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Technical note: A method for calculating offsets to ozone depletion and climate impacts of ozone-depleting substances

Gabrielle B. Dreyfus[1,2], **Stephen A. Montzka**[3], **Stephen O. Andersen**[1], **and Richard Ferris**[1]

[1]Institute for Governance & Sustainable Development (IGSD), Washington, DC 20016, USA
[2]Department of Physics, Georgetown University, Washington, DC 20057, USA
[3]Global Monitoring Laboratory, National Oceanic and Atmospheric Administration (NOAA), Boulder, CO 80305, USA

Correspondence: Gabrielle B. Dreyfus (gdreyfus@igsd.org)

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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 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 suggested unreported production of trichlorofluoromethane (CFC-11) and potentially other ODSs after 2012 despite production phaseouts under the Montreal Protocol. Furthermore, because most ODSs are powerful greenhouse gases (GHGs), there are significant climate protection benefits in collecting and destroying the substantial quantities of historically allowed production of chemicals under the Montreal Protocol that are contained in existing equipment and products and referred to as ODS “banks”. This technical note presents a framework for considering offsets to ozone depletion, climate forcing, and other environmental impacts arising from occurrences of unexpected emissions and unreported production of Montreal Protocol controlled substances, as recently experienced and likely to be experienced again. 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 Critical Use Exemption. Further, we roughly estimate the magnitude of offset each type of action could provide for ozone depletion, climate, and other environmental impacts that Montreal Protocol Parties agree warrant 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, damages agricultural and natural ecosystems including terrestrial carbon sinks, and deteriorates the built environment (UNEP/EEAP, 2019; Bais et al., 2018; Young et al., 2021). 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), carbon tetrachloride (CTC or CCl_4), and halons, are also potent greenhouse gases (GHGs) (Ramanathan, 1975) (WMO, 2022), as are long-lived hydrofluorocarbons (HFCs) used as ODS substitutes.

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 HFCs that do not contain ozone-depleting chlorine or bromine. The United States Environmental Protection Agency (US 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 (US 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 the global population, and do not include the economic consequences of the full spectrum of 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 as well as 170 to 340 deaths and 4100 to 9300 cases of cataracts that would otherwise have been avoided in the US alone (US EPA, 2020). Consider also that every ecosystem would suffer adverse effects owing to any increase in damaging UV radiation (Young et al., 2021). 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 had unexpectedly increased despite a production phaseout under the Montreal Protocol (Montzka et al., 2018). In May 2019, scientists pinpointed $\sim 60 \pm 40\,\%$ of unexpected emission increase to an area in China's northeastern 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, implied 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) confirmed unexpected emissions of CFC-11 but suggested the possibility of unexpected emissions of these other gases during 2014–2016 and called for further investigation of potential sources of these emissions (Lickley et al., 2021). Increases in global emission and atmospheric concentrations of several CFCs with production allowed under the Montreal Protocol for use as feedstocks in the production of hydrofluorocarbons, e.g., 1,1,1-trichloro-2,2,2-trifluoroethane (CFC-113a), CFC-114a, and chloropentafluoroethane (CFC-115), are also being observed, together with emission increases in CFC-13 and CFC-112a, although the driver of the increase for these latter two CFCs is unclear (Western et al., 2023).

Emissions of another Montreal Protocol-controlled substance, CTC, have also been substantially higher than expected after the phaseout of CFC production (SPARC, 2016). CTC is used as a feedstock in the production of CFC-11 and CFC-12 and as a solvent. While the ongoing CTC emissions have not yet been implicated in 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 and to offset the impacts on climate forcing.

Here we propose an approach for calculating the quantity of ODSs for offsetting adverse environmental impacts arising from occurrences of unreported and unauthorized production ODSs and chemical substitutes such as HFCs. These offsets could take the form of preventing the emissions of ODSs and HFCs that were legally produced and would otherwise be emitted, such as through collecting and destroying banks of these chemicals. Other options are highlighted that could also be considered to offset the ozone depletion, climate, and other environmental impacts arising from instances of unexpected emissions or unreported production that Montreal Protocol Parties agree warrant remedial action. Note that an offset approach could also be applied to management and destruction of ODS banks or could be used to manage halon production allowed under a Montreal Protocol Essential Use Exemption in cases where entities are allowed to use and emit available halon banks.

An important aspect of offsetting impacts relates to the timing of the impact compared to the offset. Given the added uncertainties associated with estimating the year-to-year impacts of unexpected or illicit production and the associated emission that one might hope to offset, we focus here on offsetting cumulative impacts. We note that this approach is the only possible path to offset adverse impacts of uncertain emissions that occurred in the past. We also recognize that the approach of offsetting impacts with a cumulative time frame and not year by year will lead to a different time history for an impact compared to the offset, especially when the chemical being considered for supplying an offset has a substantially different lifetime than the chemical causing the adverse impact. This latter point will likely always be true when devising an offset to an impact that has already occurred. Consider, however, that environmental justice usually requires judgment of both the environmental impact and which victims deserve and qualify for compensation. The approach to calculating offsets presented here offsets cumulative impacts but does not compensate those harmed by increased UV radiation.

2 Usage implications for estimating the magnitude of impacts to be offset

Atmospheric observations of long-lived ODS and HFC substances can provide an estimate of an unexpected emission magnitude that is to be offset. For many halocarbon substances, however, anomalous emissions will represent only a fraction of the total amount of chemical produced and the total cumulative impact, owing to the retention of chemicals in cooling appliances, fire protection equipment, closed-cell foams, and emission from the banks well after original production and use. Relating changes in atmospheric concentrations to production and, therefore, a more complete picture of the cumulative impact into the future as the banked chemical slowly escapes into the atmosphere requires an understanding of how substances are produced and used. We summarize in the Supplement typical historical production and uses for several ODSs for which unexpected emissions have been observed.

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, damage to the terrestrial carbon sink, deterioration of the built environment, and climate forcing for GHGs. In an ideal scenario, an offset would match the impacts year by year. However, this is likely to be impractical due to differences in the time-dependent impacts of different chemicals due to differences in potency and lifetimes. In addition, unreported production and emissions of the controlled substances to be offset would likely precede any offset actions. For these reasons, we focus here on estimating cumulative impacts and offsets, although we realize that there are limitations of this approach, e.g., in cases where the impact is nonlinearly related to the atmospheric abundance, as in the case of biological effects that depend on behavioral and other factors (Slaper et al., 1996). Specifically, we propose using the established metrics of ozone depletion potential (ODP) and global warming potential (GWP) when calculating offsets associated with an emission. While the ODP is defined as the ratio at steady state of calculated ozone column change for each mass unit of a gas emitted into the atmosphere relative to the calculated depletion for the reference gas CFC-11 (Fisher et al., 1990), it is also true that the ODP can reliably be used to estimate the cumulative impacts arising from a pulsed emission (Prather, 2002). In this way, ODP integrates the cumulative impact on the ozone column of a chemical relative to CFC-11 over the lifetime of the chemical and the timescale of secondary impacts. The ODP differs from the GWP in one important respect, however, in that the GWP reflects the ratio of a change in radiative forcing from an emission of gas relative to that same mass emission of carbon dioxide *integrated over a specific time horizon* (usually 100 or 20 years) and not over the lifetime of the chemical and its impacts. Choosing an appropriate integration period for estimating the impact and deriving an appropriate offset will therefore require a choice to be made, and this choice hinges on the relative importance of near-term vs. long-term impacts. We discuss additional considerations of impacts and offset metrics in this section by type of impact and conclude with an illustrative example.

3.1 Ozone depletion for ODSs

The approach of offsetting, through a reduction in emission or production of an ODS, the cumulative ozone depletion arising from unexpected or illicit emissions after weighting those emissions by the ODP, is supported by the 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 (Keeble et al., 2020; Fleming et al., 2020; Dhomse et al., 2019) as summarized in the WMO et al. (2021). This is because the impacts on stratospheric ozone of an emission roughly scale by the amount of chlorine (Cl) released into the stratosphere, all other factors (aerosol loading, etc.) being equal, and so can be applied to CFC-12, CTC, and other ODS species (Dhomse et al., 2019; Keeble et al., 2020; WMO et al., 2021). Other metrics such as the integrated ozone depletion (IOD) could be used to quantify the impact on stratospheric ozone of an emission to be offset, and use of this metric would provide results very similar to the use of ODP unless the chemical being used to offset an impact had a substantially different loss frequency in the troposphere and stratosphere (Pyle et al., 2022).

The ODPs used in Table 1 are based on atmospheric model simulations and can be expressed as a semi-empirical relationship:

$$\mathrm{ODP}_i = \frac{n_{\mathrm{Cl}}}{3} \times \frac{f_i}{f_{\mathrm{CFC\text{-}11}}} + \frac{\tau_i}{\tau_{\mathrm{CFC\text{-}11}}} + \frac{m_{\mathrm{CFC\text{-}11}}}{m_i}, \tag{1}$$

where n_{Cl} is the number of chlorine atoms in the molecule, f_i is the fractional release factor for the molecule, τ_i is the total lifetime, and m_i is the molecular mass of the molecule (Burkholder et al., 2022).

The IOD for comparison, which is not used here, is given by Eq. (2):

$$\mathrm{IOD} = \mathrm{K}E_{\mathrm{Eq}} \left(\frac{\tau_{\mathrm{atmos}}}{\tau_{\mathrm{strat}}} \right), \tag{2}$$

where $K = 100 \pm 16$ Dobson unit years per Tg Cl, and E_{Eq} is the total emission in Tg Cl, multiplied by the ratio of the whole atmosphere lifetime of the molecule to its stratospheric lifetime, $\tau_{\mathrm{atmos}}/\tau_{\mathrm{strat}}$ (Pyle et al., 2022).

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 US EPA used its Atmospheric and Health Effects Framework (AHEF) model to estimate that, in the USA alone, the unexpected CFC-11 emissions,[1] absent offset, would result in nearly 60 000 cancer deaths through 2100 that compliance with the Montreal Protocol would have avoided (US EPA, 2020). This and other health effect models can be extrapolated by 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). A calculation of the health and environmental impacts from ozone depletion and global warming of emissions is beyond the scope of this paper, as the authors are unaware of simplified metrics for these impacts analogous to the metrics for estimating ozone column and climate impacts. In addition to human health impacts, UV exposure can harm aboveground plant biomass and diminish the uptake of carbon dioxide (CO_2) by the terrestrial biosphere in its capacity as a carbon sink. Studies suggest a UV response strength of a 3 % reduction in biomass for a 10 % increase in plant-weighted surface UV fluxes which can be related to total column ozone (Young et al., 2021). These impacts could also be included in deriving appropriate offsets if desired in terms of ozone offsets for UV impacts and protection of carbon sinks or GHG mitigation to offset the CO_2 impacts (Sect. 3.3).

3.3 Climate forcing for GHGs

Offsets in carbon emissions are measured in tons of carbon dioxide equivalent (CO_2 eq.) using GWPs from the most recently published set, i.e., Burkholder et al. (2022). The issue of timescales is also important with this metric, as the GWP involves a comparison of the cumulative climate impact over a specified time interval of a pulse emission for chemicals with different lifetimes. While 100-year GWPs are most commonly used to capture the longer-term warming effects of long-lived greenhouse gases like CO_2 and CFCs, the use of a 20-year GWP may be more relevant when considering near-term warming impacts of potent but short-lived GHGs like most HFCs, such as 1,1,1,2-tetrafluoroethane (HFC-134a) (13.5-year lifetime), difluoromethane (HFC-32) (5.27-year lifetime), or pentafluoroethane (HFC-125) (30.7-year lifetime) (Burkholder et al., 2022). Such near-term impacts are particularly relevant to temperature goals such as limiting warming to 1.5 °C with no or limited overshoot, noting 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; Arias et al., 2021).

The GWP for a molecule x is given by Eq. (3):

$$\mathrm{GWP}_x = \frac{\int_0^{t'} a_x \exp\left(-\frac{t}{\tau_x}\right)\mathrm{d}t}{\int_0^{t'} a_{\mathrm{CO_2}} R(t)\,\mathrm{d}t}, \tag{3}$$

where a is the radiative efficiency per unit mass, τ_x is the global lifetime of molecule x, $R(t)$ is the decay time of a pulse of the reference gas CO_2, and t' is the time horizon over which the integrated radiative forcing is calculated (Daniel et al., 2012).

3.4 Illustrative offset calculation

When deriving offsets based on anomalies in emissions, it is important to remember to consider the potential for future emissions that have not yet escaped into the atmosphere (e.g., from banked chemicals that were produced illicitly but that have not yet reached the atmosphere; see the earlier text). In the case of the unexpected CFC-11 emissions, the TEAP Task Force found that "the estimated cumulative total of unreported CFC-11 production is 320–700 kt 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) kilotons by the end of 2019" (UNEP/TEAP, 2022). Taking the cumulative total of unreported production of 320–700 kt CFC-11, we calculate an ODP-weighted emission of 320–700 kt, a GWP_{20} of 2.7–6.0 $GtCO_2$eq., and a GWP_{100} of 2.1–4.5 $GtCO_2$eq. (Table 1). To calculate equivalent offsets, the formula in Eq. (4) is considered below to derive offsets for three ODSs that are being phased out under the Montreal Protocol with the largest remaining eligible production and consumption (Table 1).

$$\begin{aligned}&\text{Mass of chemical } X \text{ (kt)} = [\text{mass CFC-11(kt)}]\\&\quad \times [\text{metric for CFC-11}]/[\text{metric for chemical } X]\end{aligned} \tag{4}$$

Offsetting the ozone depletion from the cumulative total CFC-11 production would require one to prevent emissions of 8420 to 10 840 kt of HCFC-22, either through the destruction of that amount from existing banks or as reduced production allowances. In this case, the amount of HCFC required to offset the cumulative ozone impacts is greater than the amount that would be needed to offset the global warming impacts under both 20- and 100-year time horizons. For

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[1] 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^{-1} in 2015–2017, and 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 yr^{-1} in new emissions due to unreported production and assumes an immediate production release rate of 15 % followed by 3.5 % yr^{-1}. 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" (US EPA, 2020).

Table 1. CFC-11 cumulative production in ODP-weighted, GWP-weighted, and calculated masses of HCFC-22, HCFC-141b, and HCFC-142b to achieve equivalent offsets. ODP and GWP values are from Table A-5 in the 2022 Quadrennial Ozone Assessment (Burkholder et al., 2022).

	ODP-weighted (kt)	GWP_{20}-weighted ($GtCO_2$eq.)	GWP_{100}-weighted ($GtCO_2$eq.)
CFC-11			
Conversion values for 1 kt of CFC-11	1	8560	6410
Estimated cumulative total of unreported CFC-11 production in the period 2007–2019	320–700	2.7–6.0	2.1–4.5
HCFC-22			
Conversion values for 1 kt of HCFC-22	0.038	5610	1910
Kilotons of HCFC-22 that would need to be destroyed to offset unreported CFC-11 production in terms of the ODP- or GWP-equivalent impact	8420–10 840	488–1070	1070–2350
HCFC-141b			
Conversion values for 1 kt of HCFC-141b	0.102	2590	808
Kilotons of HCFC-141b that would need to be destroyed to offset unreported CFC-11 production in terms of the ODP- or GWP-equivalent impact	3140–6860	1060–2310	2540–5550
HCFC-142b			
Conversion values for 1 kt of HCFC-142b	0.057	5400	2190
Kilotons of HCFC-142b that would need to be destroyed to offset unreported CFC-11 production in terms of the ODP- or GWP-equivalent impact	5610–12 300	510–1110	937–2050

comparison, the estimated cumulative HCFC-22 production allowed under the Montreal Protocol phaseout schedule for controlled uses (excluding feedstocks) through 2040 is on the order of 1300 kt (Table 2). Even if recent HCFC-22 production from 2021 to 2023 was considered available for recovery and destruction, this would only amount to about 900 kt available for offset. Due to the low ozone-depleting potential of HFCF-22, it would take the additional step of recovery and destruction of CFC banks or some other actions to offset the ozone impacts of the unexpected CFC-11 production. Elimination or prevention of remaining eligible consumption for 1,1-dichloro-1-fluoroethane (HCFC-141b) and 1-chloro-1,1-difluoroethane (HCFC-142b) would also be insufficient, as those magnitudes are estimated to be 1.3 and 7.6 kt, respectively, based on reporting through the 92nd meeting of the Executive Committee of the Multilateral Fund, as reported in Table 4-1 of the TEAP Replenishment Task Force Supplementary Report (UNEP/TEAP, 2023b). However, narrowing exemptions for production of ODSs for feedstock uses could expand the number of ODSs available for offset (see Table 2).

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

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 sought – consider for example the settlement requiring Volkswagen (VW) to provide nearly USD 3 billion to the 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 preventing emissions or production of an ODS not yet subject to the Montreal Protocol’s phaseout requirements, e.g., trifluoromethyl iodide (CF_3I), methylene chloride (CH_2Cl_2), or nitrous oxide (N_2O), and/or with respect to climate forcing, avoiding cumulative emissions or removing GHGs equivalent to the near-term (20-year GWP) forcing of the unexpected and unreported emission to help pre-

Table 2. Overview of potential offset activities and indicative available offsets.

Potential offset activity	Indicative available offsets for potential activity
Accelerate the HCFC phaseout faster than mandated by the protocol (reducing both ozone depletion and climate forcing)	Based on baseline levels, phaseout schedule and current production in 2021 from Table 2 in Multilateral Fund (MLF) document 92/5 (UNEP, 2023a), we estimate the cumulative allowed HCFC production for controlled uses (excluding feedstocks) from 2024 through phaseout in 2040 to be on the order of 50 000 ODP tons, primarily HCFC-22, which is equivalent to approximately 1300 kt of HCFC-22. Allowed production for controlled uses from 2021 to 2023 totaled about 900 kt of HCFC-22.
Limiting emissions associated with feedstock exemptions	While HCFC-22 production for controlled uses is phasing out, production for exempted feedstock uses is increasing as a share of total production. HCFC-22 production for feedstock uses was 56 % of total reported production in 2017 (UNEP/TEAP, 2019) compared with reported production for controlled uses (UNEP, 2023a). If feedstock production exemptions were to be revisited by the parties to the Montreal Protocol (Andersen et al., 2021), then this sector could be considered in an offset framework. Total annual feedstock production in 2019 was estimated at 558 ODP-weighted kilotons, with emissions of 15.0–18.7 ODP kilotons (Daniel et al., 2022).
Leapfrog HFCs to low-GWP energy-efficient, next-generation fluids or technology (also mitigating ozone and climate forcing)	Estimated baseline annual HFC consumption for Article 5 parties for 2020–2022 was estimated to total 1.1 billion tons CO_2eq. using Annex F GWP_{100} in Table 3-2 (UNEP/TEAP, 2023c). Non-A5 parties are currently subject to a 10 % reduction compared to baseline consumption levels, and in 2024 will start the 40 % reduction step. For a sense of scale of potential for acceleration of phasedown, the baseline HFC consumption for the United States is 300 million metric tons (US EPA, 2023) and the European Union is 164 million metric tons (UNEP, 2023b) (both use 2007 IPCC GWP_{100} values).
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)	CFC-11 banks have been estimated to range from 70 to 1475 kt for 2018, but the lower range was considered outside the range of realistic values and the higher range includes "inaccessible" banks that would be difficult to recover, such as foams in landfills (WMO et al., 2021), with higher estimates of 2568 kt of CFC-11 (not including unexpected) and CFC-12 banks of 2900 ODP-weighted kilotons (Lickley et al., 2020). A high-end range for potential HFC offsets can be estimated from a scenario where emissions from new production and banks ceased in 2023, which would reduce cumulative emissions by 32–37 $GtCO_2$eq. relative to the Kigali Amendment schedule (Liang et al., 2022).
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 CH_2Cl_2) or GHGs not controlled under the Montreal Protocol (i.e., CH_4)	Industrial emissions were 307 kt N_2O (84 $GtCO_2$eq.) from adipic acid and 136 kt N_2O (37 $GtCO_2$eq.) from nitric acid production in 2020; US EPA estimates 80 % abatement potential at break-even costs (Davidson and Winiwarter, 2023).
Increase the energy efficiency performance of building air conditioning and residential, commercial, and industrial refrigeration together with ODS and HFC transitions	Cumulative energy-related CO_2 emissions for cooling for 2023–2050 could be reduced by 47 %–69 % through improved energy efficiency, while transitioning to low-GWP refrigerant would add a further 25 %–53 % reduction in CO_2eq. terms (UNEP/TEAP, 2023a).

vent 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 of health, life, productivity, ecological impact, and material degradation.

Offsets in ozone depletion are measured in tons of CFC-11 emission-equivalent (as an ODP-weighted emission). In the case of ozone depletion, the size of the offset estimated to be needed would ensure that the cumulative adverse impact of the unreported or illicit activity would be offset. Such an approach would contribute to ozone recovery and offsetting 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

In Table 2 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 to the Montreal Protocol 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 methyl bromide (including emergency EUEs) together with Critical Use Exemptions

(CUEs) for methyl bromide (including emergency CUEs) (UNEP/TEAP, 2005).[2] We provide indicative numbers on the potential available offsets for each type of action.

Others (WMO et al., 2021) have implicitly suggested the usefulness of offsets: "The recovery and destruction of CFC-11 banks would not only accelerate the ozone layer recovery, but would 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 eq. (GWP_{100}, 2.2 GtCO_2 eq. GWP_{20}) between 2020 and 2060 and 2.6 Gt CO_2 eq. (GWP_{100}, by 3.6 GtCO_2 eq. GWP_{20}) 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 eq. (GWP_{100}, 13 Gt GtCO_2 eq. GWP_{20}) between 2020 and 2100." Recent analysis by Lickley et al. (2022) suggests that production may have been underreported for nearly all the 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 GWP_{100}, 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 GWP_{100}, 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

This technical note describes approaches for offsetting the ozone depletion and climate forcing from 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, but we argue here that typically the most practical approach (and in some instances the only approach) will be to consider offsetting cumulative impacts without consideration of timing. The Montreal Protocol Parties have shown creativity and flexibility in their 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.

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[2] Numerous decisions of the Parties to the Montreal Protocol establish and interpret criteria and procedures for EUEs and CUEs, together with related emergency exemption applications. Examples of key decisions concerning EUEs and CUEs are provided in the references.

[3] If an alternative is identified for those essential uses preserving health and safety, halons could be a recoverable reservoir.

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