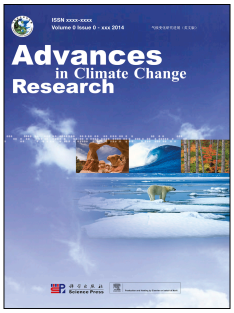

China's growing halogenated gas emissions and banks over 1980–2024: Impacts on ozone, climate, and trifluoroacetic acid

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Abstract

China's mitigation strategy design under its 2035 nationally determined contribution calls for updated inventories of halogenated gases, given their current incomplete and outdated coverage. This study established a comprehensive emission and bank inventory regarding China's halogenated gas consumption and export during 1980–2024, covering 30 substances and 23 sub-sectors. Halogenated gas emissions pose triple environment impacts: stratospheric ozone depletion, climate change, and trifluoroacetic acid (TFA) accumulation. In 2024, China's territorial and exported halogenated gas emissions increased apace to over 800 kt, with ozone depletion potential (ODP)-weighted emissions decreasing to below 15 kt CFC-11-eq and 100-year global warming potential (GWP_{100})-weighted emissions growing to approximately 2 Gt CO_2-eq. These trends highlight a shift in environmental impacts from ozone depletion to stronger climate forcing. Sector-specific bank management measures are needed to avoid massive emissions from banked halogenated gases (19 ± 3 Gt CO_2-eq by 2024). Furthermore, persistent degradation product TFA, originating from halogenated gases (notably low-GWP alternatives such as hydrofluoroolefins), accumulated to over 200 kt by 2024, underscoring the importance of integrating chemical risk governance into climate mitigation strategies.

Keywords

Ozone depleting substances (ODSs); Fluorinated greenhouse gases; Emission inventory; Climate change; Trifluoroacetic acid (TFA)

1. Introduction

Halogenated gases refer to gases composed primarily of carbon/sulfur/nitrogen atoms bonded with one or more halogen atoms (F, Cl, Br, I). Halogenated gases emissions follow two patterns: instantaneous and delayed. Instantaneous emissions arise mainly from industrial processes (e.g., chemical, metal, and electronics industries) and short-lived products such as aerosols (Robson et al., 2006; Weiss et al., 2008). In contrast, delayed emissions originate from 'active banks' in equipment and products (e.g., refrigeration and air conditioning), where gases are stored and gradually leaked through leakage during operation, servicing, and end-of-life stages until complete release if not recovered—a process spanning decades (Bert Metz et al., 2005; TEAP, 2021). Given their physical properties and widespread use, halogenated gas emissions exert triple environmental impacts.

First, impact on stratospheric ozone depletion. Ozone depleting substances (ODSs) primarily comprise chlorofluorocarbons (CFCs), halons, carbon tetrachloride (CTC), methyl chloroform (TCA), methyl bromide (CH_3Br), hydrochlorofluorocarbons (HCFCs), which have been or are being phased out under the Montreal Protocol (Ozone Secretariat, 2019). Anthropogenic halogens, particularly CFCs and halons, release reactive chlorine and bromine that catalytically deplete stratospheric ozone (Molina and Rowland, 1974; Solomon, 1999), leading to the Antarctic ozone hole (Cox and Hayman, 1988; Solomon et al., 1986; Zafra et al., 1987). By 2020, stratosphere total chlorine and bromine inputs from halogenated gases had dropped by 11% and 15% from peaks, thanks to the Protocol (WMO, 2022). But ozone layer recovery will take decades (WMO, 2018), delayed by substantial banked CFCs and HCFCs (Lickley et al., 2022).

Second, impact on climate change. ODSs were the second-largest greenhouse gas in the late 20th century (Polvani et al., 2020). Their alternatives, hydrofluorocarbons (HFCs), are regulated under the 2016 Kigali Amendment to the Montreal Protocol due to climate threat (UNEP, 2016; WMO, 2018). Perfluorocarbons (PFCs), SF_6, and NF_3—fully fluorinated greenhouse gases (FFGHGs)—join HFCs as fluorinated greenhouse gases (FGHGs) listed under the United Nations Framework Convention on Climate Change (UNFCCC) (Sovacool et al., 2021; UNFCCC, 2018, 1998). Most ODSs and HFCs have atmospheric lifetimes less than 50 years and higher 20-year global warming potential (GWP_{20}) than 100-year global warming potential (GWP_{100}), indicating strong time-horizon dependence of their climate impacts (Liu et al., 2025). Conversely, FFGHGs, with lifetimes ranging from hundreds to tens of thousands of years, sustain prolonged climate forcing (Mühle et al., 2019). Halogenated gases exert 0.41 W/m^2 of effective radiative forcing (ERF) in 2019, equivalent to 19%, 76%, and 195% of that from CO_2, CH_4, and N_2O, respectively (IPCC, 2023). Despite Kigali compliance reducing China's cumulative HFC emissions by 18.9 Gt CO_2-eq by 2060 (Wu et al., 2025), HCFC and HFC emissions are still projected at 6.4 ±1.2 Gt CO_2-eq and 17 ± 2.7 Gt CO_2-eq over 2022–2060 (Liu et al., 2024; Bai et al., 2023).

Third, impact on the accumulation of trifluoroacetic acid (CF_3COOH, TFA). Some ODSs, HFCs, and their alternatives hydrofluoroolefins (HFOs)/hydrochlorofluoroolefins (HCFOs) fall under per- and polyfluoroalkyl substances (PFAS) and degrade into persistent TFA (OECD, 2021). The TFA yield of HFOs is much higher than that of HCFCs and HFCs (EEAP, 2023). Replacing HFC-134a (CH_2FCF_3) with HFO-1234yf (CF_3CFCH_2) increased global TFA burden 33-fold in 2015 (Holland et al., 2021). Assuming HFOs replace HFCs under Kigali compliance, China's cumulative HFO-1234yf emissions over 2024–2060 are estimated at 1.7 Gt, leading to 0.4–1.0 Gt of TFA deposition (Wang et al., 2023). TFA concentrations have risen steadily across atmospheric, aquatic, and precipitation matrices from 1990 to 2024 (Zhi et al., 2024), with human blood detection raising health concerns (ATMOsphere, 2025; Zheng et al., 2023). This highlights that low-GWP alternatives may entail environmental trade-offs that warrant careful evaluation under the precautionary principle (EPCEU, 2024).

China's 2035 nationally determined contribution (NDC) and 2060 carbon neutral target cover all UNFCCC-regulated greenhouse gases (GHGs) (USDS, 2023). A comprehensive and accurate emissions inventory is therefore essential for effective policy design. Recent studies updated China's N_2O (1980–2020) and CH_4 (2011–2021) inventories (Liang et al., 2024; Zhao et al., 2024), but halogenated gases—key non-CO_2 GHGs—are understudied. China's current GHG inventory includes only a limited subset of halogenated gases (PRC, 2024) and lacks recent updates since 2021 (Bai et al., 2025; Guo and Fang, 2024; PRC, 2024; Wu et al., 2025). Existing studies often focus on individual compounds (Wu et al., 2021; Ding et al., 2023) or legacy sectors (e.g., electrical equipment, room air conditioning, and by-product emissions) (Zhou et al., 2018; Hu et al., 2023; Wang et al., 2024; Zhao et al., 2023), overlooking emerging industries such as photovoltaic manufacturing. Consequently, knowledge gaps remain regarding updated and comprehensive estimates of halogenated gas emissions, banks, and their corresponding environmental impacts. This study addresses these gaps by establishing an up-to-date, sector-wide inventory of short-chain halogenated gases and assessing their impacts on ozone depletion, climate forcing, and TFA accumulation to inform China's forward-looking mitigation strategies.

2. Methods

2.1. Emissions of instantaneous-emission sectors

Annual emissions from sectors characterized by instantaneous release are governed by corresponding activity level and emission factors (Appendix method A3). The IPCC Tier 1 (IPCC, 2006, 2019) was adopted to quantify halogenated gas emissions from fluorochemical production processes, primary aluminum, magnesium and rare earth metal production processes, flat panel display manufacturing, and photovoltaic cell manufacturing. The IPCC Tier 2a (IPCC, 2006, 2019) was applied to estimate halogenated gas emissions from semiconductor manufacturing, including unreacted input gases, by-product emissions, and CF_4 emissions generated from hydrocarbon-fueled combustion systems. Short-lived products (e.g. aerosols) were assumed to be completely emitted within a two-year period.

2.2. Emissions and banks of delayed-emission sector

For most sub-sectors within the product use sector exhibiting delayed emission, such as refrigeration and air conditioning, electrical equipment, foam blowing agents, and fire protection, this study quantified halogenated gas emissions using the equations below:

$$B_{s,i,t} = B_{s,i,t-1} + C_{s,i,t-1} - E_{s,i,t-1} \tag{1}$$

$$E_{s,i,t} = E_{char_{s,i,t}} + E_{ope_{s,i,t}} + E_{ser_{s,i,t}} + E_{dis_{s,i,t}} \tag{2}$$

$$E_{char_{s,i,t}} = C_{char_{s,i,t}} \times f_{char_{s,i}} \tag{3}$$

$$E_{ope_{s,i,t}} = B_{s,i,t} \times f_{ope_{s,i}} \tag{4}$$

$$E_{ser_{s,i,t}} = \sum_{k=1}^{l} (B_{s,i,t,k} - E_{ope_{s,i,t,k}}) \times r_{ser_{s,i,k}} \times f_{ser_{s,i}} \tag{5}$$

$$E_{dis_{s,i,t}} = \sum_{k=1}^{l} (B_{s,i,t,k} - E_{ope_{s,i,t,k}} - E_{ser_{s,i,t,k}}) \times r_{dis_{s,i,k}} \times f_{dis_{s,i}} \tag{6}$$

where, the subscripts s, i, t, k, and l represent the sub-sector, type of halogenated gases, year, product age, product lifetime, respectively. B, C, E represent the banks, consumption and total emission of halogenated gases in product use, respectively, in tonne. E_{char}, E_{ope}, E_{ser}, E_{dis} represent the halogenated gas emission from manufacture / charge, operation, servicing and disposal, respectively, in tonne. f_{char}, f_{ope}, f_{ser}, and f_{dis} is the emission factor at the time of charge, operation, servicing and disposal, respectively. r_{ser} and r_{dis} are servicing ratio and disposal ratio of the product.

Emissions from chemical export or other product use were estimated by multiplying banked halogenated gases by their emission factors (see Appendix Table A8).

2.3. Environment impacts assessments of halogenated gas emissions

This study applied 100-year global warming potential and ozone depletion potential of each substance to assess the climate impact and ozone depletion impact of halogenated gas emissions. In addition, referring to Ding et al., 2023 and Wu et al., 2014, annual average TFA formation of halogenated gases was calculated using the following equation:

$$F_{i,t} = \sum_{k=t-\tau_i+1}^{t} (E_{i,k}/\tau_i \times R_i) \tag{7}$$

$F_{i,t}$ represents the annual average TFA formation of the TFA precursor i in the year t. E_i represents the annual emission of the precursor i, in tonne. τ_i represents the lifetime of the precursor i, in years. R_i represents the TFA yield of the precursor i, see Appendix Table A2.

2.4. Uncertainty analysis

The uncertainties in parameters, including sectoral activity levels, emission factors, and TFA yield, were incorporated into a Monte Carlo simulation to estimate the uncertainty ranges of emissions, banks, and annual average TFA formation (see Appendix Method A4). The results are presented as the mean (μ) ± 1.96 × standard deviation (σ), representing the 95% confidence interval.

3. Results

3.1. Status of halogenated gas production, consumption and phase-out process

3.1.1. The substances regulated by the Montreal Protocol

ODSs and HFCs are regulated by the Montreal Protocol and its Amendments (Fig. 1b and c). After more than three decades of efforts, China had completely stopped the production and use of the five major categories of ODSs for controlled uses, namely CFCs, halons, CTC, TCA, and CH_3Br in 2010, with possible essential use exemptions such as CTC for reagent and auxiliary use (approximately 330 t in 2024). HCFC production and consumption in China were frozen in 2013 at the baselines of 29 kt CFC-11-eq and 19 kt CFC-11-eq, and would be phased out by 2030 (excluding servicing needs). HFCs, substitutes for HCFCs, were frozen in 2024 at the production and consumption baselines of 1853 Mt CO_2-eq and 905 Mt CO_2-eq and will be phased down to 20% of the baseline by 2045. As the largest producer of HFCs, China accounted for 85% and 47% of global HFC production (1730 Mt CO_2-eq) and consumption (1638 Mt CO_2-eq) in 2023 (Ozone Secretariat, 2024). In 2024, China set HCFC and HFC production quotas of 213 kt (equivalent to 364 Mt CO_2-eq and 13 kt CFC-11-eq) and 783 kt (equivalent to 1448 Mt CO_2-eq), of which approximately 50% of China's HCFC and HFC production were exported. Being potential alternatives of ODSs and HFCs, production of HFOs and HCFOs in China increased to 36 kt in 2024, of which HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), and HCFO-1233zd(E) production accounted for 31%, 3%, 15%, and 51%, respectively (ChinaIOL, 2025).

3.1.2. Fully fluorinated greenhouse gases

According to data investigation conducted by Zhejiang Research Institute of Chemical Industry Co., Ltd, China accounted for 56% of global FFGHG production in GWP_{100}-weighted terms in 2021. Among China's 2021 FFGHG production, SF_6 dominated over 62% of China's GWP_{100}-weighted FFGHG production, followed by NF_3 (35%). The estimated FFGHG (SF_6, NF_3 and PFCs) production in China was 46 kt (equivalent to 861 Mt CO_2-eq) in 2024 (Fig. 1a and c), with a consumption-to-production ratio of approximately 75%.

3.1.3. PFAS as defined by the OECD

Being precursors of trifluoroacetic acid (TFA), short-chain PFAS with carbon chain lengths of four or fewer (including HCFC-123, HFC-125, HFC-134a, HFC-143a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-365mfc, and HFO-1234yf) produced in China reached 485 kt in 2024 (Fig. 1d). Moreover, the 2024 production of hexafluoropropylene (HFP) and four fluoropolymers classified as PFAS amounted to 465 kt (Fig. A1). The production of perfluorootane sulfonates (PFOS) and perfluorooctanoic acid and its salts (PFOA/PFO) in China was below 0.2 kt in 2012 (Li et al., 2015; Zhang et al., 2012) and has been phased out (except for special purposes) in 2024 according to the China's List of New Pollutants for Key Control (2023 Edition) (MEEPRC, 2022). The PFAS production investigated for 2024 was 950 kt, nearly representing the total PFAS production in China.

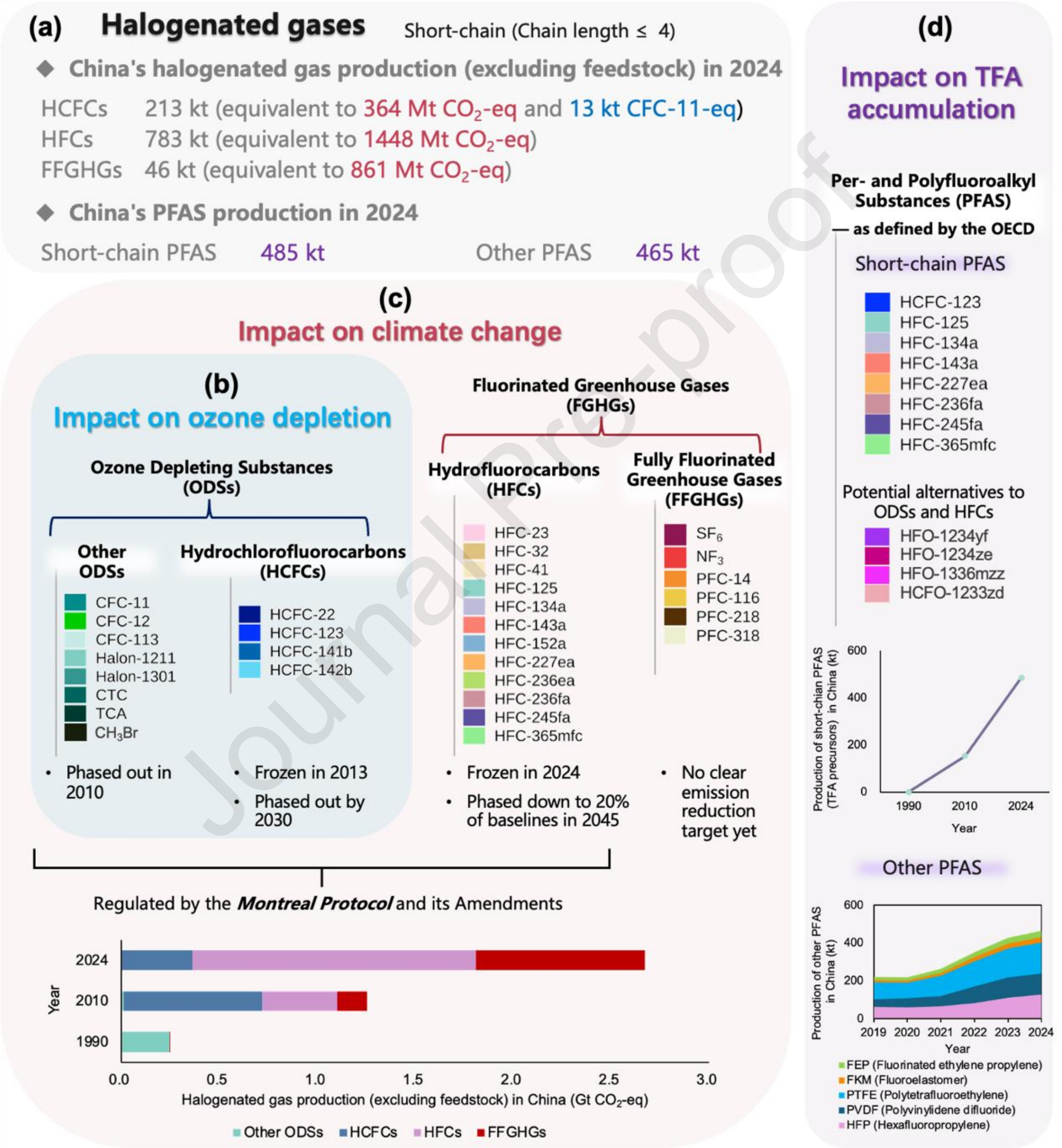

Fig. 1 The phase-out process of halogenated gases in China (1990–2024) and their production status in 2024, (a) 2024 production of halogenated gases and PFAS (This study is concerned with halogenated gases with chain lengths up to 4 (i.e., short chains). Specifically, 12 ODSs, 12 HFCs, SF_6, NF_3, 4 PFCs, and 4 HFOs/HCFOs are included, see Table A1 for details.), (b) halogenated gases depleting stratospheric ozone, (c) halogenated gases influencing climate change, and (d) short-chain halogenated gases and other PFAS contributing to TFA accumulation.

3.2. China's territorial halogenated gas emissions over the last four decades

3.2.1. Mass emissions

Halogenated gas emissions increased rapidly from 3.3 ± 0.5 kt in 1980 to 381 ± 55 kt in 2024, with a compound annual growth rate (CAGR) of 11%. Except for HCFCs, other ODS emissions decreased rapidly since 2000 and reached below 3 kt in 2024 (Fig. 2a). The growth of HCFC emissions slowed after 2012, and from 2019 onwards, the emissions began to decline, reaching 125 ± 19 kt by 2024. As alternatives to HCFCs, HFC emissions showed a marked upward trend, increasing to 229 ± 28 kt in 2024.

From 1980 to 2024, cumulative halogenated gas emissions reached 5.6 ± 0.9 Mt, with short-lived substances accounting for 90% (Fig. 2b). The top five gases by mass emissions changed from HCFC-22, HCFC-141b, HFC-134a, HFC-23 and CFC-11 during 2005–2014 to HCFC-22, HFC-134a, HFC-32, HCFC-141b and HFC-125 during 2015–2024 (Fig. 2c). Although HCFC-22 has dominated historically, its emissions have declined since 2018. HFC-32 is about to overtake HFC-134a as the highest emitting HFC, with mass emissions of 76 ± 9 kt in 2024. FFGHG emissions were below 25 kt in 2024, dominated by PFC-14 and SF_6.

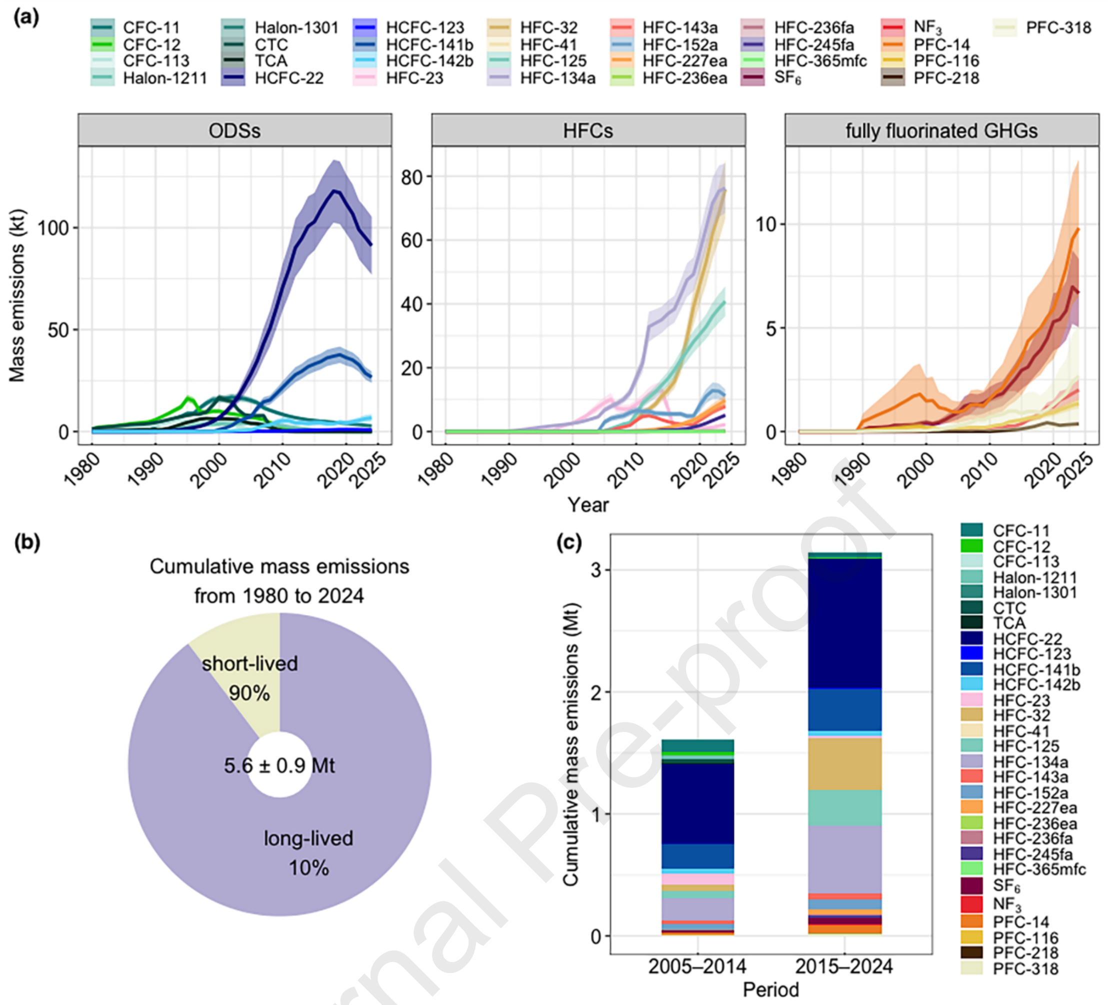

Fig. 2 China's halogenated gas mass emissions by substance, (a) halogenated gas mass emissions by substance 1980–2024, (b) cumulative mass emissions for long-lived (>100 years) and short-lived (<100 years) halogenated gases from 1980 to 2024, and (c) cumulative halogenated gas mass emissions by substance in the periods 2005–2014 and 2015–2024.

3.2.2. ODP-weighted emissions (impact on stratospheric ozone depletion)

China's ODS emissions peak in 2000 at 69 ± 14 kt CFC-11-eq and diminished to 9.2 ± 1.2 kt CFC-11-eq in 2024, with the transition from CFCs to HCFCs to HFCs progressively (Fig. 3a). Total ODS emissions were cumulated to 1.3 ± 0.2 Mt CFC-11-eq between 1980–2024, largely attributable to Halon-1211, CFC-11, CFC-12, and CTC. Despite the substantial mass emissions of HCFCs, their emission proportion to the cumulative ODP-weighted emission was less than 10% due to the relatively low ODP. In 2024, ODP-weighted emission ranked in HCFC-22 (3.4 ± 0.5 kt CFC-11-eq), CFC-11 (2.7 ± 0.3 kt CFC-11-eq), and HCFC-141b (2.5 ± 0.3 kt CFC-11-eq).

3.2.3. GWP-weighted emissions (impact on climate change)

When converted to GWP_{100}-weighted, halogenated gas emissions rose from 17 ± 3 Mt CO_2-eq in 1980 to 0.93 ± 0.18 Gt CO_2-eq in 2024 (Fig. 3b). As stated previously, short-lived (<100 year) gas emissions during this period were about 8 times of long-lived (>100 year) gas emissions, hence cumulative GWP_{20}-weighted emissions (31 ± 5 Gt CO_2-eq) were 1.8 times greater than cumulative GWP_{100}-weighted emissions (17 ± 3 Gt CO_2-eq) over 1980–2024. While the overall emission trends are similar between GWP_{20} and GWP_{100} weightings, short-lived substances (e.g., HCFC-22, HFC-134a) contribute a larger proportion under GWP_{20}, whereas long-lived substances (e.g., SF_6, CF_4) contribute less (Fig. A2 and Fig. A3).

Overall, GWP_{100}-weighted emissions of ODS began to decrease, while those of FGHGs (including HFCs, SF_6, NF_3, and PFCs) showed an increasing trend. China's FGHG emissions accounted for 77% in China's 2024 halogenated gas emissions and 40% in global 2023 FGHG emissions (1.7 ± 0.5 Gt CO_2-eq (UNEP, 2024a)). HFCs, exceeding ODS since 2011 in terms of emissions, dominate in halogenated gas GWP_{100}-weighted emissions, accounting for 411 ± 51 Mt CO_2-eq or 44% of total emissions in 2024. Changes in the proportion of HFC-23 destroyed have resulted in fluctuations in historical HFCs' GWP-weighted emissions (Fig. A2). Moreover, with extremely high GWP_{100}, FFGHGs increased rapidly to 306 ± 99 Mt CO_2-eq in 2024 with CAGR of 12% over the period 2014–2024. In terms of GWP_{100}-weighted emissions, the top five substances were ranked HCFC-22, SF_6, HFC-125, HFC-134a, and PFC-14 in 2024. HCFC-22 emissions will continue to decline through Montreal compliance, while other four substances have not yet shown a downward trend.

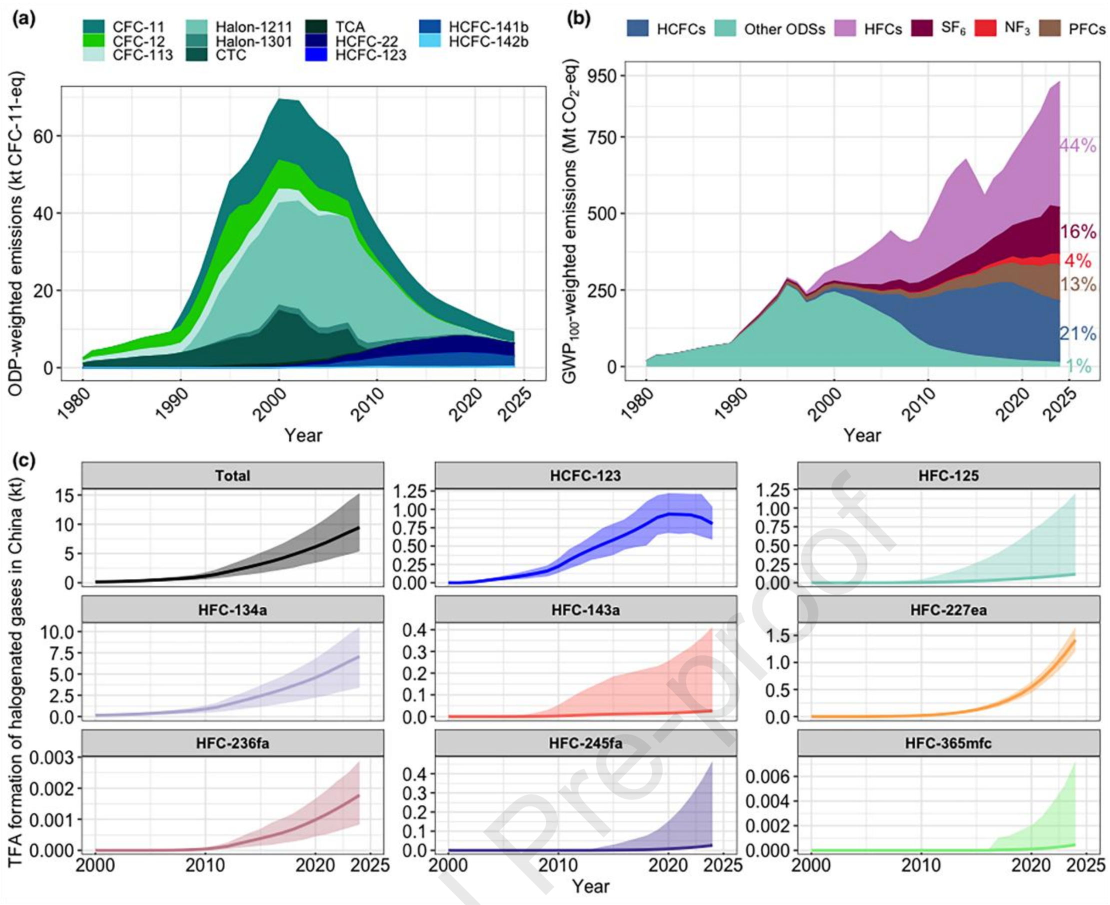

Fig. 3 Halogenated gas emissions under different environment impact indicators in China, (a) ODP-weighted emissions over 1980–2024, (b) GWP_{100}-weighted emissions over 1980–2024, and (c) annual average TFA formation from halogenated gases over 2000–2024.

3.2.4. TFA formation (impact on TFA accumulation)

Emissions of TFA precursors grew rapidly to 140 ± 16 kt in 2024 in China, 37% of China's total halogenated gas emissions. Corresponding to this increase, annual average TFA formation in China rose to 9.5 (5.4–15.3) kt in 2024 at CAGR of 18% between 2005–2024, as shown in Fig. 3c. Cumulatively, TFA formation in China reached 74.7 (40.7–119.5) kt during 1980–2024, primarily driven by HFC-134a (dominated 76%), HCFC-123 (14%), and HFC-227ea (8%). Without taking HFOs into account, HFC-134a will continue to be the main contributor to TFA formation in China. Although HCFC-123 was the second-largest source, its contribution has declined, whereas HFC-227ea are increasing markedly.

3.3. China's snowballing halogenated gas banks in sectors featured by delayed emissions

3.3.1. Emission sources

Over the period 2005–2024, 67% of halogenated gas GWP_{100}-weighted emission came from the delayed emission sectors (Fig. 4a). The chemical industry contributed 18% (2.2 ± 0.9 Gt CO_2-eq) of cumulative emissions, the metal industry 3% (0.3 ± 0.3 Gt CO_2-eq), the electronics industry 7% (0.9 ± 0.1 Gt CO_2-

eq), and product use 72% (8.9 ± 1.1 Gt CO_2-eq). Within these sectors, the top five emission sources in 2024 were industrial and commercial refrigeration and air conditioning (213 ± 23 Mt CO_2-eq), household refrigeration and air conditioning (135 ± 14 Mt CO_2-eq), semiconductor manufacturing (100 ± 11 Mt CO_2-eq), electrical equipment (69 ± 11 Mt CO_2-eq), and foam (62 ± 8 Mt CO_2-eq).

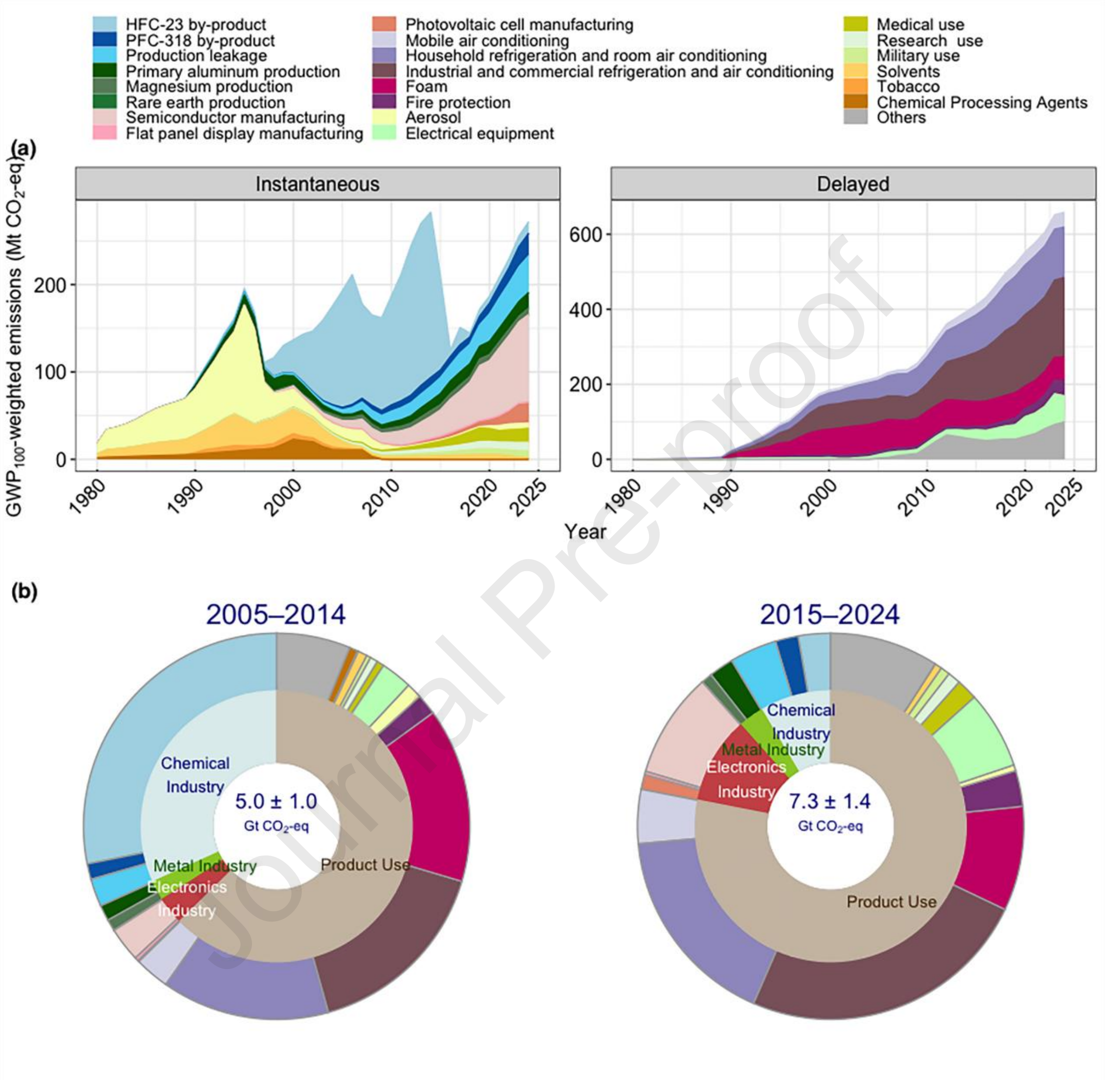

Fig. 4 Halogenated gas emissions by sector in China, (a) annual halogenated gas GWP_{100}-weighted CO_2-eq emissions in instantaneous and delayed sectors from 1980 to 2024, and (b) cumulative halogenated gas GWP_{100}-weighted CO_2-eq emissions over 2005–2014 and 2015–2024 periods by sector.

The period 2015–2024 saw halogenated emissions of 7.3 ± 1.4 Gt CO_2-eq, representing an increase from the 5.0 ± 1.0 Gt CO_2-eq during 2005–2014 (Fig. 4b). Comparison of the two periods highlights three key trends: 1) emissions from chemical industry, particularly HFC-23 as by-products, were mitigated through effective destruction measures; 2) electronics industry emissions increased 4.6-fold, reflecting rapid sectoral expansion; and 3) within product use, alongside refrigeration, air conditioning, and foam sub-sectors, electrical equipment has emerged as a major emission source.

3.3.2. Halogenated gas banks

In the product use sector, over 95% of halogenated gas consumption occurred in sub-sectors with delayed emissions. Their banks have snowballed over 1980–2024 and reached 2.7 ± 0.3 Mt in 2024, dominated by HCFC-22 (613 ± 70 kt), HFC-32 (602 ± 62 kt), and HFC-134a (317 ± 41 kt) (Fig. 5a). Of these banks, 0.9 ± 0.1 Mt (33%) are TFA precursors, mainly consisting of HFC-134a in mobile air conditioning, industrial and commercial refrigeration and air conditioning, HFC-125 in industrial and commercial refrigeration and air conditioning, and HFC-227ea in fire protection (Fig. 5b).

ODS banks declined to 68 ± 8 kt CFC-11-eq in 2024, dominated by foam (83%) (Fig. 5c). The top three substances by ODP-weighted banks were HCFC-141b (26 ± 3 kt CFC-11-eq), HCFC-22 (23 ± 3 kt CFC-11-eq), and CFC-11 (11 ± 1 kt CFC-11-eq). In GWP_{100}-weighted terms, halogenated gas banks reached 8.3 ± 1.7 Gt CO_2-eq in 2024 (Fig. 5d), approximately 66% of cumulative emissions in the product use sector during 1980–2024 (Fig. A4). Of these, 45% (3.9 ± 0.4 Gt CO_2-eq of SF_6) came from the electrical equipment, followed by foam (16%), industrial and commercial refrigeration and air conditioning (12%), fire protection (10%), and household refrigeration and room air conditioning (10%). SF_6 dominated the GWP_{100}-weighted banks, with HCFC-22 and HFC-125 also exceeding 0.8 Gt CO_2-eq.

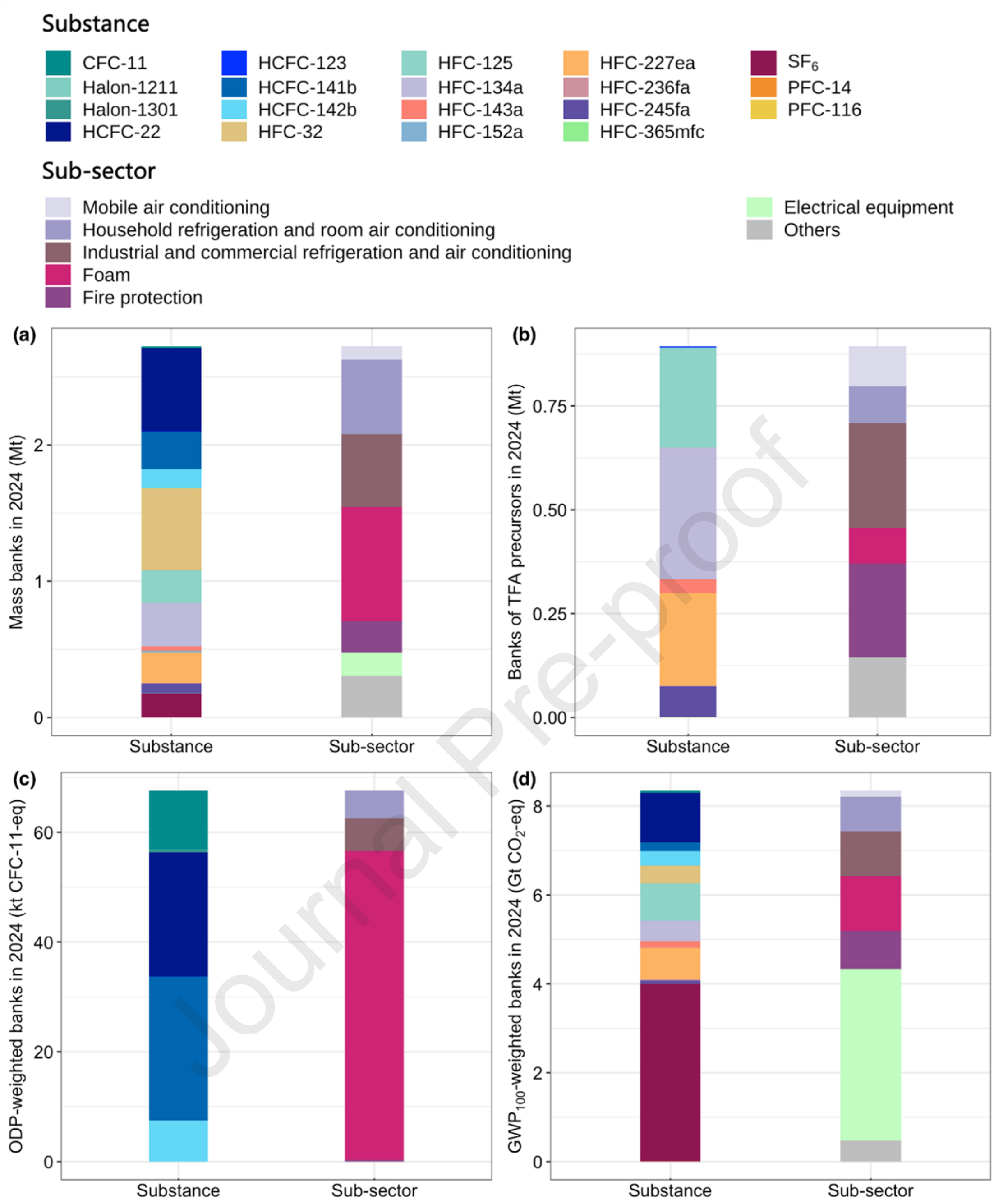

Fig. 5 Halogenated gas banks in 2024 by substance and by sub-sector in China, (a) mass-based banks, (b) banks of TFA precursor, (c) ODP-weighted banks, and (d) GWP_{100}-weighted banks.

3.4. Emissions and banks from China's halogenated gas exports

Exported emissions from China's halogenated gas exports increased to 442 ± 30 kt in 2024 (Fig. 6a), equivalent to 891 ± 70 Mt CO_2-eq and 4.8 ± 0.2 kt CFC-11-eq. HCFC-22, HFC-32, HFC-125, and HFC-134a were the main exported and emitted substances. In the same year, exported banks totaled 3.7 ± 0.5 Mt, corresponding to 11 ± 1 Gt CO_2-eq and 41 ± 7 kt CFC-11-eq—1.25 times the cumulative exported emissions over 2005–2024 in CO_2 equivalent terms (Fig. 6b).

In 2024, TFA precursors accounted for 54% of exported emissions and 33% of banked halogenated gas exports. Annual average TFA formation from exported halogenated gas has accelerated since the introduction of HFO-1234yf in 2019, reaching 19.1 (11.4–29.2) kt in 2024 (Fig. 6c) and totaling 129.4 (74.6–198.0) kt cumulatively from 2005 to 2024. Though HFO-1234yf represented merely 0.3% of export emissions over 2005–2024, it contributed a dominant 12% of total TFA formation across the nine precursors. Thus, while HFOs offer low-GWP alternatives to HFCs, their high TFA yields are likely to drive rapid increases in local TFA formation when widely adopted.

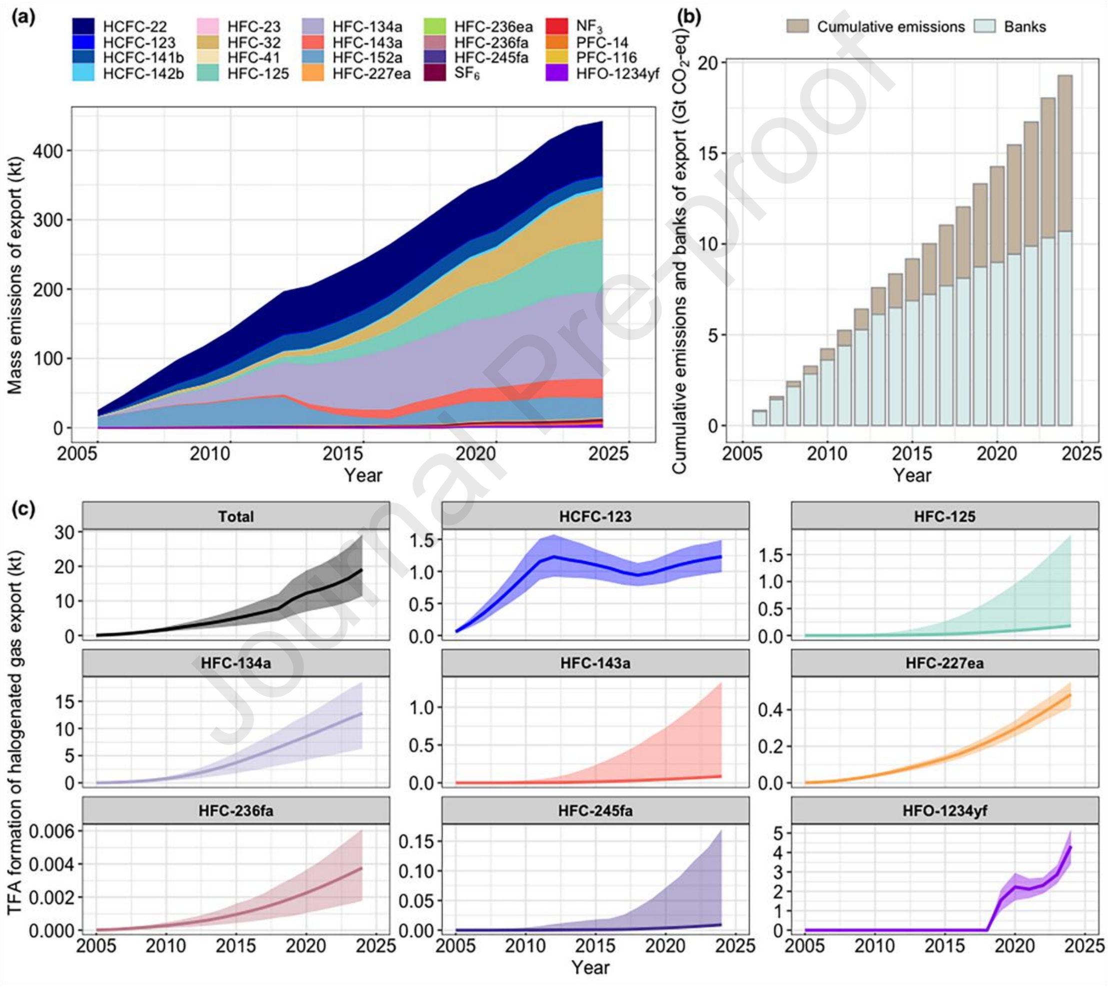

Fig. 6 Emissions and banks regarding China's halogenated gas exports over 2005–2024, (a) mass emissions, (b) GWP_{100}-weighted cumulative emissions and banks, and (c) annual average TFA formation of China's halogenated gas export.

4. Discussion

The focus of halogenated gas emission reductions is gradually shifting to combating climate change with the decrease in ODS emissions and the increase in GHG emissions. While the impact of China's territorial and exported halogenated gas emissions on ozone depletion (below 15 kt CFC-11-eq in 2024) has markedly declined, their contribution to climate change (nearly 2 Gt CO_2-eq in 2024) has seen a remarkable rise. Overall, China's territorial halogenated gas emissions have been showing an upward trend and accounted for 6% of other main GHG emissions (12.5 Gt CO_2-eq, including CO_2, CH_4, and N_2O) in 2021 (PRC, 2024). The First Biennial Transparency Report on Climate Change of China reported 462 Mt CO_2-eq of FGHG emissions (including HFCs, SF_6, CF_4 and C_2F_6) in 2021 (PRC, 2024), whereas this study estimated 493 ± 92 Mt CO_2-eq for the same gases, plus an additional 45 ± 23 Mt CO_2-eq from NF_3 and other PFCs (mainly c-C_4F_8). This comparison reveals a gap of 0.1 Gt CO_2-eq regarding FGHG emissions in official reporting. In 2024, China's territorial emissions of FGHGs regulated by the UNFCCC reached 717 ± 150 Mt CO_2-eq, with an additional 213 ± 34 Mt CO_2-eq of considerable ODS emissions, underscoring the significance of halogenated gas mitigation.

Placing these results in the global context highlights their policy relevance. Under current unconditional NDCs, global GHG emissions are projected at 54 (46–60) Gt CO_2-eq in 2035, far above the 29 Gt CO_2-eq (21–35 Gt CO_2-eq) limit needed to keep warming below 1.5 ℃ (UNEP, 2024a). China and the United States of America together accounted for 41% (22 Gt CO_2-eq) of global GHG emissions in 2023 (UNEP, 2024a). The United States has set an economy-wide target of reducing net greenhouse gas emissions by 61%–66% below 2005 levels in 2035 (USA, 2021). In China, ODS emissions will continue declining under existing policies, but FGHG emissions are increasing apace. The delayed emission sectors (mainly refrigeration and air conditioning, electrical equipment, and foam) dominated 95% of halogenated gas consumption in the product use sector and 67% of China's halogenated gas GWP_{100}-weighted CO_2-eq emission over 2005–2024, implying substantial time-lagged emissions before 2035, even with Kigali compliance. In addition, emissions from electronics industry, particularly semiconductor manufacturing, are rising rapidly with the expansion of high-tech industries. Taken together, these trends point to the urgent need for a stricter mitigation pathway aligned with China's 2035 NDC and 2060 carbon neutral targets.

Beyond annual emissions, the accumulation of banks poses a long-term challenge. Substantial ODS banks remain, and FGHG banks are even larger (6.7 ± 0.7 Gt CO_2-eq for territorial and 9.3 ± 0.9 Gt CO_2-eq for exported in 2024) and still growing. Accelerating the phase-out of controlled substances is one avenue to limit further bank growth, but managing existing banks is equally critical. Effective bank management reduces the need for virgin production, curbs banked emissions, and facilitates compliance with phase-down targets (UNEP, 2022). A study points out that bank management in refrigeration and air conditioning, foam, and fire protection could avoid up to 8.0 Gt CO_2-eq of cumulative emissions by 2060 in China, with 93.2% attainable at costs below 10 USD/t CO_2-eq (Chen et al., 2025), lower than global total carbon price (30–50 UDS/t CO_2) for the period 2015–2021 (World Bank, 2024) and China's composite price for carbon market closing (7–11 UDS/t CO_2) over 2021–2022 (MEEPRC, 2024). Owing to their lower mitigation costs and their role as supplementary mitigation actions falling outside the scope of Kigali Amendment requirements, emission reductions resulting from bank management measures are well suited for integration into domestic market-based instruments, such as national carbon emissions trading system.

Addressing banks effectively requires sector-specific and priority-based approaches. First, in electrical equipment, 175 ± 17 kt (3.9 ± 0.4 Gt CO_2-eq) of SF_6 is currently banked in operational assets, with nearly 90% of emissions expected during servicing and end-of-life phases. Given asset lifespans of 30–40 years, mandatory recovery systems, particularly for high-voltage applications, should be prioritized to prevent large future releases. Second, in refrigeration, air conditioning and heat pump (RACHP), life-cycle refrigerant management (LRM), encompassing leakage prevention, recovery, recycling, reclamation, and destruction (UNEP, 2024b), provides a comprehensive pathway to address existing halocarbon refrigerant banks exceeding 2 Gt CO_2-eq in China. Third, in foam applications, where blowing agents accounted for 83% (56 ± 7 Mt CFC-11-eq) of ODP-weighted and 16% (1.2 ± 0.2 Gt CO_2-eq) of GWP_{100}-weighted banks in 2024, recovery and incineration upon decommissioning should be prioritized over landfill disposal to minimize release. Together, these measures define a near-term policy pathway that combines high mitigation potential, low cost, and early emission avoidance.

While bank management addresses legacy emissions embedded in existing assets, future environmental risks from substitutes also warrant parallel attention. Though low- or zero-GWP alternatives can avoid considerable upstream emissions, certain options—HFOs/HCFOs—present environmental trade-offs due to their high yields of persistent degradation product TFA. By 2024, TFA formed from China's territorial and exported halogenated gas emissions had accumulated to 74.7 (40.7–119.5) kt and 129.4 (74.6–198.0) kt, respectively, with precursor banks reaching 2.1 ± 0.3 Mt. TFA concentrations will continue to rise as these banks are released and HFO/HCFO adoption expands. Remediating challenging emerging ultra-short-chain PFAS such as TFA in European water and soil is estimated to cost about 100 billion EUR annually, accumulating to around 2 trillion EUR over 20 years (Garry, 2025; FPP, 2025).

With HFOs/HCFOs poised for large-scale adoption as HFC alternatives, their deployment should therefore be accompanied by systematic life-cycle risk assessment, routine environmental monitoring of TFA, and precautionary governance of degradation products. In parallel, recovery and destruction systems must be designed to ensure compatibility with mixed HFC–HFO refrigerant streams, so as to avoid infrastructure lock-in and the risk of amplifying TFA formation from large-scale uncontrolled emissions. Integrating climate mitigation objectives with chemical risk governance is thus essential to prevent the substitution pathway from creating new long-term environmental burdens.

Despite these insights, several limitations should be acknowledged. First, in the absence of clarity on the specific uses of exported chemicals, we used bank emission factors of each substance to calculate export emissions, making the estimates less certain than territorial ones. Second, the bank figures provided in this study were total banks, without distinguishing active and inactive foam banks. Third, this study estimated historical emission and TFA formation but did not model future demand, emission trends, TFA formation and deposition fluxes under substitution and mitigation pathways. Addressing these gaps through scenario-based analyses in subsequent research will be critical to inform 2035 Beautiful China goal, China's 2060 carbon neutrality objective, and the global Paris Agreement targets.

5. Conclusions

This study develops a comprehensive inventory of China's halogenated gas emissions and banks over 1980–2024, covering 30 substances across 23 sub-sectors, and assesses their impacts on ozone depletion, climate forcing, and TFA accumulation. Key findings include:

(1) China's halogenated gas emissions show declining stratospheric ozone depletion impacts. In 2024, China's territorial and exported halogenated gas emissions exceeded 800 kt. Their ODP-weighted emissions dropped below 15 kt CFC-11-eq due to effective ODS phase-out, which is 20% of the 2000 peak (approximately 70 kt CFC-11-eq).

(2) China's territorial and exported halogenated gas emissions, weighted by GWP_{100}, rose to approximately 2 Gt CO_2-eq in 2024, driven by rapid FGHG growth, signifying a transition in their environmental impacts from ozone depletion to enhanced climate forcing. Combined banks reached 19 ± 3 Gt CO_2-eq by 2024, largely from electrical equipment, RACHP, foam, and fire protection, posing substantial long-term climate risks. Sector-specific bank management provides a near-term pathway with high mitigation potential, low cost, and early emission avoidance.

(3) Low-GWP HFOs raise concerns over TFA accumulation. By 2024, cumulative TFA from territorial and exported emissions exceeded 200 kt. Notably, HFO-1234yf—only 0.3% of export emissions (2005–2024)—contributed 12% of TFA formation, underscoring substitution trade-offs. Integrating climate mitigation with chemical risk governance is essential to prevent substitution pathways from creating new long-term environmental burdens.

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Fu-Li Bai: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Zi-Wei Chen**: Investigation, Writing – review & editing. **Peng-Nan Jiang**: Investigation, Writing – review & editing. **Xu Zhang**: Investigation, Writing – review & editing. **Xing-Chen Zhao**: Investigation, Writing – review & editing. **Jing Wu**: Investigation, Writing – review & editing, Funding acquisition. **Jian-Jun Zhang**: Investigation, Writing – review & editing. **Jian-Xin Hu:** Conceptualization, Investigation, Writing – review & editing, Supervision, Funding acquisition.

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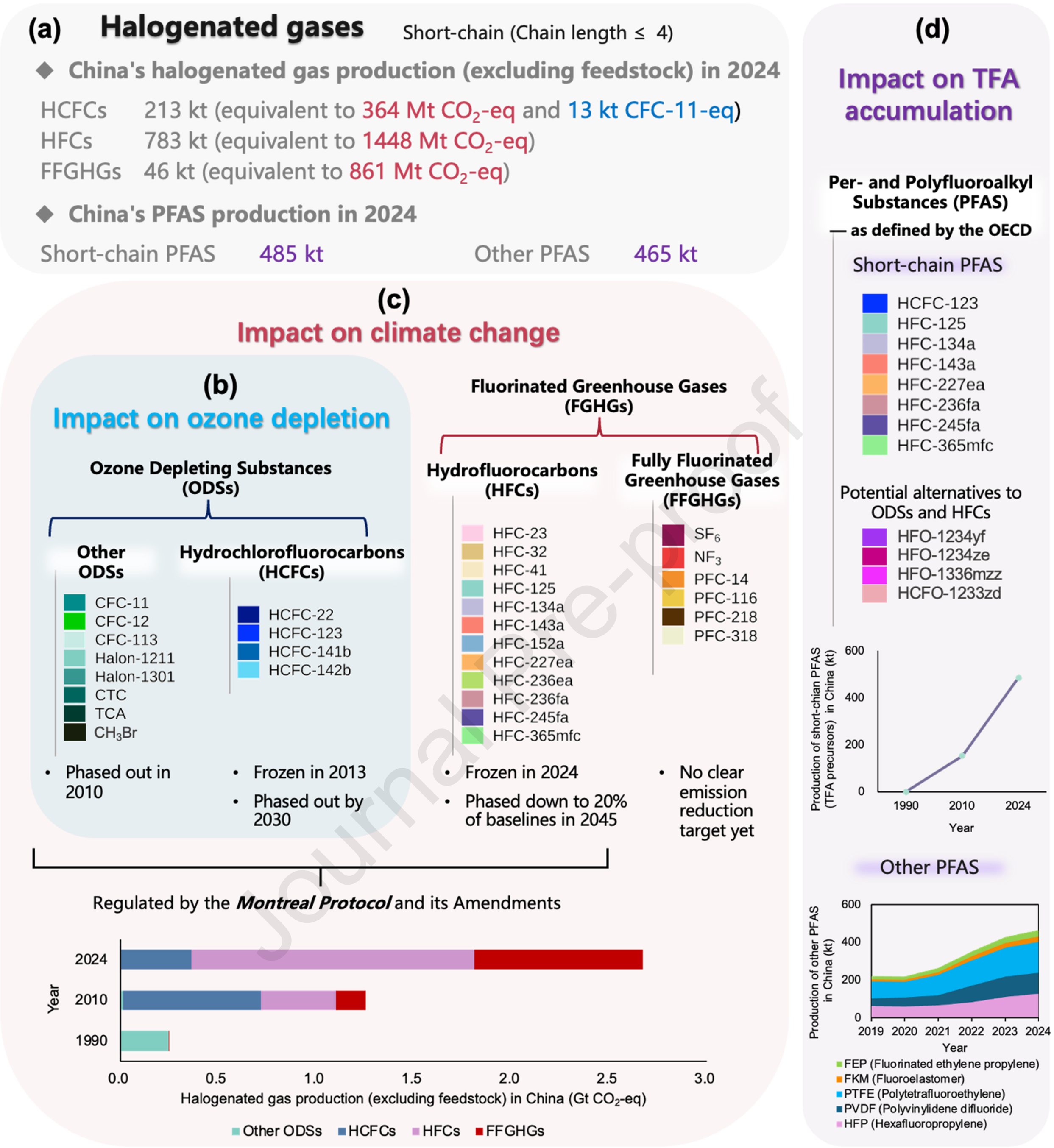
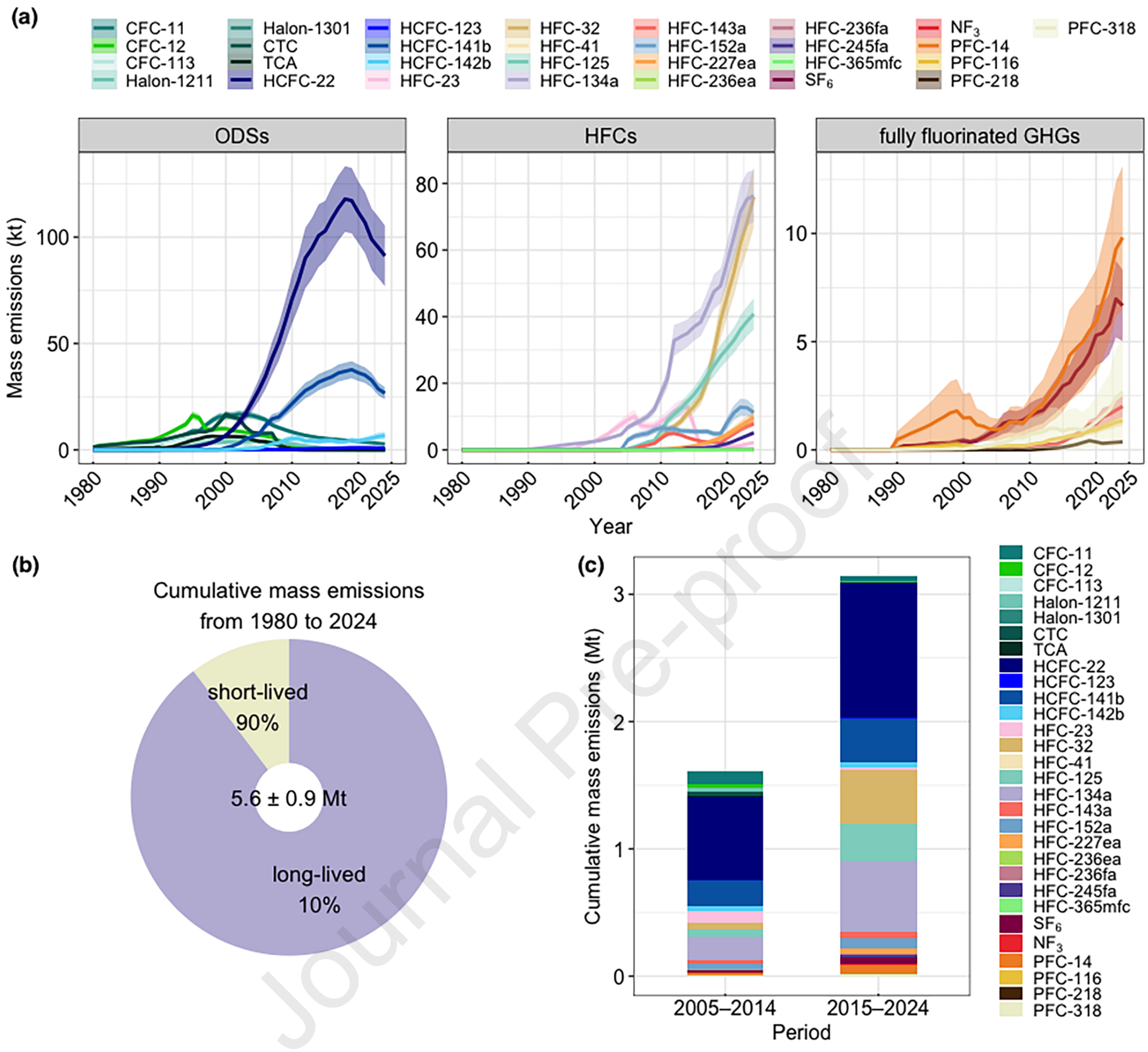
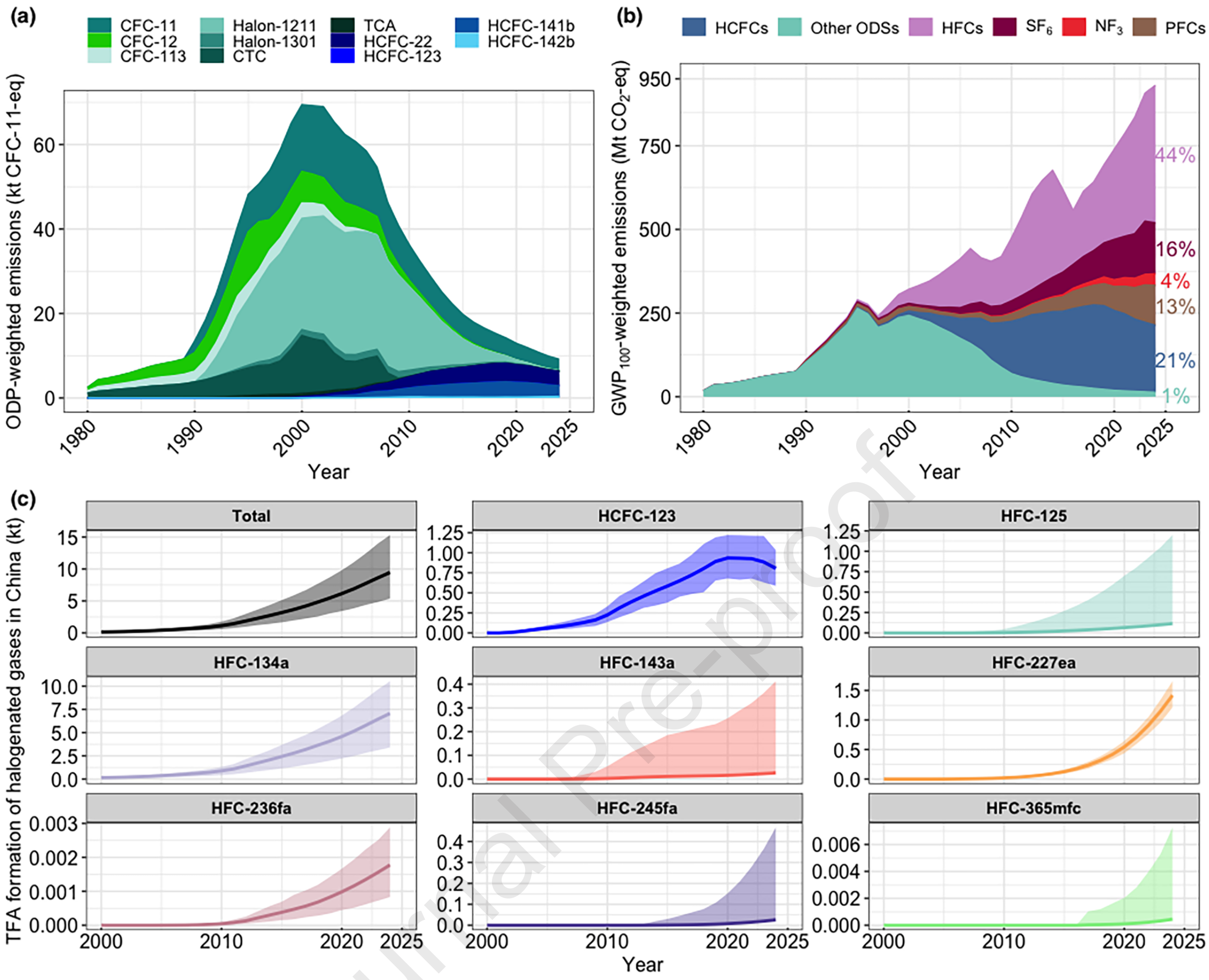
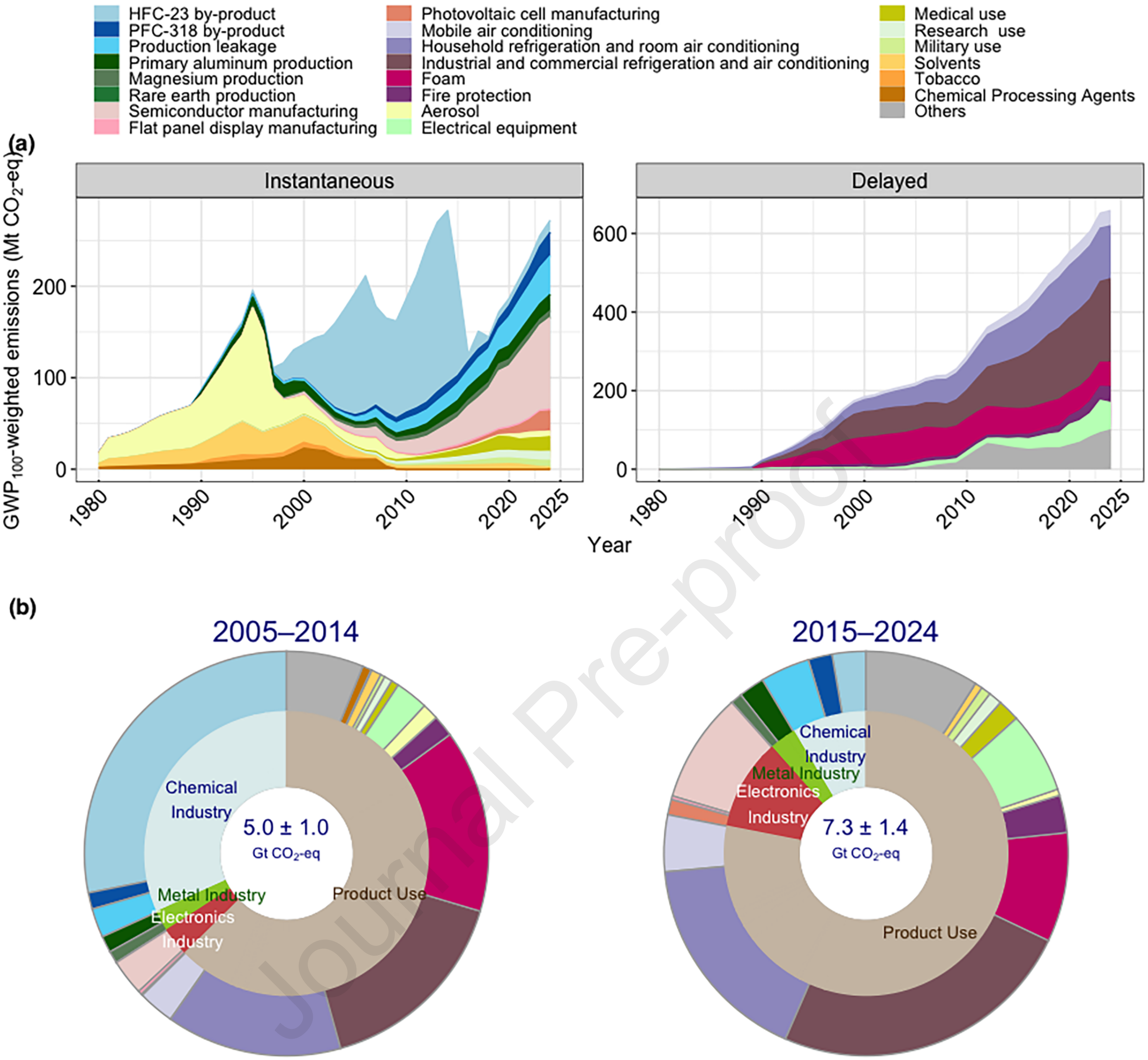
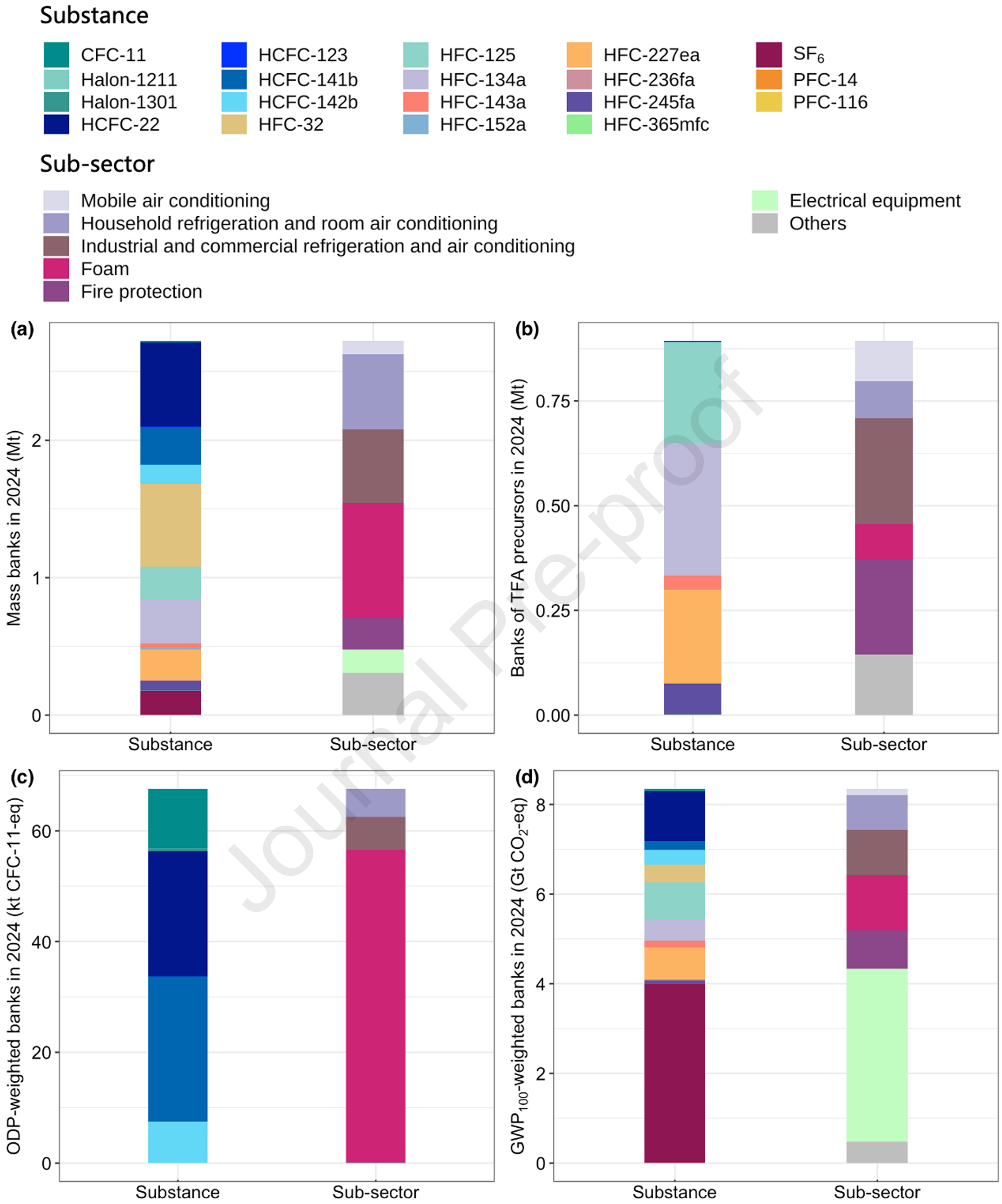
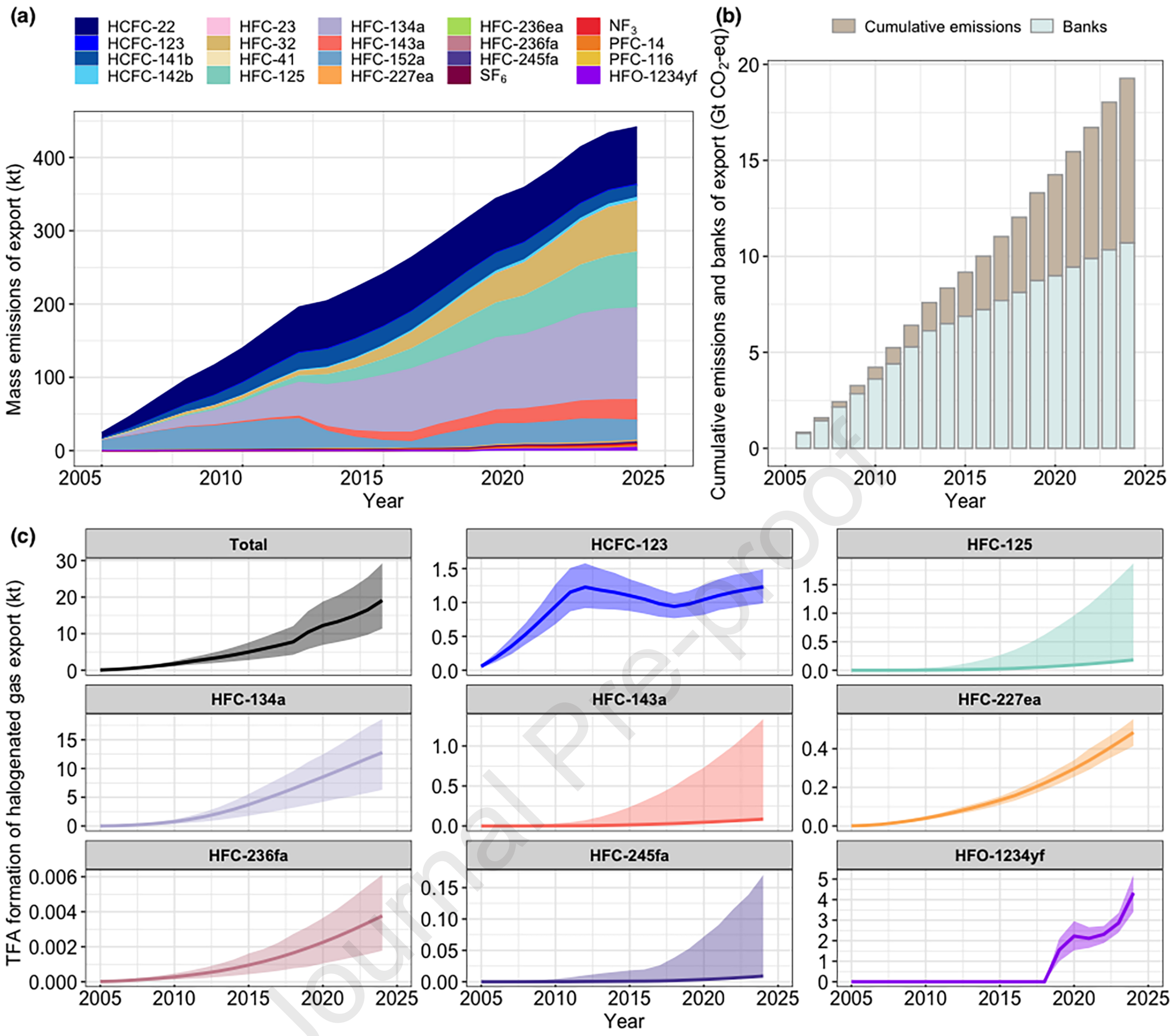

(a) Halogenated gases
Short-chain (Chain length ≤ 4)
◆ China's halogenated gas production (excluding feedstock) in 2024
HCFCs 213 kt (equivalent to 364 Mt CO_2-eq and 13 kt CFC-11-eq)
HFCs 783 kt (equivalent to 1448 Mt CO_2-eq)
FFGHGs 46 kt (equivalent to 861 Mt CO_2-eq)
◆ China's PFAS production in 2024
Short-chain PFAS 485 kt
Other PFAS 465 kt
(c) Impact on climate change
(b) Impact on ozone depletion
Ozone Depleting Substances (ODSs)
Other ODSs
CFC-11
CFC-12
CFC-113
Halon-1211
Halon-1301
CTC
TCA
CH_3Br
Hydrochlorofluorocarbons (HCFCs)
HCFC-22
HCFC-123
HCFC-141b
HCFC-142b
Fluorinated Greenhouse Gases (FGHGs)
Hydrofluorocarbons (HFCs)
HFC-23
HFC-32
HFC-41
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-227ea
HFC-236ea
HFC-236fa
HFC-245fa
HFC-365mfc
Fully Fluorinated Greenhouse Gases (FFGHGs)
SF_6
NF_3
PFC-14
PFC-116
PFC-218
PFC-318
• Phased out in 2010
• Frozen in 2013
• Phased out by 2030
• Frozen in 2024
• Phased down to 20% of baselines in 2045
• No clear emission reduction target yet
Regulated by the *Montreal Protocol* and its Amendments
Year
2024
2010
1990
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Halogenated gas production (excluding feedstock) in China (Gt CO_2-eq)
Other ODSs
HCFCs
HFCs
FFGHGs
(d) Impact on TFA accumulation
Per- and Polyfluoroalkyl Substances (PFAS)
— as defined by the OECD
Short-chain PFAS
HCFC-123
HFC-125
HFC-134a
HFC-143a
HFC-227ea
HFC-236fa
HFC-245fa
HFC-365mfc
Potential alternatives to ODSs and HFCs
HFO-1234yf
HFO-1234ze
HFO-1336mzz
HCFO-1233zd
Production of short-chian PFAS (TFA precursors) in China (kt)
600
400
200
0
1990
2010
2024
Year
Other PFAS
Production of other PFAS in China (kt)
600
400
200
0
2019
2020
2021
2022
2023
2024
Year
FEP (Fluorinated ethylene propylene)
FKM (Fluoroelastomer)
PTFE (Polytetrafluoroethylene)
PVDF (Polyvinylidene difluoride)
HFP (Hexafluoropropylene)


(a)
CFC-11
CFC-12
CFC-113
Halon-1211
Halon-1301
CTC
TCA
HCFC-22
HCFC-123
HCFC-141b
HCFC-142b
HFC-23
HFC-32
HFC-41
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-227ea
HFC-236ea
HFC-236fa
HFC-245fa
HFC-365mfc
SF_6
NF_3
PFC-14
PFC-116
PFC-218
PFC-318
ODSs
HFCs
fully fluorinated GHGs
Mass emissions (kt)
0
50
100
0
20
40
60
80
0
5
10
1980
1990
2000
2010
2020
2025
Year
(b)
Cumulative mass emissions
from 1980 to 2024
short-lived
90%
5.6 ± 0.9 Mt
long-lived
10%
(c)
Cumulative mass emissions (Mt)
0
1
2
3
2005–2014
2015–2024
Period
CFC-11
CFC-12
CFC-113
Halon-1211
Halon-1301
CTC
TCA
HCFC-22
HCFC-123
HCFC-141b
HCFC-142b
HFC-23
HFC-32
HFC-41
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-227ea
HFC-236ea
HFC-236fa
HFC-245fa
HFC-365mfc
SF_6
NF_3
PFC-14
PFC-116
PFC-218
PFC-318


(a)
CFC-11
CFC-12
CFC-113
Halon-1211
Halon-1301
CTC
TCA
HCFC-22
HCFC-123
HCFC-141b
HCFC-142b
ODP-weighted emissions (kt CFC-11-eq)
0
20
40
60
1980
1990
2000
2010
2020
2025
Year
(b)
HCFCs
Other ODSs
HFCs
SF_6
NF_3
PFCs
GWP_{100}-weighted emissions (Mt CO_2-eq)
0
250
500
750
950
44%
16%
4%
13%
21%
1%
1980
1990
2000
2010
2020
2025
Year
(c)
TFA formation of halogenated gases in China (kt)
Total
0
5
10
15
HCFC-123
0.00
0.25
0.50
0.75
1.00
1.25
HFC-125
0.00
0.25
0.50
0.75
1.00
1.25
HFC-134a
0.0
2.5
5.0
7.5
10.0
HFC-143a
0.0
0.1
0.2
0.3
0.4
HFC-227ea
0.0
0.5
1.0
1.5
HFC-236fa
0.000
0.001
0.002
0.003
HFC-245fa
0.0
0.1
0.2
0.3
0.4
HFC-365mfc
0.000
0.002
0.004
0.006
2000
2010
2020
2025
Year


HFC-23 by-product
PFC-318 by-product
Production leakage
Primary aluminum production
Magnesium production
Rare earth production
Semiconductor manufacturing
Flat panel display manufacturing
Photovoltaic cell manufacturing
Mobile air conditioning
Household refrigeration and room air conditioning
Industrial and commercial refrigeration and air conditioning
Foam
Fire protection
Aerosol
Electrical equipment
Medical use
Research use
Military use
Solvents
Tobacco
Chemical Processing Agents
Others
(a)
Instantaneous
Delayed
GWP$_{100}$-weighted emissions (Mt CO$_2$-eq)
0
100
200
400
600
1980
1990
2000
2010
2020
2025
Year
(b)
2005–2014
Chemical Industry
5.0 ± 1.0
Gt CO$_2$-eq
Metal Industry
Electronics Industry
Product Use
2015–2024
Chemical Industry
Metal Industry
Electronics Industry
7.3 ± 1.4
Gt CO$_2$-eq
Product Use


Substance
CFC-11
Halon-1211
Halon-1301
HCFC-22
HCFC-123
HCFC-141b
HCFC-142b
HFC-32
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-227ea
HFC-236fa
HFC-245fa
HFC-365mfc
SF$_6$
PFC-14
PFC-116
Sub-sector
Mobile air conditioning
Household refrigeration and room air conditioning
Industrial and commercial refrigeration and air conditioning
Foam
Fire protection
Electrical equipment
Others
(a)
Mass banks in 2024 (Mt)
0
1
2
Substance
Sub-sector
(b)
Banks of TFA precursors in 2024 (Mt)
0.00
0.25
0.50
0.75
Substance
Sub-sector
(c)
ODP-weighted banks in 2024 (kt CFC-11-eq)
0
20
40
60
Substance
Sub-sector
(d)
GWP$_{100}$-weighted banks in 2024 (Gt CO$_2$-eq)
0
2
4
6
8
Substance
Sub-sector


(a)
HCFC-22
HCFC-123
HCFC-141b
HCFC-142b
HFC-23
HFC-32
HFC-41
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-227ea
HFC-236ea
HFC-236fa
HFC-245fa
SF$_6$
NF$_3$
PFC-14
PFC-116
HFO-1234yf
Mass emissions of export (kt)
0
100
200
300
400
2005
2010
2015
2020
2025
Year
(b)
Cumulative emissions
Banks
Cumulative emissions and banks of export (Gt CO$_2$-eq)
0
5
10
15
20
2005
2010
2015
2020
2025
Year
(c)
TFA formation of halogenated gas export (kt)
Total
HCFC-123
HFC-125
HFC-134a
HFC-143a
HFC-227ea
HFC-236fa
HFC-245fa
HFO-1234yf
0
10
20
30
0.0
0.5
1.0
1.5
0
5
10
15
0.0
0.2
0.4
0.000
0.002
0.004
0.006
0.00
0.05
0.10
0.15
0
1
2
3
4
5
2005
2010
2015
2020
2025
Year

Declaration of competing interest

The authors declare no conflict of interest.