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Discussions

A Method for Calculating Offsets to Ozone Depletion and Climate Impacts of Ozone-Depleting Substances

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Abstract. By phasing out production and consumption of most ozone depleting substances (ODSs), the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) has avoided consequences of increased ultraviolet (UV) radiation, and it will restore stratospheric ozone to pre-1980 conditions by mid-century, assuming compliance with the phaseout. However, several studies have documented an unexpected increase in emissions and unreported production of trichlorofluoromethane (CFC-11) and other ODSs that occurred after 2012 despite production phaseouts under the Montreal Protocol. Furthermore, because most ODSs are powerful greenhouse gases there are significant climate protection benefits in collecting and destroying the substantial quantities of historically allowed products under the Montreal Protocol that are contained in existing equipment and products and referred to as ODS "banks". Here we present a framework for considering offsets to ozone depletion, climate forcing, and other environmental impacts arising from this or other occurrences of unexpected emissions and unreported production of Montreal Protocol controlled substances. We also show how this methodology could be applied to the destruction of banks of controlled ODSs and GHGs, or to halon or other production allowed under a Montreal Protocol Essential Use Exemption or emergency exemption. Further, we explore a range of potential actions that could offset the ozone depletion, climate, and other environmental impacts arising from instances of unexpected emissions or unreported production should Montreal Protocol Parties agree require remedial action.

1 The stratospheric ozone layer and the Montreal Protocol

The stratospheric ozone layer shields Earth against ultraviolet (UV) radiation that causes skin cancer and cataracts, suppresses the human immune system, and damages agricultural and natural ecosystems and the built environment (UNEP EEAP, 2018; Bais et al., 2018). Human-made ozone-depleting substances (ODSs) deplete stratospheric ozone, thus increasing the amount of UV radiation reaching Earth's surface. Some ODSs, primarily chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons; are also potent greenhouse gases (GHGs) (Ramanathan, 1975) (World Meteorological Organization (WMO), 2018), as are the long-lived ODS-substitutes that are hydrofluorocarbons (HFCs).

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The 1987 Montreal Protocol is an international treaty that has already phased out more than 99% of the production and consumption of about 100 ozone-depleting GHGs and will soon phase down about a dozen hydrofluorocarbon (HFC) GHGs that don't contain ozone-depleting chlorine or bromine. Use of these HFCs was once thought necessary to rapidly protect the ozone layer and avoid ozone tipping points, but environmentally superior replacements are available in some applications and will soon be available in others, making their use no longer necessary in most applications.[1] The United States Environmental Protection Agency (EPA), has estimated that ODS phaseout under the fully revised and Amended Montreal Protocol compared with a scenario of no controls will prevent approximately 443 million cases of skin cancer, 2.3 million skin cancer deaths, and 63 million cataract cases for people in the United States born in the years 1890–2100 (EPA, 2020; Madronich et al., 2021). Global impacts are significantly higher considering that these estimates are for the US alone, representing about 4.25% of global population, and do not include the economic consequences of the full spectrum in health, agricultural productivity, and product deterioration. Even a seemingly small increase in UV radiation from unexpected emissions of unreported CFC-11 production has been estimated to contribute to an additional 31,600 to 59,800 cases of skin cancer and 170 to 340 deaths and 4,100 to 9,300 cases of cataracts that would otherwise have been avoided in the US alone (EPA, 2020). Consider also that every ecosystem would suffer adverse effects owing to any increase in damaging UV radiation. Furthermore, the family and community consequences are far worse in societies without adequate health and where food is already in short supply (Andersen and Sarma, 2002).

In May 2018, scientists warned that emissions of CFC-11 unexpectedly increased despite a production phaseout under the Montreal Protocol (Montzka et al., 2018). In May 2019, scientists pinpointed ~60 ± 40% of unexpected emission increase to an area in China's north-eastern provinces of Shandong and Hebei and found no evidence of a significant increase in CFC-11 emissions from any other locations where monitoring stations are sensitive to emissions on a regional scale (Rigby et al., 2019; Adcock et al., 2020). Over the course of 2018 and 2019, the unexpected emissions and unreported production of CFC-11 globally and from eastern China dropped substantially (Montzka et al., 2021; Park et al., 2021). Enhanced emissions of dichlorodifluoromethane (CFC-12) from eastern China, perhaps associated with CFC-11 production, have also been suggested (Park et al., 2021). A separate study, which analyzed 27 whole air samples collected in 2016 over Hebei province imply new production and emissions of CFC-11, CFC-12, and 1,2-dichlorotetrafluoroethane (CFC-114) in various locations in China during spring 2016 (Benish et al., 2021). Another analysis of global atmospheric concentrations of CFC-11, CFC-12, and 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113) suggests unexpected emissions during 2014-16 and called for further investigation of potential sources of these emissions (Lickley et al., 2021).

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[1] The Technology and Economic Assessment Panel (TEAP) to the Montreal Protocol under the United Nations Environment Programme (UNEP) provides technical information related to alternative technologies that have been investigated and employed to make it possible to virtually eliminate use of ODS and to phasedown high global warming potential HFCs. TEAP annual and quadrennial assessment reports are available at https://ozone.unep.org/science/assessment/teap.

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Emissions of another Montreal Protocol-controlled substance, carbon tetrachloride (CCl_4), also have been substantially higher than expected after the phaseout of CFC production (SPARC, 2016). CCl_4 is used as a feedstock in the production of CFC-11 and CFC-12. While the ongoing CCl_4 emissions have not been tied to non-compliance with the Montreal Protocol, they add significantly to the ozone-depleting halogen burden of the atmosphere. Hence, stakeholders may benefit from understanding how to offset the impacts of such emissions on stratospheric ozone and its recovery.

Here we propose an approach for estimating the ozone depletion, climate forcing, and other environmental impacts arising from occurrences of unreported production of Montreal Protocol controlled substances, in this case CFC-11, and we show how this approach could be applied to additional unexpected production and emissions of CFCs and HCFCs. Note that these offset calculations could also be applied to management and destruction of ODS banks or could be applied to halon production under a Montreal Protocol Essential Use Exemption in cases where entities are allowed to use and emit available halon banks.

Furthermore, we explore a range of potential actions that could offset the ozone depletion, climate, and other environmental impacts arising from instances of unexpected emissions or unreported production should Montreal Protocol Parties agree require remedial action.

2 Usage implications for timing of emissions relative to production

Relating changes in atmospheric concentrations to production and emission requires an understanding of how substances are produced and used. We summarize here typical historical production and uses for several ODSs for which unexpected emissions have been observed.

2.1 CFC-11 and CFC-12

Historically, CFC-11 was manufactured using CCl_4 as a feedstock and was typically co-produced with CFC-12 to optimize chemical process efficiency. One implication is that detection of unexpected CFC-11 production is likely to be also associated with unreported production of CFC-12. Furthermore, if there is no clandestine market for unavoidable production of either substance, the substance will likely eventually be discharged and escape to the atmosphere, since destruction would involve added cost and complication.

Prior to phaseout under the Montreal Protocol, CFC-11 was principally used as a foam blowing agent and as a low-pressure refrigerant. If used for manufacturing flexible foam, emissions of CFC-11 are immediate. If used for manufacturing rigid foam or as a refrigerant, emissions of CFC-11 are distributed over the life of the product whether in its product application or in disposal unless incinerated. The 2019 Montreal Protocol Technology and Economic Assessment Panel (TEAP) Task Force concluded that “it is likely that a resumption of newly produced CFC-11 usage in closed-cell foams in some regions was the

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dominant cause for the emission increase after 2012, due to technical ease and economic advantage of its use." (UNEP TEAP, 2019) The implication is that emissions lag production, so the CFC-11 contained in these newly produced foams will continue to escape to the atmosphere and enhance CFC-11 emissions for many years into the future. The TEAP conclusion does not rule out increases in other historic CFC-11 uses adding to the unexpected emission increase after 2012, such as drug manufacture, uranium enrichment by gaseous diffusion, wind chambers, and other specialized experimental, analytical, and laboratory uses.

CFC-12 was principally used prior to phaseout as a propellant in aerosol products and as refrigerant. Propellent emissions are coincident with product use, while refrigerant emissions are small during manufacture of refrigeration and air conditioning appliances (McCulloch et al., 2003). Larger CFC-12 refrigerant emissions are associated with leakage during installation, servicing, use, and disposal at end of the refrigeration and air conditioning appliance life. The implication is that emissions from air conditioning and refrigeration equipment lag production (Andersen et al., 2007).

2.2 CFC-113

CFC-113 was predominantly used prior to phaseout as an electronics and aerospace solvent, with ongoing use as a feedstock. Where entirely used as a feedstock, CFC-113 is currently exempted from production (and consumption) controls under the Montreal Protocol (Andersen et al., 2021). The implication is that annual emissions in solvent uses were roughly equivalent to production (adjusted for quantities held in inventory). In contrast, ongoing use of CFC-113 as a feedstock likely results in annual emissions in the amount of production that is not chemically converted into new chemicals. Early in the history of the Montreal Protocol, parties assumed that feedstock emissions would be *de minimis,* but they are now realized to be significant, arising from the manufacturing of chemicals and products such as plastics (Andersen et al., 2021).

Finally, products made with or containing CFC-11 and CFC-12 are typically easily identified. Products made using CFC-113 solvent are almost impossible to identify due to evaporation of the solvent with no discernible residue.

3 Quantifying ozone depletion, environmental, and climate impacts

The damages from unexpected emissions and unreported production of substances controlled under the Montreal Protocol can be quantified for the impacts related to ozone depletion for ODSs, UV radiation exposure to estimate health and environmental effects, and climate forcing for GHGs.

3.1 Ozone depletion for ODSs

A key step in developing a workable offset calculation is the finding of near-linear relationships between cumulative emissions of a particular long-lived ODS and stratospheric ozone impacts from that ODS, both globally and over the Antarctic, documented in several studies (Keeble et al., 2020; Fleming et al., 2020; Dhomse et al., 2019) summarized in (WMO, 2021). These impacts on stratospheric ozone were assessed to roughly scale by the amount of chlorine released, so this methodology can be applied to other ODS species. A recent assessment report (WMO, 2021) discussed the following relationships for CFC-11. Per 1000 Gg of cumulative CFC-11 emissions, mean global column ozone is decreased by 0.4–0.7 Dobson Units (DU), and 1980 return dates are delayed 3 years (Keeble et al., 2020; Fleming et al., 2020); and over the Antarctic, springtime column ozone is decreased by 5 DU, and 1980 return dates delayed by 4–7 years (Dhomse et al., 2019; WMO, 2021).

Importantly, these relationships apply to cumulative emissions, implying that unreported production and associated likely additional future emissions from the resulting banks need to be included in order to accurately estimate impacts. In the case of the unexpected CFC-11 emissions, the TEAP Task Force found: "the estimated cumulative total of unreported CFC-11 production is 320-700 kilotonnes in the period 2007-2019. Assuming usage in closed-cell foam production, this cumulative unreported CFC-11 production would lead to an estimated increase in the magnitude of the CFC-11 bank of 300 (266-333) kilotonnes by the end of 2019." (UNEP TEAP, 2021)

Several studies have found that impacts on stratospheric ozone roughly scale by the amount of chlorine (Cl) released, all other factors (aerosol loading, etc.) being equal, so can be applied to CFC-12, CTC, and other ODS species (Dhomse et al., 2019; Keeble et al., 2020; WMO, 2021). More recently, (Pyle et al., 2022) have proposed an "integrated ozone depletion" (IOD) metric that is a linear function of the total halogen emission (in Tg Cl) multiplied by the gas-dependent ratio of the whole atmosphere to stratospheric lifetime. Ideally, use of this metric to derive an offset reduction in production or emission of an ODS would be applied to a chemical or gas having a similar atmospheric lifetime so that the time-dependence of the adverse effect would be effectively offset throughout the entire time-interval of impact. In practice, however, it seems likely that the chemical used for the offset would have a different atmospheric lifetime. The net effect would be that on a cumulative basis over many years the adverse impact would be offset in its entirety, whereas during shorter time intervals, the offset could be smaller or larger than the adverse impact being offset.

3.2 Environmental impacts from ozone depletion

UV radiation exposure can be estimated from ozone depletion to estimate health and environmental effects. For example, the EPA used its Atmospheric and Health Effects Framework (AHEF) model to estimate that in the U.S. alone the unexpected

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CFC-11 emissions,[2] absent offset, would result in nearly 60,000 cancer deaths through 2100 that compliance with the Montreal Protocol would have avoided (EPA, 2020). This and other health effects models can be extrapolated taking into account geographic location, genetic vulnerability, lifestyle differences, and access to preventative and therapeutic mitigation (Slaper et al., 1996; Longstreth et al., 1998; Struijs et al., 2010; van Dijk et al., 2013).

3.3 Climate forcing for greenhouse gases (GHGs)

Offsets in carbon emissions are measured in tonnes of carbon dioxide-equivalent (CO_2-eq) using Global Warming Potentials from the most recently published set, e.g. (World Meteorological Organization (WMO), 2018; Smith et al., 2021). The issue of timescales is also important with this metric, as it allows for a comparison of the cumulative climate impact over a specified time interval of a pulse emission for chemicals having different lifetimes. While cumulative warming over a 20-year time period aligns most closely with the timeframe associated with the possibility of crossing the 1.5°C warming target of the Paris Agreement as soon as the 2030s (Abernethy and Jackson, 2022; Xu et al., 2018; Intergovernmental Panel on Climate Change, 2021), it ignores any additional differences in the warming supplied by the different gases after that 20-yr period.

Given the likely differences in atmospheric lifetime associated with the chemical being used to supply an offset and the chemical causing the adverse effect, it is worth considering the offset on both an annual and cumulative timescale. For the CFC-11 case, cumulative emissions from the increased banks are projected to add 0.4–1.4 $GtCO_{2\text{-eq}}$ (20-year GWP) [0.3–1.0 $GtCO_{2\text{-eq}}$ (100-year GWP)] between 2020 and 2060 (WMO, 2021).

Ozone damage and enhanced UV also likely diminish the uptake of CO_2 by the terrestrial biosphere in its capacity as a carbon sink (Young et al., 2021). These impacts could also be included in deriving appropriate offsets if desired.

4 Offsets are one option to maintain the integrity of ozone and climate protection under the Montreal Protocol

The idea of an offset to unexpected emissions and unreported production of ozone depleting GHGs is to collect and destroy any combination of banked ODS and HFCs that were legally produced and would otherwise be emitted such that the integrated chlorine-equivalent and CO_2-equivalent values are similar over a period of time. Using the methodology presented in this

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[2] This estimate is based on the "bank scenario", which assumes that CFC-11 emissions began increasing in 2012 above those expected under the reference WMO A1 scenario, peak around 77 Gg/yr in 2015–2017, then decline sharply through 2100. While the end date of unreported production is unclear, the report states that: "In the fourth scenario, CFC-11 emissions were estimated based on Dhomse et al. (2019), which constructs an emissions scenario curve based on initial rapid increase in CFC-11 emissions and slower release from accumulated CFC-11 banks. This scenario first takes the estimate of 13 Gg/year in new emissions due to unreported production and assumes an immediate production release rate of 15 percent followed by 3.5 percent/year. This creates a gradually decreasing emissions curve where CFC-11 emissions continue past 2100 due to releases from the accumulated bank even after production goes to zero." (EPA, 2020)

paper, scientists could craft a remedy mindful of the importance of fast return of the atmosphere to the condition without any unexpected or unreported production and emission, which could be accomplished by destruction of short-lived ozone pollutants like HCFC-22 or HCFC-141b and short-lived climate pollutants such as methane and HFCs. Similar consideration should be given for the longer-term trajectory to assure ozone recovery and climate mitigation.

While any given instance of unexpected and unreported emissions may seem small in terms of atmospheric impacts, such impacts are cumulative and in absolute terms significant compared to other environmental violations where compensation is demanded—consider for example the settlement between the US government and Volkswagen (VW) requiring VW to provide nearly US$3 billion to an Environmental Mitigation Trust to "fully remediate the excess NO_x emissions from the illegal vehicles" (Breyer, 2016). Stratospheric ozone depletion and climate-forcing offsets can compensate for unexpected and unreported production by: reducing production or emissions of an ODS produced legally prior to phaseout under the Montreal Protocol or by reducing emissions of an ODS not yet subject to the Montreal Protocol's phaseout requirements (e.g., CF_3I, CH_2Cl_2, or N_2O); and/or with respect to climate forcing, avoiding cumulative emissions or removing GHGs equivalent to the near term (20-year) forcing of the unexpected and unreported emission to help prevent triggering tipping points and longer-term climate change (Lenton et al., 2019). In the absence of chemical offsets being applied, an alternative approach might be to calculate cumulative health impacts and determine monetary compensation and/or punitive damages of loss in health, life, productivity, ecological impact, and materials degradation.

Offsets in ozone depletion are measured in tonnes of CFC-11 emission-equivalent (in terms of tonnes of Cl released). In the case of ozone depletion, the offset would have two goals: rapidly reduce the chlorine-equivalent stratospheric concentration to the levels expected without the unexpected and unreported emission, and it would ensure that the cumulative offset is comparable to the damage or impact of the unreported activity. Such an approach would accelerate ozone recovery sufficiently to offset the health and environmental damage done prior to mitigation.

5 Potential actions that could offset the ozone depletion and climate impacts of unexpected and unreported production

Below we present a non-exhaustive list of potential actions that could be used to offset the ozone depletion, climate, and other environmental impacts arising from instances of unexpected and unreported production that Parties may agree warrant remedial action. Any of these measures could also be employed to offset the ozone and climate impacts of Essential Use Exemptions (EUEs) for ODSs other than HCFCs, and Critical Use Exemptions (CUEs) for methyl bromide, or emergency use.

- Accelerate the hydrochlorofluorocarbon (HCFC) phaseout faster than mandated by the Protocol (reducing both ozone depletion and climate forcing);
- Leapfrog hydrofluorocarbons (HFCs) to low-global warming potential (GWP) energy-efficient, next-generation fluids or technology (also mitigating ozone and climate forcing);

- Accelerate the HFC phasedown and transition to technologies with lower environmental impacts including non-fluorocarbon replacements (also not-in-kind -- NIK);
- Collect and destroy ODSs and HFCs banks (ozone and climate mitigation for ODS destruction; climate mitigation only for HFC destruction);
- Replace inefficient air conditioners (ACs) with super-efficient, low-GWP ACs and destroy recovered ODS and HFC refrigerants;
- Reduce production and emissions of ozone-depleting GHGs not controlled under the Montreal Protocol (i.e., N_2O) or GHGs not controlled under the Montreal Protocol (i.e., CH_4); and
- Increase the energy efficiency performance of building air conditioning and residential, commercial, and industrial refrigeration together with ODS and HFC transitions.

For example, (WMO, 2021) shows the following. “The recovery and destruction of CFC-11 banks would not only accelerate the ozone layer recovery, but also yield climate benefits. Based on the TEAP/UNEP (2019b) scenario, recovery and destruction of the active and inactive banks would reduce emissions by 1.6 Gt $CO_{2\text{-eq}}$ [100-year; 2.2 Gt$CO_{2\text{-eq}}$ 20-year] between 2020 and 2060 and 2.6 Gt $CO_{2\text{-eq}}$ [100-year; by 3.6 Gt$CO_{2\text{-eq}}$ 20-year] between 2020 and 2100 (see Table 5.2). Using their estimates of much larger banks, Lickley et al. (2020) estimated that recovery and destruction of the CFC-11 and CFC-12 banks would reduce emissions by 9 Gt $CO_{2\text{-eq}}$ [100-year; 13 Gt Gt$CO_{2\text{-eq}}$ 20-year] between 2020 and 2100.” Recent analysis by (Lickley et al., 2022) suggests that production may have been underreported for nearly all chemicals examined, implying larger banks, and they conclude that “in terms of climate impacts, CFC-11, CFC-12, and HCFC-22 are the largest banked materials weighted by GWP100, accounting for 36 %, 14 %, and 36 % of current [ODS] banks, respectively. When banks are weighted by ODP, CFC-11 and CFC-12 represent 46 % and halons also represent 46 % of current banked chemicals…. In terms of GWP100, CFC-11 banks largely reside in foams, whereas CFC-12 and HCFC-22 are largely in non-hermetic refrigeration. The latter may be more readily recoverable. In terms of ODP, CFC-11 foams and CFC-12 non-hermetic refrigeration remain important, along with halons which are all contained in fire extinguishers, a recoverable reservoir.”[3]

6 Conclusion

Options are available to offset the ozone depletion and climate forcing from any unexpected and unreported production and associated emissions of ozone-depleting substances (ODSs) (e.g., CFC-11, CFC-12, CFC-113, and CTC). Scientists can calculate the contribution of each option in offsetting potentially both the annual and cumulative ozone depletion and climate forcing over the atmospheric lifetime of the ODSs. The Montreal Protocol Parties have shown creativity and flexibility in their

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[3] Halons are a recoverable reservoir provided that an adequate alternative is identified for those essential uses preserving health and safety.

non-compliance remedies (UNEP, 1992). Parties to the Montreal Protocol may wish to consider action on compliance to minimize ozone and climate consequences and to discourage future unexpected and unreported production.

Author contribution

SOA conceptualized the study. GBD, SAM, SOA, RF wrote the paper.

Competing interests

The authors declare that they have no conflict of interest.

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