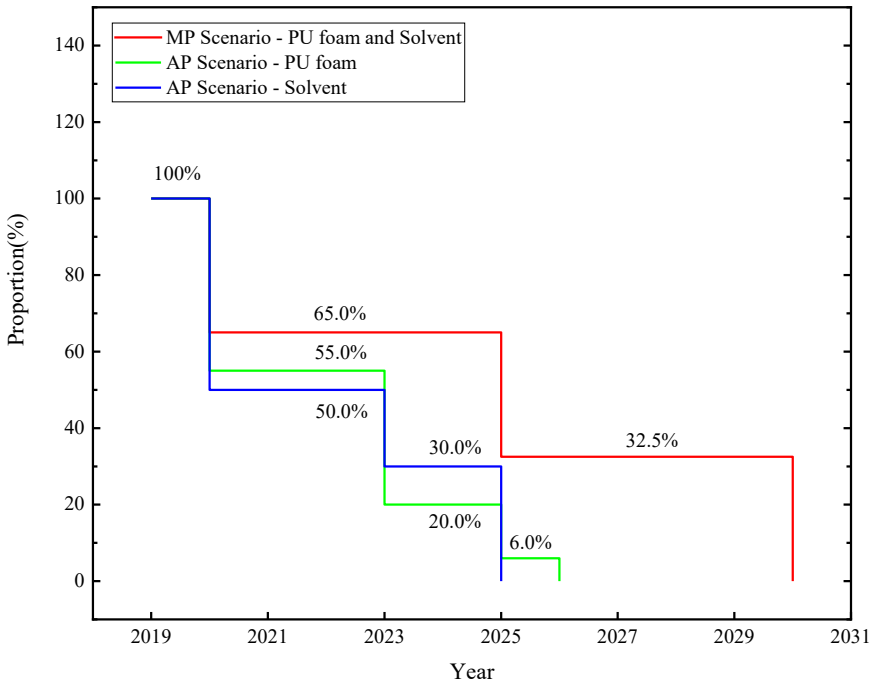

Fig. 1. The phase-out schedule under MP and AP scenarios.

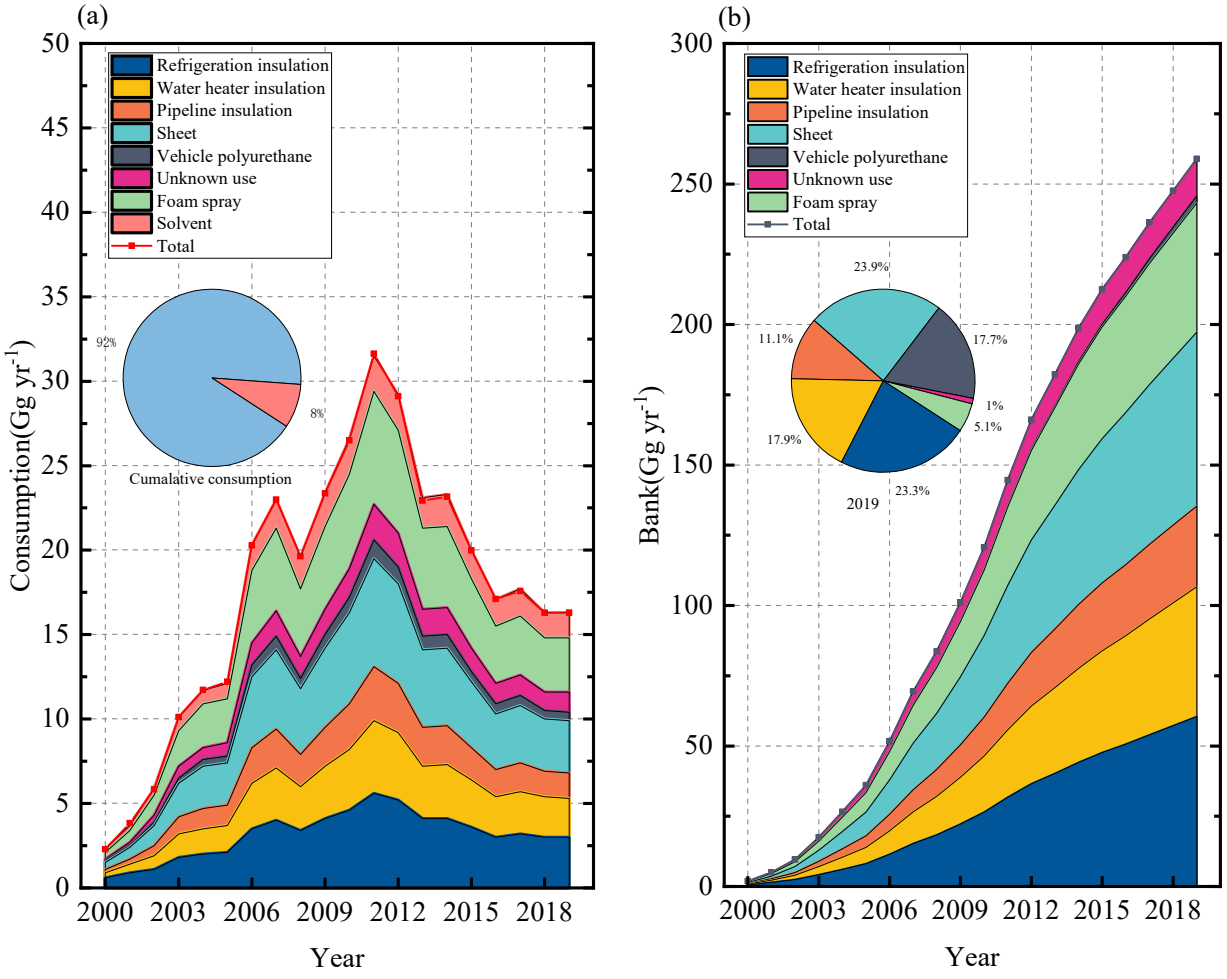

Fig. 2. Historical HCFC-141b consumption (a) in PU foam and solvent sectors and (b) the total banks in PU foam sector.

cumulative consumption of 62.7 Gg, 70.0 Gg, and 73.1 Gg, respectively and three of them accounted for 63.5% to the total HCFC-141b consumption in PU foam sector.

The HCFC-141b annual bank in eastern China showed an upward trend year by year, from 1.9 Gg in 2000 to 253.6 Gg in 2019 (Fig. 2(b)). In 2019, the sub-sector of sheet had the largest bank, accounting for 23.9%, followed by refrigeration insulation, accounting for 23.3%, and vehicle polyurethane and unknown use were smaller, accounting for only 6.1% of the total bank.

3.2 Historical HCFC-141b Emissions

As shown in Fig. 3(a), the HCFC-141b emissions in eastern China increased from 0.4 Gg yr^{-1} in 2000 to 7.4 Gg yr^{-1} in 2011, and then remained at around 6.5 Gg yr^{-1}, and reached 7.1 Gg yr^{-1} in 2019, with the cumulative emissions of 98.5 Gg. The results of the HCFC-141b emissions in this study was consistent with the recent study by Western *et al.* (2022) (Fig. 3(a)). During 2011–2019, the annual HCFC-141b emissions were relatively stable, suggesting that under the control of the Montreal protocol, the eastern China has controlled the annual emissions of HCFC-141b. We calculated the contribution of HCFC-141b emissions in eastern China estimated in this study to the total HCFC-141b emissions in China estimated by Fang *et al.* (2019) and Yi *et al.* (2021) using the top-down approach. The results showed that the proportion increased from 31.0% in 2011 to 46.4% in 2017 when compared with Fang *et al.* (2019), and varied between 43.4–65.4%during 2009–2019 when compared with Yi *et al.* (2021).

For each consumption sector (Fig. 3(b)), the HCFC-141b emissions from the PU foam sector showed an upward trend from 0.3 Gg yr^{-1} in 2000 to 5.6 Gg yr^{-1} in 2019, with the cumulative emissions of 70.9 Gg. However, the HCFC-141b emissions from the solvent sector increased from 0.1 Gg yr^{-1} in 2000 to a peak (2.1 Gg yr^{-1}) in 2011 and then decline to 1.5 Gg yr^{-1} in 2019, with the cumulative emissions of 27.6 Gg. The main sub-sectors of PU foam were spray foam, vehicle polyurethane, and refrigeration insulation, respectively, (Fig. 3(b)) and their total cumulative HCFC-141b emissions from 2000 to 2019 were 24.5 Gg, 11.1 Gg, and 7.4 Gg, accounting for 34.6%, 15.7%, and 10.4%, respectively.

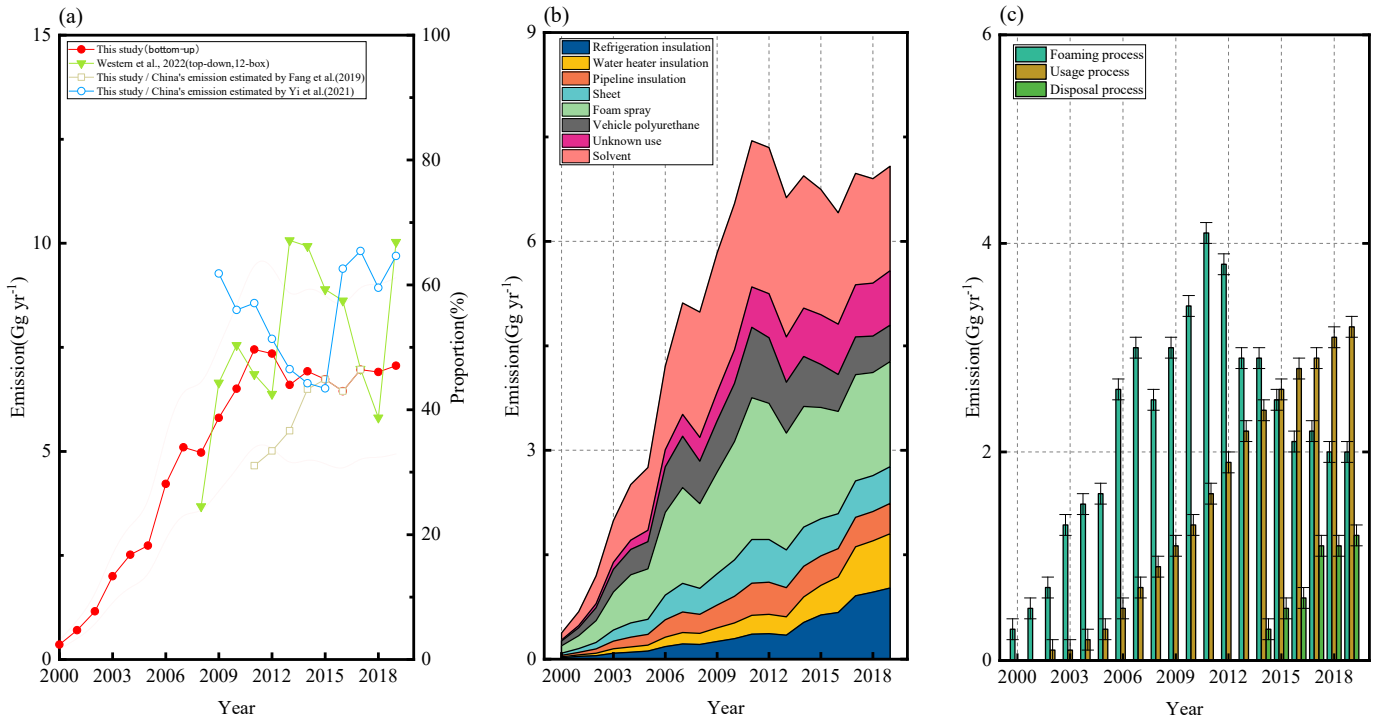

Fig. 3. Comparison results of the HCFC-141b emissions and the historical HCFC-141b emissions in different sectors. (a) Comparison of HCFC-141b emissions from top-down studies in eastern China by Western *et al.* (2022), Fang *et al.* (2019) and Yi *et al.* (2021). (b) The historical HCFC-141b emissions in PU foam and solvent sector and (c) The HCFC-141b emissions during different processes in various sub-sectors of PU foam.

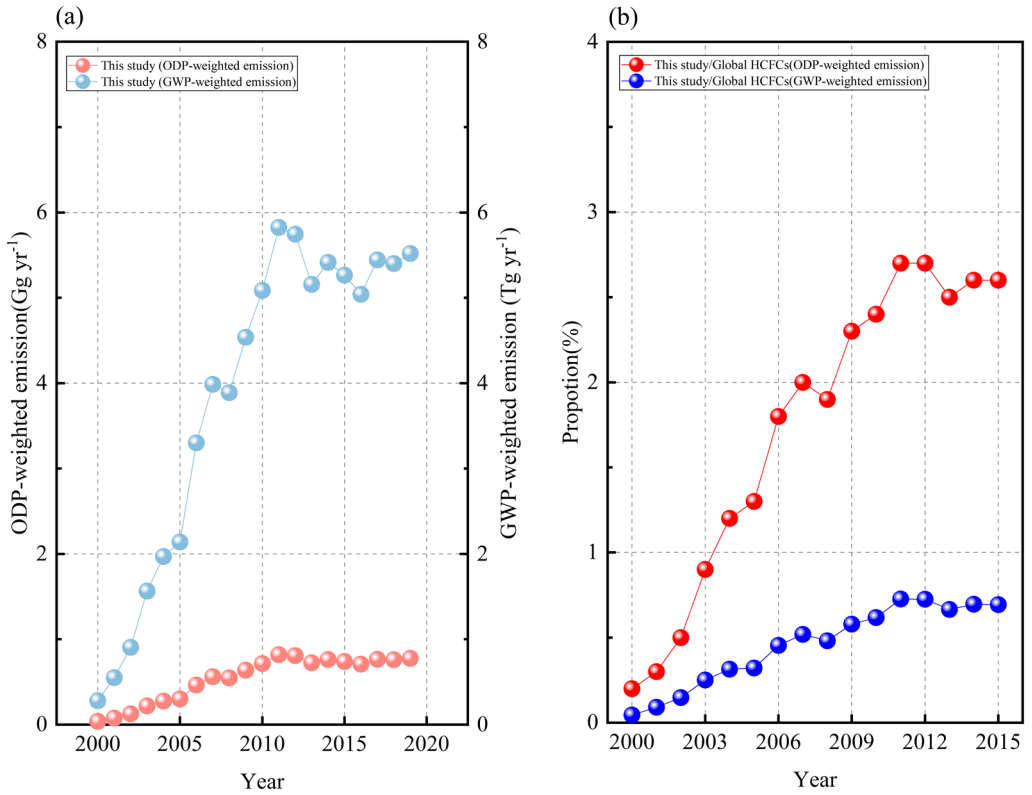

Fig. 4. The HCFC-141b ODP-weighted emissions and GWP-weighted emissions in eastern China (a) from 2000–2019 and (b) The proportion of the HCFC-141b ODP-weighted emissions and GWP-weighted emissions in eastern China to global HCFC ODP-weighted emissions and GWP-weighted emissions from 2000–2019, respectively.

For each life cycle stage (Fig. 3(c)), the emissions of the annual foaming process always accounted for the highest proportion, ranging from 0.0%–58.4% before 2011, followed by the usage process (4.5%–58.4%). After 2012, the usage process accounted the highest proportion (54.9%–79.7%), followed by the foaming process (45.5%-32.2%), and the disposal process had accounted for the lowest proportion (0.0%–25.3%). Take 2019 as an example, the emissions from the foaming, usage, and disposal processes were 2.0 Gg yr^{-1}, 3.2 Gg yr^{-1}, and 1.2 Gg yr^{-1}, accounting for 31.4%, 49.8%, and 18.8%, respectively. Notably, the disposal emissions increased yearly from 0.3 Gg yr^{-1} in 2014 to 1.2 Gg yr^{-1} in 2019, with an annual growth rate of 32.0%, which was higher than that of the usage process (6.3%). For different provinces in eastern China, Jiangsu, Zhejiang and Shandong provinces had the largest cumulative HCFC-141b emissions (46.3 Gg) in 2000–2019, accounting for 62.3% of the total HCFC-141b emissions in eastern China.

To quantify the impact of the HCFC-141b emissions on ozone layer depletion and global warming, the ODP-weighted emissions and GWP-weighted emissions from eastern China were calculated by using their ODP and 100-year GWP values. The global HCFC emissions reported by Simmonds *et al.* (2017) were used to calculate the proportions of eastern China. As shown in Fig. 4(a), the results showed that ODP-weighted emissions and GWP-weighted emissions of HCFC-141b increased year by year, with the cumulative emissions of 10.8 Gg CFC-11-eq and 77.0 Tg CO_2-eq. As shown in Fig. 4(b), the contribution of cumulative HCFC-141b emissions in eastern China during 2000–2015 to global ODP-weighted and GWP-weighted HCFC emission were 1.7% and 0.5%, respectively.

3.3 Predicted Emission and Reduction Potential

As shown in Fig. 5, if China did not implement the Montreal Protocol, under the BAU scenario, the HCFC-141b emissions in eastern China will rapidly increase, reaching 64.4 Gg yr^{-1} in 2050, with the cumulative emissions of 1162.6 Gg.

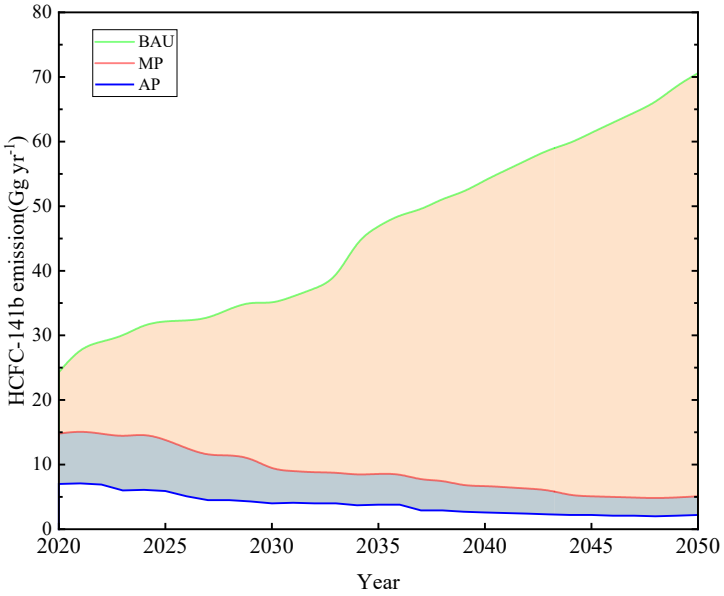

Fig. 5. Predicted emissions of HCFC-141b during the period of 2020 to 2050 in eastern China.

Under the MP scenario, the HCFC-141b consumption in each sector will be reduced based on the phase-out schedule of MP, and the HCFC-141b emissions will reach a peak at 8.7 Gg yr^{-1} in 2024 and then decline to 2.9 Gg yr^{-1} in 2050, with the cumulative emissions of 160.5 Gg (equivalent to 17.7 Gg CFC-11-eq and 125.5 Tg CO_2-eq). Compared to the BAU scenario, the cumulative HCFC-141b emission reduction potential in MP scenario will be 1002.1 Gg (equivalent to 110.2 Gg CFC-11-eq and 783.6 Tg CO_2-eq).

Under the AP scenario, the HCFC-141b consumption in each sector will be rapidly reduced according to the Chinese latest accelerated phase-out schedule, and the HCFC-141b emissions will increase from 7.4 Gg yr^{-1} in 2020 to a peak of 7.5 Gg yr^{-1} in 2021 and then decline to 2.2 Gg yr^{-1} in 2050, with the cumulative emissions of 127.8 Gg.

Compared to the BAU scenario, the cumulative emission reduction potential under the AP scenario will be 1034.8 Gg (equivalent to 113.8 Gg CFC-11-eq and 809.2 Tg CO_2-eq) and will get the additional cumulative reduction emission potential of 32.7 Gg (equivalent to 3.6 Gg CFC-11-eq and 25.5 Tg CO_2-eq) when compared to the MP scenario during 2020–2050. Considering that China will adopt a faster accelerated phase-out plan than the MP, the accelerated emission reduction of HCFC-141b in eastern China may make a significant contribution to protecting the ozone layer and mitigating climate change.

4 CONCLUSIONS

Based on the bottom-up method, this study firstly estimated the HCFC-141b emission inventory in eastern China from 2000 to 2019 and predicted the HCFC-141b emissions from 2020 to 2050 under BAU, MP, and AP scenarios.

From 2000 to 2019, the HCFC-141b emissions in eastern China increased from 0.4 Gg yr^{-1} to 7.1 Gg yr^{-1} in 2019, the cumulative emissions were 98.5 Gg. During 2011–2019, the annual HCFC-141b emissions were relatively stable around at 6.5 Gg yr^{-1}, suggesting that under the control of MP, eastern China has controlled the annual HCFC-141b emissions. Jiangsu, Zhejiang, and Shandong provinces have higher emissions than the other provinces in eastern China, accounting for 62.3% of total emissions.

Under the MP scenario, the cumulative emission reduction potential will be 1002.1 Gg (equivalent to 110.2 Gg CFC-11-eq and 783.6 Tg CO_2-eq) compared with the BAU scenario. Under the AP scenarios, eastern China will get an additional cumulative reduction emission potential of 32.7 Gg (equivalent to 3.6 Gg CFC-11-eq and 25.5 Tg CO_2-eq) during 2020–2050, which will make a greater contribution to protecting the ozone layer and mitigating climate change.

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