The net effective radiative forcing from ozone-depleting substances and Its uncertainty

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The Net Effective Radiative Forcing From Ozone-Depleting Substances and Its Uncertainty

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Key Points:

- Simple models can be used to separate the contributions to net effective radiative forcing (ERF) for each ozone-depleting substance
- CFC-12 has by far the largest net ERF of ozone-depleting substances (ODS)
- The net ERF from ODS has increased much less rapidly than the direct radiative forcing

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The direct effective radiative forcing (ERF) of long-lived ozone-depleting substances (ODS) is around 15%–20% of the pre-industrial to present-day ERF of CO_2, but their net ERF, including indirect chemical adjustments, remains poorly constrained. We use an adapted simple climate model, trained on bulk indirect ODS forcing from complex climate models, to quantify uncertainty in net ERF over time and the net ERF across individual ODS. We find that the direct ODS ERF in 2019 of 0.35 (0.31, 0.39) W m^{-2} is reduced to a net ERF of 0.11 (−0.02, 0.26) W m^{-2} when chemical adjustments are included. Most net ERF arises from CFC-12 and HCFC-22 (0.18 W m^{-2}), with chemical adjustments substantially reducing the net ERF of many other substances. Since the implementation of the Montreal Protocol, the total ODS net ERF has increased much less rapidly than the direct ERF.

Plain Language Summary Ozone-depleting substances, such as chlorofluorocarbons (CFCs), damage the ozone layer and also contribute to climate change by trapping heat. Their direct warming effect is quite well understood. However, their net total impact on climate, including the climate impact due to changes in the chemistry of the atmosphere, is less certain. In this study, we used a simple climate model to account for these chemical effects. Our model helps identify how much each substance contributes to the net total impact on climate, which is difficult in larger climate models. We find that most of the warming comes from one, CFC-12, with much of the additional warming coming from HCFCs, which are one class of replacement gases for CFCs and cause less damage to the ozone layer. Our results highlight the need for further research to better understand these climate effects.

1. Introduction

Changes in the Earth's radiative budget are largely controlled by changes in the radiative forcing from gases and aerosols in the Earth's atmosphere. Carbon dioxide, methane, and nitrous oxide are individually the anthropogenic greenhouse gases that contribute the most to increases in the global mean temperature. In addition, there are many halogenated greenhouse gases, almost entirely man-made in origin and at much lower abundances in the atmosphere, which can alter the Earth's radiative budget.

The halogenated greenhouse gases are a large group of greenhouse gases, with the commonality that they all contain halogens (fluorine, chlorine, bromine, and/or iodine). Chlorinated and brominated greenhouse gases are notorious for their role in stratospheric ozone depletion. Following the discovery of this damaging process, the Montreal Protocol on Substances that Deplete the Ozone Layer was introduced, which has led to the phase out of the production of the most damaging ozone-depleting substances (ODS) in 2010 for all uses except chemical production, with their replacement ODS (hydrochlorofluorocarbons, HCFCs) set to be phased out by 2040. The most abundant group of controlled ODS in the atmosphere is chlorofluorocarbons (CFCs).

The instantaneous radiative efficiency (the change in the radiative balance of the Earth per molecule in a static atmosphere) of CFCs and other ODS is generally orders of magnitude higher than for the three main anthropogenic greenhouse gases (Burkholder & Hodnebrog, 2023), and, as a result, the Montreal Protocol has been said to have largely mitigated additional warming (Newman et al., 2009; Velders et al., 2007; Young et al., 2021).

The Effective Radiative Forcing (ERF) is now the favored measure of radiative forcing (e.g., Forster et al., 2021), which consists of the Instantaneous Radiative Forcing (IRF) and resulting atmospheric adjustments that occur in the absence of surface temperature change. The ERF could be taken to comprise both physical (temperature, humidity, cloud etc.) and chemical adjustments (which themselves lead to further physical adjustments). Here we

distinguish between direct ERFs resulting from the ODS themselves and indirect ERFs, which result from their impact on atmospheric chemistry and hence composition, which we refer to as chemical adjustments; this includes ozone depletion itself and its subsequent consequences on tropospheric chemistry. The chemical adjustments themselves lead to further physical adjustments, but as will be noted, the quantification of these, with the exception of stratospheric temperature adjustment, is in its infancy. The net ERF from ODS is then the sum of the direct and indirect ERFs. The indirect ERFs are less well understood than the direct ERFs.

The quantification of radiative forcing from ODS has a long history (Ramanathan, 1975). Despite this history, there have been wide-ranging estimates for the radiative forcing due to ODS, reflecting the uncertainty in their quantities. Additional complications stem from different estimates of the effect of chemical adjustments in the radiative forcing calculation. For example, the ERF due to ODS, including some chemical adjustments, has been reported to be negative in 2014 using a single climate model (-0.18 ± 0.04 W m^{-2}, with no stated confidence level for the uncertainty) (O'Connor et al., 2021), to be likely positive at 0.09 ± 0.06 W m^{-2} (mean and 1 s.d. uncertainty) in 2010 from an ensemble of six climate models (Morgenstern et al., 2021), or as large as 0.24 W m^{-2} in 2005 using a single model (Chiodo & Polvani, 2022) when instead considering Stratospheric Adjusted Radiative Forcing (SARF).

The use of deterministic or small ensembles of model runs makes complete characterization of uncertainty difficult. Individual ensemble members can largely influence mean quantities, which has been the case when quantifying changes in radiative forcing due to stratospheric ozone depletion (Skeie et al., 2020). The computational expense of running complex climate models means that the quantification of uncertainty using large ensembles is infeasible. As a result, reduced complexity climate models (see, e.g., Z. Nicholls et al., 2021; Z. R. J. Nicholls et al., 2020), which are approximations of their larger-scale counterparts, have been used for uncertainty quantification.

Here, we use a reduced complexity model to quantify the uncertainty in the net ERF from ODS. This approach allows uncertainties in the various forcing components to be fully characterized and allows the quantification of the net ERF from individual and grouped ODS. The reduced complexity model is trained on results from more complex climate models. Our results on the bulk characteristics of the net ERF from ODS are therefore not novel, but the exploration of its uncertainty over time using large, reduced-complexity ensembles and attribution of the net ERF of each individual ozone-depleting substance including the chemical adjustment is. We focus on the year 2019 as it is the most recent year published in the IPCC 6th Assessment Report (Forster et al., 2021). Section 2 describes the method used to characterize the uncertainty in ERF, Section 3 presents the results, which are discussed in Section 4 and conclusions drawn in Section 5.

2. Methods

We adapt the CICERO-SCM reduced complexity climate model (Sandstad, Aamaas, et al., 2024; Sandstad, Sanderson, et al., 2024) to emulate global responses to stratospheric bromine and chlorine loading and other processes contributing to the ERF from ODS. The adaptations made are described in the following subsections. Using this model, we generate an ensemble of simulations to estimate the uncertainty in the resultant net ERF of ODS. These simulations are performed from input emissions, rather than prescribed surface mole fractions, to allow subsequent changes and adjustments in the atmosphere.

2.1. Input Data Sets for Emissions and Lifetimes

The input global mean emissions for the ODS are derived from measurements made by the Advanced Global Atmospheric Gases Experiment (AGAGE) network (Prinn et al., 2018) and a simple model of atmospheric transport (see Western et al. (2025)), and are taken from the 2022 Scientific Assessment of Ozone Depletion (Laube & Tegtmeier, 2023). These emissions data sets are through 2020, and begin in various years. For years where emissions derived using AGAGE measurements are unavailable, we use those from Z. R. J. Nicholls et al. (2020). Where emissions are not available from either source, emissions are assumed to be zero. The halogenated greenhouse gases considered are CFC-11, CFC-12, CFC-13, CFC-113, CFC-114, CFC-115 (CFCs), HCFC-22, HCFC-141b, HCFC-142b, HCFC-124, HCFC-133a (HCFCs), CCl_4, CH_3CCl_3 (solvents), H-1211, H-1301, H-2402 (halons), and CH_3Br. Non-ODS halogenated gases (such as hydrofluorocarbons) are not included here. We only consider anthropogenic emissions of CH_3Br, which we take to be the emissions above the

assumed emissions in 1900. Any possible non-anthropogenic sources for the other ODS are negligible. The atmospheric lifetimes for all gases listed in the previous paragraph are taken from Burkholder and Hodnebrog (2023). Any ocean and soil sinks are neglected for these gases (see, e.g., Wang et al., 2021; Yvon-Lewis & Butler, 2002). We expect this impact to be small.

2.2. Stratospheric and Tropospheric Rapid Adjustments

The instantaneous radiative efficiencies of greenhouse gases can be altered to consider the rapid temperature responses in the stratosphere due to the presence of the forcer (see Shine and Myhre (2020)), yielding the SARF. We take the values for radiative efficiencies considering these stratospheric adjustments from Burkholder and Hodnebrog (2023). We assume that uncertainties in radiative efficiencies can be described using a 1 standard deviation of 8.5% for compounds with total atmospheric lifetimes greater than 5 years and 14.6% with lifetimes less than 5 years (Hodnebrog, Aamaas, et al., 2020).

Tropospheric adjustments of ODS due to changes in temperature, clouds, and water vapor further modify the radiative forcing, yielding the direct ERF. Tropospheric adjustments have only been quantified for CFC-11 and CFC-12, and have been estimated to increase radiative forcing by 13% ± 6% (1 s.d. uncertainty) and 12% ± 8.5%, respectively (Forster et al., 2021; Hodnebrog, Myhre, et al., 2020). For all other halogenated greenhouse gases, an uncertainty of 0% ± 7.9% has been estimated for this adjustment (Forster et al., 2021).

2.3. Breakdown Products

When ODS degrade in the atmosphere, their breakdown products and resulting reservoir species can also contribute to additional radiative forcing. In the absence of any evidence to the contrary, we assume the SARF from the breakdown products are equal to their ERF. We consider radiative forcing from four breakdown products of ODS, namely carbonyl fluoride (COF_2), phosgene ($COCl_2$), carbonyl chlorofluoride (COClF), and chlorine nitrate ($ClONO_2$), resulting from the breakdown of CFC-11, CFC-12, CFC-113, HCFC-22, and CCl_4 (Burkholder et al., 2015). The additional radiative forcing of these breakdown products and reservoir species has been estimated (Thornhill et al., 2024), and results in an additional 2.6% ± 0.3% to the SARF for CFC-11, 1.5% ± 0.2% for CFC-12, 2.3% ± 0.2% for CFC-113, 0.5% ± 0.05% for HCFC-22, and 15.3% ± 1.7% for CCl_4.

2.4. Stratospheric Ozone Depletion

Ozone-depleting substances destroy stratospheric ozone, which is itself a greenhouse gas, reducing their net ERF. We approximate the change in ERF of stratospheric ozone due to ODS since preindustrial times (we use 1900 as preindustrial for halogenated greenhouse gases) by assuming that the loss of stratospheric ozone in a given year is a linear function of equivalent effective stratospheric chlorine (EESC) (Steinbrecht et al., 2018), and that the ERF due to changes in stratospheric ozone is a linear function of this loss (Daniel et al., 1995). Following Forster et al. (2021), we assume that SARF and ERF for stratospheric ozone depletion are identical, although there is emerging evidence (see Discussion) that this is not the case.

Equivalent effective stratospheric chlorine (EESC) is a proxy of the chlorine and bromine available to deplete stratospheric ozone (Daniel et al., 1995). We use the 3-year EESC formulation from Newman et al. (2007), representative of the mid-latitude stratosphere, in our formulation. Despite advances in the formulation of EESC (Engel et al., 2018), the Newman et al. (2007) formulation is very similar and is more computationally efficient. We use quantified fractional release rates where available (Engel et al., 2018), otherwise we use a parametric fit to approximate the fractional release rate (Papanastasiou et al., 2018).

We fit the linear function using EESC since 1920 to the ERF estimate presented in Szopa et al. (2021) for 2019, considering the uncertainty (available from Blichner, 2022). The result is an ERF due to a change in stratospheric ozone defined by $-14.3 \pm 4.8 \times 10^{-5}$ W m^{-2} ppt^{-1} times the EESC.

2.5. Methane Lifetime and Subsequent Adjustments

The depletion of stratospheric ozone and the presence of ODS will further alter the reactive chemical balance of the atmosphere. A decrease in stratospheric ozone will allow more ultraviolet radiation to reach the lower stratosphere and troposphere, which will change its oxidation capacity through increased production of the

hydroxyl radical (OH). An increase in the stratospheric abundance of chlorinated ODS will release chlorine radicals following photodissociation. Both hydroxyl and chlorine radicals are atmospheric sinks for methane.

The CICERO-SCM defines the lifetime of methane using the relationship described by Ehhalt et al. (2001), which depends on a range of atmospheric constituents. We add an additional term to this relationship, dependent on EESC (as a proxy for stratospheric ozone depletion), where the lifetime of methane due to the OH radical is linearly dependent on EESC by a factor of $5.3 \pm 2.6 \times 10^{-5}$. This factor was optimized using the reported impact of ODS on methane lifetime for 2019 (Szopa et al., 2021), and using a Laplace approximation for the uncertainty.

The CICERO-SCM contains a range of adjustments as a result of changes in the lifetime of methane. As the total abundance of methane in the atmosphere will affect the OH sink, and therefore its own lifetime, the impact of OH on the methane sink is considered in the relationship from Ehhalt et al. (2001). The radiative efficiencies of methane and nitrous oxide (N_2O) are approximated using the expressions from Etminan et al. (2016), and the resultant SARF is converted to ERF using an increase of 14% for methane and of 7% for N_2O (Forster et al., 2021). Because of spectral overlap, the N_2O radiative efficiency is dependent on the global mole fraction of methane. A change in methane oxidation will also result in a change in stratospheric water vapor levels, and we use the unchanged simplified expression of CICERO-SCM for this, where the ERF from changes to stratospheric water vapor is assumed to be 9.2% of the ERF of methane (Forster et al., 2021; Sandstad, Aamaas, et al., 2024; Winterstein et al., 2019). Finally, we consider the effect of methane on tropospheric ozone concentrations, where we use the default in the CICERO-SCM (Ehhalt et al., 2001; Sandstad, Aamaas, et al., 2024). This states that, in a given year, tropospheric ozone concentrations change by 6.7 times the logarithmic ratio of the methane mole fraction compared to a reference year of 2010. The resultant SARF in a given year is a scaling of the tropospheric ozone SARF in 2010 (assumed to be 0.5 W m^{-2}) by the change in the burden of tropospheric ozone.

The hydroxyl radical also acts as a sink for many ODS. While a change to the oxidation capacity of the atmosphere would also impact the lifetime of many ODS, we ignore this impact because of the lack of a simplified expression in the current model.

2.6. Aerosols and Clouds

Changes in aerosols impact radiative forcing through aerosol-cloud (cloud seeding and brightening) and aerosol-radiation (direct effects from the presence of aerosols) interactions. The properties and production of aerosols is known to be impacted by the oxidation capacity of the atmosphere (Karset et al., 2018). The depletion of stratospheric ozone alters the oxidation capacity of the atmosphere (Section 2.5), thus affecting the formation and properties of aerosols. The indirect forcing on aerosols from ODS is very uncertain (Szopa et al., 2021).

In the CICERO-SCM, the aerosol-cloud interaction is assumed to be linearly dependent on sulfur dioxide emissions (Kretzschmar et al., 2017). We increase this linear dependence by a factor $1 + F \times \text{EESC}$, where $F = 2.1 \times 10^{-6} \pm 4.4 \times 10^{-5}$ ppt^{-1}. This has been optimized for the ERF values in 2019 from Szopa et al. (2021). For aerosol-radiation interactions, we increase the radiative forcing from the defaults in the CICERO-SCM by the same factor as the aeorosol-cloud interaction for both sulfur dioxide and organic carbon, due to changes in interactions with OH.

2.7. Generation of Probability Densities

Probability densities are generated using 100,000 ensemble members for each group of compounds (e.g., ODS or CFCs) and 10,000 ensemble members for each individual compound. The net ERF for each ensemble member is calculated using two runs, with and without the target compound or group of compounds. For each member, all uncertain parameters described in this section are independently sampled from a normal distribution with the described uncertainties. Sampling is performed using quasi-random sampling using a Sobol sequence (Sobol, 1967). The final probability density distributions are estimated using kernel density estimation, using a Gaussian kernel, and the uncertainties are calculated using the percentiles of this distribution.

3. Results

This section presents the probability density of the various ERF components of the ODS. Here, we present these values for 2019, although they can be derived for all years through 2020 using Supporting Information S1. Table

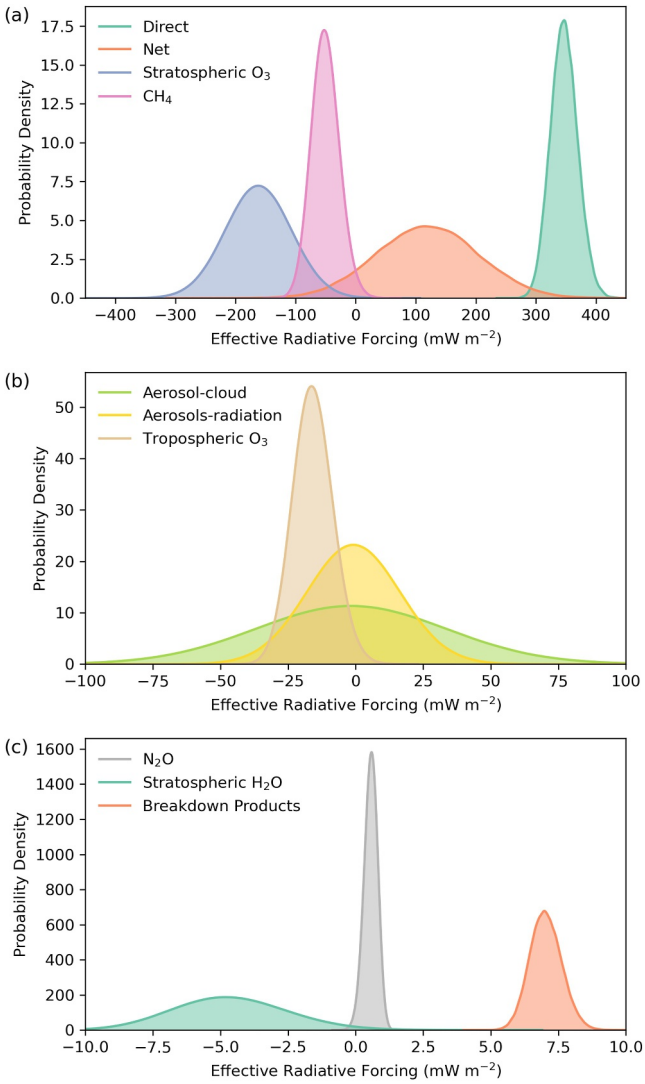

Figure 1. The probability density of the components of radiative forcing contributing to the net effective radiative forcing (ERF) from ozone-depleting substances in 2019. (a) The direct ERF, the net ERF, the ERF due to a change in levels of stratospheric ozone and due to a change in methane lifetime. (b) Changes in tropospheric ozone, aerosol-cloud, and aerosol-radiation. (c) Changes in the radiative efficiency of N_2O, changes in stratospheric water vapor, and from breakdown products.

S1 in Supporting Information S1 shows the forcing components for 2019 for all groups of ODS, which are also shown in Figures S1–S4, and Tables S2–S6 in Supporting Information S1 show the forcing components for each separate ODS.

The quantified forcing components for all ODS are shown in Figure 1. The direct ERF for ODS in 2019 is 347 (311, 385) mW m^{-2} (mode and 90% uncertainty). Considering chemical adjustments due to the emissions of ODS yields a net ERF of 114 (−21, 260) mW m^{-2}, which has a 92% probability of a net positive forcing. The only forcing adjustments that have a positive modal forcing are from breakdown products, 7.0 (6.1, 8.0) mW m^{-2}, and a change in the radiative efficiency of N_2O, 0.6 (0.1, 1.0) mW m^{-2} due to a change in the mole fraction of methane, both of which are very minor contributors. Stratospheric ozone depletion has the largest negative ERF, with −162 (−252, −71) mW m^{-2}, followed by changes to the lifetime of methane, −53 (−87, −11) mW m^{-2}. The probability that stratospheric ozone and methane have a negative ERF are over 98% and 99%, respectively, given the ensemble. The result of changes in methane levels on tropospheric ozone, −16 (−28, −3.4) mW m^{-2}, and stratospheric water vapor, −4.8 (−8.0, −1.0) mW m^{-2}, have the next largest contribution. Finally, aerosol-cloud, −1.6 (−59.8, 56.6) mW m^{-2}, and aerosol-radiation, −0.8 (−29.3, 27.2) mW m^{-2}, have negative modal forcing, although in both cases there is a 48% probability that these impacts contributed a positive ERF in 2019.

While the net ERF from ODS is most likely positive, this is not the case for all groups of ODS. Halons have a net ERF of −43 (−69, −16) mW m^{-2}. This is a large reduction compared to its direct ERF, 2.0 (1.8, 2.3) mW m^{-2}. The same is true for solvents (CCl_4 and CH_3CCl_3), which have their direct ERF reduced from 13 (11, 16) mW m^{-2} to a net ERF of −25 (−47, −2) mW m^{-2} when considering indirect effects.

The positive net ERF of all ODS is dominated by CFCs and HCFCs. The CFCs have a positive net ERF of 150 (68, 231) mW m^{-2}, and are the largest contributing ODS group to the total net ERF. The large atmospheric abundance of CFCs leads to a direct ERF of 270 (236, 307) W m^{-2}. The probability that the net ERF in 2019 was positive for CFCs is over 99%. The HCFCs, with a lower ozone-depleting potential than other long-lived ODS, have a net ERF of 50 (40, 64) W m^{-2}, compared to a direct ERF of 61 (51, 72) W m^{-2}.

The two most abundant long-lived ODS in the atmosphere are CFC-11 and CFC-12. The direct ERF of CFC-11 and CFC-12 is 62 (52, 73) W m^{-2} and 177 (146, 214) mW m^{-2}, respectively, or around 70% of the total direct ERF for ODS. The net ERF is 0.4 (−35.6,40.6) mW m^{-2} for CFC-11, which equates to a 53% probability of any warming impact in 2019. CFC-12 has a net ERF of 129 (89, 179) mW m^{-2}, which is greater than the total net ERF for all ODS.

4. Discussion

The modal direct ERF derived here (0.35 W m^{-2}) is equal to that reported using measured surface mole fractions in IPCC AR6 (Forster et al., 2021). The net ERF derived in this study (mode and 68% uncertainty) is 0.095 (−0.030, 0.20) W m^{-2} in 2000, 0.10 (−0.023, 0.21) W m^{-2} in 2005, 0.12 (0.01, 0.21) W m^{-2} in 2014, and 0.11 (0.034, 0.20) W m^{-2} in 2019. Here, 68% uncertainties (1 standard deviation equivalent) are given to better compare with previous literature. Uncertainties were given in Section 3 as 90% to be consistent with the IPCC.

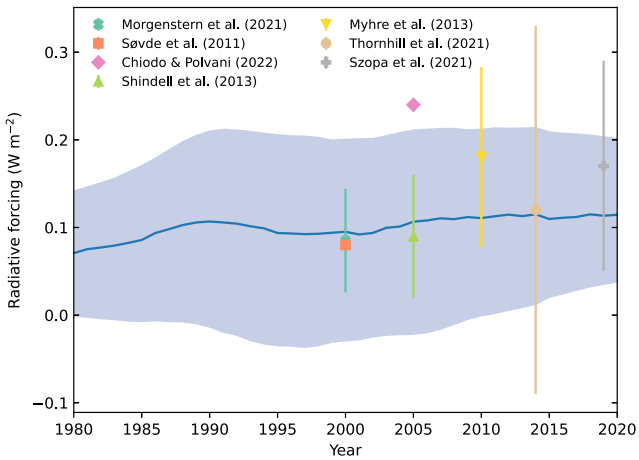

Figure 2. The blue line shows the modal net effective radiative forcing of ozone-depleting substances, and the 68% (1 standard deviation equivalent) uncertainty is shown by the shading, using the ensemble from this work. Colored symbols show the radiative forcing reported in literature, with the error bars showing the 1 standard deviation uncertainty in the reported values (Chiodo & Polvani, 2022; Morgenstern et al., 2021; Myhre et al., 2013; Shindell et al., 2013; Søvde et al., 2011; Szopa et al., 2021; Thornhill et al., 2021). The metric of radiative forcing used differs between literature sources. Please see the main text for details. The 1 standard deviation uncertainty from literature may be that of a single model or from the spread of multiple models. Note that the result of Morgenstern et al. (2021) is partially obscured by the result of Søvde et al. (2011).

Estimates of the net radiative forcing from ODS from previous studies come from a mixture of reported radiative efficiencies, broadband radiation codes and adjustments computed using Earth System Models. We do not know the degree to which these different calculations impact the radiative forcing metrics. The net ERF, including some chemical adjustments, for 2000 was previously estimated to be 0.085 ± 0.059 W m^{-2} (1 standard deviation uncertainty, Morgenstern et al., 2021) and, in the same year, the SARF was estimated to be 0.08 W m^{-2} (Søvde et al., 2011). Additional studies have quantified a net ERF in 2005 of 0.09 ± 0.07 W m^{-2} (Shindell et al., 2013), net SARF in 2010 of 0.18 ± 0.103 W m^{-2} (Myhre et al., 2013), net ERF in 2014 of 0.12 ± 0.21 W m^{-2} (Thornhill et al., 2021) and in 2019 of 0.071 ± 0.12 W m^{-2} (Szopa et al., 2021). Two studies fall out of the 68% uncertainty range. A study by Chiodo and Polvani (2022) quantified net SARF for 2005 of 0.24 W m^{-2}, which is substantially larger than other estimates of quantified for any year. Figure 2 shows these comparisons. In contrast, a study by O'Connor et al. (2021) quantified a 2014 net ERF of -0.18 ± 0.04 W m^{-2}, which is much smaller than the other studies for any year and is the only study to confidently estimate a negative ERF from ODS. However, this result is thought to be a result of excessive ozone depletion (see later in this Discussion) and has been excluded from Figure 2. It has previously been assumed that SARF and ERF for stratospheric ozone are identical (Forster et al., 2021). However, as suggested by Forster et al. (2021), there is recent evidence that using SARF as a metric to quantify the radiative forcing from stratospheric ozone depletion may underestimate its contribution by as much as half compared to ERF, based on projected changes in radiative forcing due to ozone recovery (Collins et al., 2025). Therefore, not all studies offer a like for like comparison.

The study by Szopa et al. (2021), which extended the work by Thornhill et al. (2021), was used to train the radiative forcing adjustments in the simple model used in this work (see Section 2). There is therefore some circularity in these comparisons and the agreement simply shows that the simple model meets its intended use of emulating the uncertainty in large-scale complex climate models, with the exception of outlying studies. The mean and uncertainty in previous studies are derived either from a single model or a small ensemble of models. A single outlying member of a small ensemble of models can largely skew the estimate of the mean and standard deviation derived. In Thornhill et al. (2021), a SARF due to the depletion of stratospheric ozone from ODS of -0.15 ± 0.10 W m^{-2} was derived using an ensemble of six models. One of the models, UKESM1, which has been known to see high levels of stratospheric ozone depletion (Keeble et al., 2021; Skeie et al., 2020), had a SARF of -0.33 W m^{-2}, much more negative than the other members. As the training data set for this emulator (Szopa et al., 2021) is an extension of Thornhill et al. (2021, 2024), this outlier persists in the training set. In the work by Thornhill et al. (2021), removing this outlier would increase (i.e., make less negative) the SARF from ozone depletion to -0.11 ± 0.07 W m^{-2}, or around 25%. As stratospheric ozone depletion is the largest cooling impact from ODS, removing this climate model would also increase the radiative impact of ODS if propagated into the training set used here. As our intention is to explore the uncertainty that is present between more complex models, the discrepancy between models is a feature of our analysis, rather than a source of error.

Potential outliers are present in underlying estimates for many of the parameterizations in the simple model used here. For example, the effect of rapid adjustments on the IRF of CFC-11 was negative in one of the four underlying models used to derive its value (Hodnebrog, Myhre, et al., 2020); however, a sample size of four models is not sufficient to confidently identify this as an outlier and the hope is that the large uncertainties assigned to this value is a true representation of its uncertainty. Improvements in complex climate models and the analysis of larger ensembles will improve the exploration of uncertainty.

A simple model or emulator will never capture the true complexities of the climate system, nor is it intended to. The assumptions made in this work are simplistic by design. However, there are known processes that have been neglected in the method used here, which would likely impact the resultant net ERF. Many chemical and

dynamical drivers impact the variability of stratospheric ozone depletion (Ball et al., 2019; Chipperfield et al., 2018; Solomon, 1999), which cannot be captured using such simplistic modeling. Interpretation of our results should be made in the context of long-term trends and the uncertainty surrounding them rather than quantification for particular years.

The CICERO-SCM uses a fixed change in surface albedo, due to land use change, over time. In modeling studies, ODS have been shown to increase Arctic warming and sea ice loss (Polvani et al., 2020; Sigmond et al., 2023) more than CO_2, per unit of radiative forcing. This impact is primarily through direct radiative warming, a strong lapse rate feedback and a weakening of the negative net cloud feedback in the Arctic. The impact of ODS on global mean temperature changes has not been explored here. A better understanding of the feedbacks of ODS on Arctic warming and sea ice loss, and the subsequent changes to the Earth's albedo and its uncertainty, could allow emulation of these feedbacks and their impact on global mean temperatures.

Additional impacts related to the loss of ODS from the atmosphere are also neglected. The primary sink of many ODS, such as HCFCs, is OH. As discussed in Section 2.5, stratospheric ozone depletion increases levels of OH and its shortening of methane lifetime is considered in the simple model. However, the ODS are treated as having a fixed lifetime that is not impacted by a change in OH concentrations. Any resultant adjustments in the lifetime of ODS would lead to additional adjustments in the net ERF, which has not been included.

The sampling method used to generate the probability densities assumes that all input variables are independent and uncorrelated. While this assumption is likely an oversimplification, there is little evidence to support the contrary. For example, one might reasonably expect that models showing more stratospheric ozone depletion would lead to a larger increase in atmospheric oxidation and be strongly correlated with a larger decrease in methane lifetime. However, there is no such pattern observed between models (Thornhill et al., 2021).

We do not report an additional error in the quantification of radiative forcing from using a simple model, its underlying parameterization or the representativeness of the small ensemble of model outputs used as training data. This additional error would likely be large and may be systematic, whereas errors have been assumed otherwise to be random. These systematic errors may also be present in the climate model simulations used to parameterize the emulator, which would propagate into the results presented here. If known, the systematic errors, and the uncertainty in these errors, can be accounted for using simple models to better quantify the uncertainty. However, more work would be needed to better understand these errors in complex climate models. A better understanding of the atmospheric processes and adjustments that affect radiative forcing will ultimately improve its uncertainty quantification.

Past studies have demonstrated the benefits of the Montreal Protocol for the climate, where a lack of controls would have led to a large increase in warming (Velders et al., 2007). The conclusion was based on projected future growth of CFCs and our results support that the controls of the Montreal Protocol have avoided a large increase in warming from CFCs. However, the projected net radiative forcing avoided would likely be reduced if additional adjustments were included beyond the SARF from loss of stratospheric ozone. Our results presented in Figure 2 show that the net ERF from all ODS has not largely changed since the implementation of the Montreal Protocol in 1987. The benefits of the Montreal Protocol for the climate may be muted or amplified compared to those presented in Velders et al. (2007) if other ODS, such as halons with a negative net ERF or HCFCs with a positive net ERF, were included in the future projection, depending on their future relative growth rates. Regardless of the impact on global temperatures, any such scenario of unfettered growth of ODS would have been disastrous for stratospheric ozone, ecosystems, and human health (Newman et al., 2009; Young et al., 2021). An affine fit to the net ERF between 1987 and 2019 produces an annual growth rate of 0.9 (−0.7, 2.6) mW m^{-2} yr^{-1} (median and 90% uncertainty across slopes for all ensemble members). While CFC mole fractions have declined, reducing the direct ERF, it has been offset by a decline in mole fractions of ODS that have a negative net ERF and an increase in the atmospheric mole fraction of HCFCs, which have a strongly positive net ERF. The direct ERF from HCFCs has declined since 2021 (Western et al., 2024). A decline in HCFCs in the atmosphere should reduce the net ERF from ODS, although HCFCs are not expected to return to their 1980s levels in the atmosphere until the 2080s (Western et al., 2024).

Hydrofluorocarbons (HFCs) are a group of gases controlled under the Kigali Amendment to the Montreal Protocol but are not ODS. We have not quantified the ERF of these halocarbons, although HFCs were included in some earlier studies (e.g., O'Connor et al., 2021; Thornhill et al., 2021) and were separated from ODS in Szopa

et al. (2021). The HFCs are becoming increasingly larger contributors to direct radiative forcing from halocarbons (Forster et al., 2021; Liang & Rigby, 2023). Understanding of the uncertainties in the net ERF of HFCs is simplified over that of ODS, given the very small impact of HFCs on stratospheric ozone depletion (Hurwitz et al., 2015; Ravishankara et al., 1994), although uncertainties still exist in the stratospheric and tropospheric adjustments to their radiative efficiencies (Burkholder & Hodnebrog, 2023; Hodnebrog, Aamaas, et al., 2020), changes in stratospheric water vapor (Hurwitz et al., 2015) and impacts on atmospheric oxidation. If current policy continues, direct ERF from HFCs is expected to peak around the middle of the current century (Velders et al., 2022).

5. Conclusions

We have quantified the uncertainty in various contributors to the net ERF of ODS using a simple climate model. The net ERF of ODS is smaller than the direct ERF, mainly due to the depletion of stratospheric ozone and an increase in the oxidation capacity of the atmosphere, which decreases the atmospheric lifetime of methane. These conclusions have been drawn in earlier studies and the simple model has been used to emulate these results. The simple modeling approach has allowed the net ERF to be broken down by individual ODS by approximating their impact using EESC. Our results show that CFC-12 is by far the largest contributor to the net ERF from ODS.

The total net ERF of ODS has slightly increased since the implementation of the Montreal Protocol. This increase has been due to a combination of the decline in the abundance of substances that reduce the net ERF of ODS and an increase in the abundance of HCFCs, primarily HCFC-22. It may be beneficial to target recovery and destruction of those gases with larger net ERF to mitigate future warming from ODS. Uncertainties in the indirect and hence the net ERF are large and a better understanding of atmospheric adjustments will aid future uncertainty quantification.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All accompanying data sets of the ensembles used are available at Western (2025a). This work used a modified version of the CICERO-SCM, which implements the adjustments from ozone-depleting substances, which is available at Western (2025b). The latest version of the CICERO-SCM is available at Sandstad et al. (2026).

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