Response to reviewers for preprint egusphere-2025-2277:

Banked CFC-11 contributes to an unforeseen emission rise and sets back progress towards carbon neutrality

EC#1 (on behalf of the 3rd reviewer)

Comment #1

This is an analysis of CFC-11 emissions on global and regional scales through recent years when measured atmospheric changes suggested global emissions increased and subsequently decreased. These changes were described in previous papers as having been associated primarily with increased production (and emission) in part in and from China. With a dynamic material flow model to estimate emissions to the atmosphere from the relevant processes, the authors study the sensitivity of calculated emissions from a range of different parameters in an overall useful analysis. They suggest that some increase in emissions might be expected during recent years based on how materials containing CFC-11 were handled during decommissioning and "end-of-life". This suggestion isn't particularly novel, as it was explored to some extent in those initial 4 papers from 2018-2021, was mentioned in Chapter 7 of the 2005 IPCC/TEAP special report (led by P. Ashford et al., although the expected increases were anticipated to be slow and to occur in future years), and is worth repeating, as is the importance of management of these chemicals during decommissioning for minimizing future emissions and their adverse impacts. However, a number of other aspects of the work prevent me from suggesting that it is publishable in its current form, see below.

The abstract is overly general and vague on the main point emphasized there: "bank related emissions could have led to an increased CFC-11 emissions from 2014 to 2018". Figures in the paper actually show global totals declining through this period, and regional emissions from multiple regions that are also decreasing or essentially unchanged if one considers the uncertainties associated with the analysis. Ignoring the range of uncertainties and focusing on only their mid-range estimates, the results can be used to suggest that bank-related emissions increased from only China during this period, but this raises important questions: 1) why is the potential emission increase in China quite different from the decreases derived for the other regions? 2) What are the specific region-based factors/assumptions that cause this uniqueness for China in the model, and what is the supporting information that backs up these choices? Is the uniqueness of China related to the timing and fraction of CFC-11 in different sub-sectors or perhaps of assumptions on lifespan of foam product applications (Table S3)? Many input parameters are provided in tables, but no clarity on the specific ones that make China unique with respect to the time evolution of CFC-11 bank emissions is discussed. 2) Should an increase in Chinese bank-related emissions actually have occurred, the global decreasing trend would imply that the increases in China were offset by unexpectedly rapid decreases in other areas. Is this reasonable?

Reply: We extend our heartfelt thanks for your incisive and constructive appraisal. Your expertise has provided invaluable guidance, and we have meticulously incorporated every suggestion into the revised manuscript to enhance its clarity and rigor.

We fully acknowledge that the potential for increased CFC-11 emissions during decommissioning was previously explored in the initial four studies (2018–2021) and noted in the 2005 IPCC/TEAP Special Report (Chapter 7). However, our work advances the understanding through a systematic, uncertainty-driven analysis of emission trajectories. Specifically, our study quantifies the impact of parameter variability on emissions, contributing to a more robust assessment of potential outcomes. This analytical focus represents a nuanced departure from previous research, offering a more comprehensive understanding of the variability in emissions.

In practice, our results can be calibrated to align with 2014–2018 top-down emission trends by adjusting Weibull scale/shape parameters (product lifespans) or end-of-life (EoL) emission fractions. However, given the spatiotemporal fluctuations in these parameters (SI Tables S3–S4), we prioritized robust uncertainty quantification over strict calibration of annual trends. To model CFC-11 emissions, we employed a systematic Monte Carlo simulation framework. This approach propagates parameter uncertainties through the emission model, generating output distributions. We treated the Weibull scale (u) and shape (β) parameters, manufacturing-stage emission factor (EF, $Ef_{man}(Y)$) and use-stage EF ($Ef_{use}(Y)$) as independent normal variables truncated at zero to exclude non-physical negative values. Distributions were defined using regional/global means (Tables S7-S13), with standard deviations set to 25% of respective means to reflect plausible variability. For instance, in the global boardstock/laminate subsector, mean Weibull scale (u) and shape (β) are 50 and 6, while the EFs for manufacturing ($Ef_{man}(Y)$) and use ($Ef_{use}(Y)$) are 6% and 1%, respectively, yielding standard deviations of 12.5, 1.5, 1.5%, and 0.25%. After defining distributions for all parameters, we generated 10,000 random samples per foam subsector (e.g., Figure S14). EoL and post-life EFs were treated as constant values due to poorly constrained ranges in literature. Annual emissions were computed for each parameter combination, and realizations were aggregated to construct the probability distribution. Uncertainty ranges are reported as the 0.5th to 99.5th percentile interval, corresponding to a

99% confidence interval. The dynamically fluctuating emission ranges in Figure 1a represent physically plausible outcomes within these uncertainty bounds.

Our bottom-up modeling reveals that emission trajectories—such as those in the U.S. and Europe—are influenced by the lifespan of CFC-11-containing foam products. Moreover, the lifespans of polyurethane (PUR) foams exhibit considerable spatiotemporal variability, which may lead to either an upward or downward shift in estimated emission trends. These divergent trends could also manifest within global emission trajectories, falling within the uncertainty ranges depicted in Figure 1.

China's emission trajectory diverges from those of the U.S. and Europe due to the differences in 'the timing and fraction of CFC-11 in different sub-sectors', 'assumptions on lifespan of foam product applications', and higher EoL release fractions. First, the timing and sectoral distribution of CFC-11-containing PUR foam differ markedly. In the U.S. and Europe, construction applications dominated (SI Figs. S3, S5), whereas in China, appliance insulation accounted for the majority of use, with peak consumption occurring several years later (SI Fig. S6). Second, appliances generally have shorter lifespans compared to construction materials (SI Table S8 vs. S11). Third, China's EoL release fractions exceed those in developed economies, a discrepancy attributed to less stringent waste management practices (SI Table S8 vs. S11). The combination of shorter product lifespans and higher EoL release fractions amplified the magnitude of the emission increase. These factors collectively explain China's unique peak in bank emissions.

This study investigates uncertainties from previously underexplored sources to enhance the understanding of CFC-11 emission trajectories. The broader uncertainty ranges established here capture plausible variability in the estimates. To improve clarity and provide a more comprehensive interpretation, we have expanded the methodological description and elaborated on the results in the revised manuscript. We address the specific concerns point by point in the responses below.

Comment #2

The main message of the abstract is written so that it is easy for the reader to be misled into thinking that perhaps CFC-11 production didn't increase. This is inconsistent with the main text of the paper, discussions of scenarios, and the mismatch on a global scale between expected and atmosphere-derived emission in Figure 1a that would seem to require post-2010 production as an explanation.

Reply: Thank you for your valuable comments on the description of the abstract regarding unreported production.

As suggested, we have revised the abstract, lines 18–32:

> "An unexpected rise of trichlorofluoromethane (CFC-11) emissions has undermined the efforts behind the Montreal Protocol. However, the sources of these increased emissions, from CFC-11 banks to unreported production, remain contentious. Here, we enhanced the bottom-up dynamic material flow analysis model to characterize the stocks and flows of CFC-11, retrospectively and prospectively from 1950 to 2100. We find that dynamic changes in bank-related emissions may have contributed to the increased CFC-11 emissions from 2014 to 2018, implying potential overestimation of unreported production. Under Scenario 2 (mid-range unreported production levels), long-term emission of banked CFC-11 will accumulate to 980 (600–1500) kilotons (kt), equivalent to 4.7 (2.9–7.1) gigatons (Gt) CO_2, between 2025 and 2100. Scenario analysis highlights the potential to reduce up to 50% of emissions through optimized end-of-life (EoL) management strategies. Our results call for further investigation into the lifespan and EoL processes of products containing ozone-depleting substances (ODSs) to reconcile emission estimates derived from bottom-up and top-down modeling approaches. The modeling approach could also be applied to estimate and project the bank-related emissions and impacts of other ODSs."

Comment #3

Some points are also difficult to reconcile: inventory-based model-derived emissions are argued to be consistent with atmosphere-based results in the US, Europe, and China, yet the authors argue that there was substantial unreported production. Are we to conclude that it must have occurred outside these regions despite the contrary evidence provided elsewhere?

Reply: Thank you for your attention to this detail. We appreciate the opportunity to clarify the consistency between inventory-based and atmospheric-based emissions data. Our analysis indicates bank-related emissions partially explain the observed increase in CFC-11 emissions during 2014–2018. While previous studies show declining emissions in China, our analysis suggests a rise from 8 (4–13) kt/yr in 2008–2012 to 11 (5–13) kt/yr in 2014–2018. This upward trend aligns Park et al. (2021), who reported a 7 ± 4 kt/yr increase from eastern China during 2014–2017 versus 2008–2012, albeit with a slightly lower magnitude.

Redington et al. (2023) confirmed declining emissions in western Europe (2008–2021) through top-down modeling, while identifying persistent regional hotspots that the area including northern France, Belgium, the Netherlands, and Luxembourg (Benelux) showed consistently elevated emissions of CFC-11. Our model supports this spatial variability through plausible lifespan parameter adjustments.

Our findings do not suggest that unreported production must have occurred outside these regions. Increased bank-related emissions in China demonstrate that growth during 2014–2018 could originate within these areas.

Comment #4

On the regional analyses.

Any revision should be sure to reflect on the uncertainties associated with the assumptions required to perform the analysis in the main text and be more circumspect about the conclusions. For example, China's emissions are said to have increased from 8 (4-13) kt/yr during 2008-12 to 11 (5-13) kt/yr during 2014-18, but given these large uncertainties justifying a conclusion that emissions actually increased is problematic. Discussion of the very small increases reported by Redington et al. are mentioned without consideration of their uncertainties and that they are very small. Did atmosphere-based emissions from these regions actually increase above detectability? The manuscript doesn't indicate that Dunse et al and Manning et al. actually suggested emissions increases through this period, although a reading of lines 43-46 would suggest otherwise. This very slight change in the Redington et al. study is very different from the much larger increase that the inventory model derives for Europe, in apparent contradiction to the wording and assertion on lines 313-314.

These points are central with respect to the stated purposes of this study, which is related to assertions that previous analyses "did not adequately consider the variabilities in lifespans of foam products and their EoL management" and that "surveys reveal significant temporal and spatial variability in the actual lifespans of buildings". Many of the more recent inventory-based studies did provide an analysis of a range of parameter values. Providing more clarity on how the new model adds clarity and understanding to the situation is needed but currently lacking.

Reply: Thank you for your critical feedback. A core methodological distinction of our study is its explicit focus on emission variability arising from plausible parameter fluctuations. Rather than deriving a single best-fit trend calibrated to atmospheric data, we quantify potential bounds of emissions and identify key drivers of variability to enhance the interpretation of regional dynamics. This explains our emphasis on ranges over point estimates.

For instance, regarding China's emissions, the shift from 8 kt/yr (2008–2012) to 11 kt/yr (2014–2018) represents a statistically plausible scenario emerging from region-specific parameter combinations (SI Table S11), with all parameter values remaining within empirical and literature-supported constraints.

Extending this logic to European emissions, we recognize that Redington et al. (2023) reported small, localized emission increases with their own associated uncertainties—findings we do not contradict. Our model, which allows for greater parameter flexibility, captures both increasing and declining trends as well as larger potential fluctuations. This does not introduce contradiction but rather highlights that regional emission trajectories are sensitive to inputs, with observed small increases representing one end of a broader plausible spectrum. Similarly, while Dunse et al. and Manning et al. do not explicitly emphasize emission increases, our analysis contextualizes their findings by showing how parameter variability can reconcile seemingly divergent trends across studies.

Comment #5

Details:

Further, the juxtaposition in Figure 1b of top-down and bottom-up estimates for "China" may not be appropriate, given that I believe some (or all) of the top-down estimates represent emissions from only portions of China, whereas I'm guessing the bottom-up estimates are for all of China.

Reply: We sincerely appreciate this important nuance regarding the geographic scope of Figure 1b. To address this, we have added explicit clarification of the spatial coverage of each dataset. This ensures transparency about scale differences and enables accurate interpretation of the figure.

Please refer to lines 268–274 of the main text:

> "Using top-down approaches, Park et al. (2021) estimated a 7 ± 4 kt/yr increase in emissions from eastern China during 2014–2017 compared to 2008–2012. Our national-scale bottom-up modelling aligns the upward trend reported by Park et al. (2021), albeit with a slightly smaller magnitude. Yi et al. (2021) reported a national trend that climbed from 8.3 ± 1.6 kt/yr in 2009 to a peak of 13.9 ± 2.4 kt/yr in 2017, followed by a decline to 10.9 ± 1.7 kt/yr in 2019. Our independent estimates of 7 (4–14), 11 (5–14), and 10 (4–13) kt/yr for the corresponding years are broadly consistent with these findings when considering overlapping uncertainties."

Comment #6

Following up on the comment related to the abstract: the authors don't address in the main text why the relative increase suggested in decommission- or EOL-related emissions for China, the US and the EU are so different. Were different parameters used for these different regions based on the unsupported suggestion that they depend on "cultural, economic, and political factors"? Why is different language used to describe the processes for these different regions? More clarity is needed here as to the cause for these differences.

Reply: Thank you for this valuable critique. As addressed in our response to Comments #1, we would like to summarize the key points again.

Please refer to the revised main text, lines 350–355:

> "China's distinct emission trajectory, relative to the U.S. and Europe, arises from region-specific factors. First, appliances dominate CFC-11 use in China PUR foams, whereas construction prevails in the U.S. and Europe (Figures S3/S5 vs. S6). Second, appliances generally have shorter lifespans than construction materials. Third, China exhibits higher release fractions during waste management processes (SI Tables S8 vs. S11). The synergistic interaction of shorter lifespans and elevated EoL release fractions amplified the magnitude of China's emission surge."

Comment #7

With respect to the scenarios, some values for emission and unreported production are provided, with uncertainties, but no indication of how those numbers were arrived at and what constraints were used to allow those values to be estimated. Again, further clarity is needed here.

Reply: Thank you for your critical comments.

We have expanded the scenarios development with additional methodological detail. Please refer to the revised main text, lines 204–222:

> "TEAP (2019; 2021) identified the most likely routes for unreported CFC-11 production: (a) large-scale carbon tetrachloride (CTC) conversion (≥50 kt/yr capacity), and (b) micro-scale operations (0.1–2 kt/yr) producing low-grade CFC-11 for foam blowing. China's 2018 enforcement actions revealed no evidence of large-scale CFC-11 usage within the country (China MEE, 2019). During these actions, 177.6 metric tons of CFC-11 precursor materials and 29.9 tons of illegally produced CFC-11 were seized. Among 1,172 inspected polyether enterprises, 10 small-scale operations were found to have partially used CFC-11. Considering these findings, we developed three scenarios.

Scenario 1 (S1) serves as a baseline, representing an extreme situation with no unreported production. Scenario 2 (S2) is designated as an intermediate scenario with mid-range unreported production levels. For S2, we assume microscale plants (0.1–2 kt/yr) with unreported production of 25 kt/yr during 2014–2018—half the TEAP large-scale estimate—with 10 kt in 2013. This assumption would yield a 3–8 kt/yr increase in CFC-11 emissions, depending on its application in PUR appliance or spray insulation foam. Scenario 3 (S3) indicates an extreme worst case of unreported CFC-11 production, approximately 23 ± 7 kt/yr of emissions caused by the unreported production of CFC-11 during 2014–2018 (Lickley et al., 2021; TEAP, 2021). Given the diverse end uses of foam products, two subscenarios have been formulated under both S2 and S3. Subscenario 1 assumes unreported CFC-11 is used in spray insulation foams (_SIF), which exhibit a substantial release fraction during their manufacturing. Subscenario 2 involves unreported CFC-11 use in appliance insulation foams (_AIF), characterized by a lower release fraction during manufacture and a shorter product lifespan compared to construction spray foams."

Please refer to the revised Figure 3:

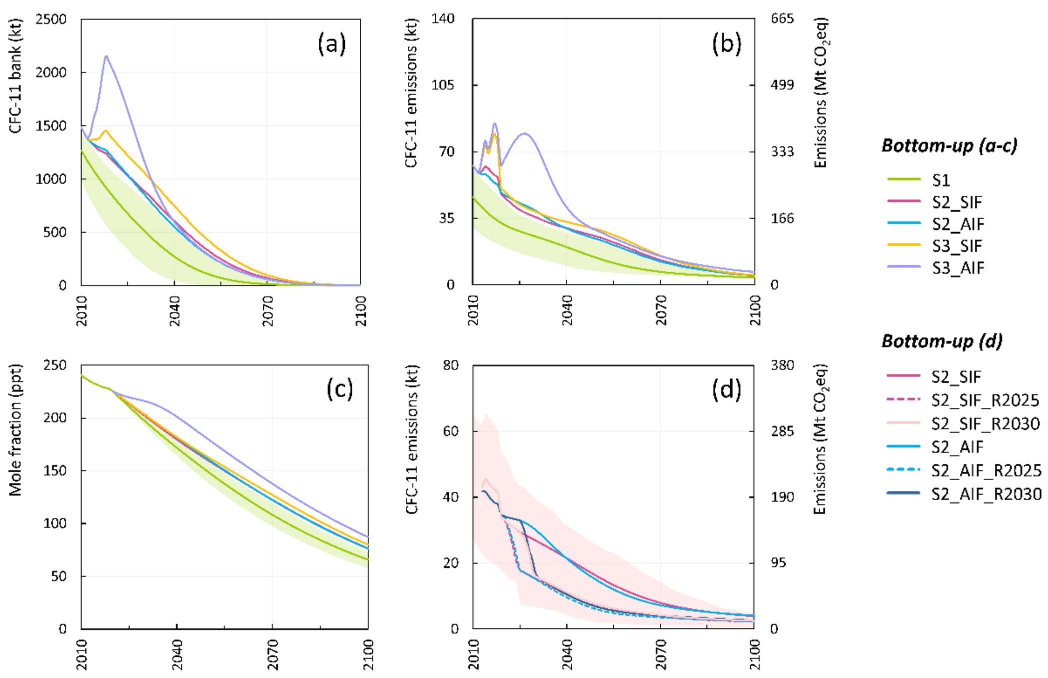

Figure 3 CFC-11 banks, emissions and impacts considering unreported production and mitigation potential. (a) CFC-11 banks based on scenario analysis. (b) CFC-11 emissions and corresponding CO_2-equivalent (CO_2-eq) emissions under various scenarios. (c) CFC-11 global mole fractions in part per trillion (ppt) under various scenarios. (d) Estimated mitigation potential of CFC-11

and its CO_2-eq emissions under scenario 2 (S2). The shaded regions represent the 99% confidence interval for S1 in panels (a–c) and for S2 in panel (d).

Please refer to the revised version in the main text, lines 375–398:

"Under S1, global CFC-11 banks declined from 1270 (1000–1500) kt in 2010 to 1040 (720–1250) kt in 2015, and further to 680 (350–950) kt in 2025, with projections indicating a continued decrease to 120 (10–300) kt by 2050. These estimates closely align with those reported by TEAP (2021) and are further validated by TEAP's (2019) independent assessment using Ashford et al. (2005) methodology, to estimate 2015 banks at 1070–1292 kt. Cumulative time-lagged global emissions for 2025–2100 under S1 reach 890 (550–1350) kt, equivalent to 4.2 (2.6–6.4) Gt CO_2.

Under S2, unreported production totaled 135 kt during 2013–2018, increasing the 2019 bank by up to 120 (70–130) kt (S2_SIF) and 90 (75–105) kt (S2_AIF). These values are slightly higher than estimated 75 (46–112) kt for China but lower than TEAP assessments of 320–700 kt (Park, et al., 2021; TEAP, 2021). By 2030, this bank increase declines to 75 (45–90) kt (S2_SIF) and 45 (0–105) kt (S2_AIF), falling further to 40 (0–75) kt and 1 (0–15) kt by 2050. Unreported production under S2_SIF may have increased emissions by 7 (4–13) kt during 2014–2018. Cumulative global emissions for 2025–2100 could reach 980 (600–1500) kt, equivalent to 4.7 (2.9–7.1) Gt CO_2.

Under S3, cumulative unreported production (390–1100) kt moderately exceeds TEAP's (2021) upper estimate (320–700 kt), primarily due to differences in direct emissions from foam manufacturing. For S3_AIF, this production increased the 2019 bank by 950 (700–1000) kt, causing a second peak of 1,800 (1500–2,100) kt following the 1995 maximum (Fig.3a). Unreported production may have increased emissions by 22 (12–38) kt (S3_SIF) and 26 (20–35) kt (S3_AIF) during 2014–2018. Emissions from unreported production under S3_AIF are projected to rise from 2020, peaking at 43 (22–67) kt by 2027 (Fig.3b). Cumulative global CO_2-equivalent (CO_2-eq) emissions for 2025–2100 under S3_AIF could reach 7.5 (4.9–10.5) Gt, corresponding to 18% (12–26%) of global greenhouse gas emissions in 2023 (Friedlingstein et al., 2023). Based on surveys from China (China MEE, 2019) and investigations into illegal production capacity by the TEAP (2019; 2021), S3 is considered less plausible, suggesting more optimistic outcomes for climate and the ozone recovery."

Comment #8

Lines 240-241, what is the evidence for this assertion and what do "(b)" and "(a)" refer to?

Reply: Thank you for your insightful comments. The discussion of unreported production has been relocated to the section titled 'Scenarios for unreported CFC-11 production'. The text previously located in lines 240–241 has been removed as it was deemed unnecessary.

Comment #9

Lines 253-255, "if all decommissioned…" that's a striking assertion without any clear demonstration and the time dependence of resulting emissions (and how they might compare to atmosphere-based if this were true) is not mentioned.

Reply: We appreciate this constructive suggestion. The statement that "if all decommissioned..." was indeed inappropriate.

We have revised the relevant paragraph as follows (lines 283–294):

> "Figs. 1c–1d depicts our refined assessments of CFC-11 banks and flows at both global and Chinese scales, incorporating a 38-year average lifespan for PUR boardstock and panel foams. This lifespan falls within the distribution range for such foams (Fig. S14). Our analysis yields 2014–2018 use-stage emissions averaging 13±2 kt/yr, while CFC-11 contained in obsolete products reaches up to 65±1 kt/yr. In developing countries, inadequate waste management systems may accelerate CFC-11 release from obsolete product (Gómez-Sanabria et al., 2022; Liu et al., 2024). In addition, the transboundary movement of used appliances (or e-waste) containing CFC-11 (excluded here due to data limitations) from developed to developing economies could redistribute EoL flows (Martínez et al., 2022). Substantial uncertainty surrounds EoL release fractions, with estimates ranging from 20% (UNEP, 2021) to 100% (McCulloch et al., 2001; Liu et al., 2024). Adopting a higher release fraction would bring our global bottom-up CFC-11 emissions into closer alignment with the top-down estimate of 69 ± 10 kt/yr (Montzka et al., 2018; 2021)"

Comment #10

Lines 277-279, why would errors related to emissions estimated in one application (CFC-12 in AC and refrig) apply to CFC-11 whose emissions are from different processes? Gallagher estimates for CFC-11 look reasonably accurate.

Reply: We appreciate your insightful feedback. CFC-11 and CFC-12 are emitted through fundamentally different processes: CFC-11 is primarily from foam-containing products, whereas CFC-12 is largely associated with refrigeration and air-conditioning equipment. Prior EPA methodology assumed 100% retirement of equipment at average lifetime. Gallagher et al. (2013) demonstrated this approach to be overly simplistic, resulting in significant underestimation of CFC emissions in 2008. To address this limitation, they developed a more refined methodology to better capture equipment age distributions at end-of-life. While Gallagher et al. (2013) eventually achieved an accurate estimate for CFC-11, this followed correction of a systematic bias initially identified in the modeling of CFC-12. Our original reference to CFC-12 was intended solely to illustrate the methodological implications of lifespan assumptions, not to imply mechanistic similarities between the two compounds.

Recognizing that this comparison could be misinterpreted, we have removed the relevant sentence. This deletion does not affect the core arguments or conclusions of the manuscript.

Comment #11

Consider projecting the results in panels a-h of Figure 4 out to 2030, as the differences between the bottom-up approaches and assumption should become even larger through this period, and could enable an assessment of their reliability with the atmosphere-based results as they are updated.

Reply: Thank you for this constructive suggestion. Given that Figure 4 focuses specifically on emission sensitivity to various parameters, we have retained its temporal scope up to 2020 to maintain this focused analysis. However, we fully recognize the value of extending projections to facilitate future comparisons with updated atmosphere-based results. To address this, we have revised Figure 3, which presents projections of CFC-11 banks, emissions, and associated impacts—including scenarios that account for unreported production—extending out to 2100. This revised Figure 3 provides a more comprehensive view of the long-term implications and supports the assessment of reliability against atmospheric-based results.

Please refer to the revised Figure 3 in our response to Comment #7.

Comment #12

IPCC/TEAP study reference mentioned above: Ashford, P. et al. in Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons (eds Metz, B. et al.) Ch. 7 (Cambridge Univ. Press, Cambridge, 2005).). How do you results compare to this (while this could be referred to in the abstract, it perhaps is more a topic of discussion for the main text)?

Reply: Thank you for your suggestion. In the IPCC/TEAP study 'Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons' Ch.7 (Ashford, P. et al., 2005), foam products are indeed a significant topic. Chlorofluorocarbons (CFCs) were used as foam blowing agents. CFC - 11, which is the focus of our current research, was among the CFCs used in the production of foam products.

According to the IPCC/TEAP study, the increase in CFC emissions is projected to peak at nearly 100 Mt CO_2eq during the period between 2030 and 2050, reflecting the impact of decommissioning CFC-containing products from buildings. Our analysis yields emissions of 115 (70–150) Mt CO_2eq in 2030, declining to 65 (33–105) Mt CO_2eq by 2050. These dynamically fluctuating emission ranges represent physically plausible outcomes and are broadly consistent with the projections reported by the IPCC/TEAP study.

TEAP (2019) applied the bottom-up methodology outlined in the IPCC/TEAP study to assess CFC-11 banks and emissions over the period 2002–2015. Subsequently, TEAP (2021) refined and updated the modeling framework for CFC-11 banks and emissions. Our analysis results have been systematically compared with those reported by TEAP (2019, 2021), as detailed in our response to Comment #7.

We have added the comparison with the IPCC/TEAP study as follows (lines 375–379):

> "Under S1, global CFC-11 banks declined from 1270 (1000–1500) kt in 2010 to 1040 (720–1250) kt in 2015, and further to 680 (350–950) kt in 2025, with projections indicating a continued decrease to 120 (10–300) kt by 2050. These estimates closely align with those reported by TEAP (2021) and are further validated by TEAP's (2019) independent assessment using Ashford et al. (2005) methodology, to estimate 2015 banks at 1070–1292 kt."