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**Options to accelerate
ozone recovery**

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Options to accelerate ozone recovery: ozone and climate benefits

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Abstract

Hypothetical reductions in future emissions of ozone-depleting substances (ODSs), including N₂O, are evaluated in terms of effects on equivalent effective stratospheric chlorine (EESC), globally-averaged total column ozone, and radiative forcing through 2100. Due to the established success of the Montreal Protocol, these actions can have only a fraction of the impact that regulations already in force have had. If all anthropogenic ODS emissions were halted beginning in 2011, ozone is calculated to be higher by about 1–2% during the period 2030–2100 compared to a case of no additional ODS restrictions. Radiative forcing by 2100 would be about 0.23 W/m² lower due to the elimination of N₂O emissions and about 0.005 W/m² lower due to destruction of the chlorofluorocarbon (CFC) bank. The ability of EESC to be a suitable metric for total ozone is also quantified. Responding to the recent suggestion that N₂O should be considered an ODS, we provide an approach to incorporate N₂O into the EESC formulation.

1 Introduction

The Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments and adjustments have been successful in halting the increasing trend in stratospheric ozone depletion (WMO, 2007); these actions have also reduced climate forcing over the last 2 decades (Velders et al., 2007), and have thus presumably reduced the rate of climate change over this period compared to what would have otherwise occurred. The production and consumption of many of the most important chlorine- and bromine-containing ozone-depleting substances (ODSs) are already phased out. Most of the others are controlled, with schedules in place to phase out their production and consumption in the next few decades.

However, the Protocol does not limit some types of ODS production and consumption and does not directly regulate ODS emissions at all. Several activities involving

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ODSs are thus expected to continue to lead to atmospheric emissions. Restricting these sources represents an opportunity to accelerate ozone recovery. For example, because the Montreal Protocol regulates production and consumption rather than emissions, it does not limit the release of ODSs already produced and currently residing in existing equipment or applications, such as firefighting equipment, air conditioners, refrigerators, and foams. Production of hydrochlorofluorocarbons (HCFCs) and CH_3Br also continues. Production of HCFCs is to be virtually phased out globally by 2030 with stepwise reductions in place in the intervening time under the current Protocol. CH_3Br use for quarantine and preshipment purposes is unrestricted and critical use exemptions have been granted every year since 2005. Production of CCl_4 for non-feedstock use has been globally phased out since the beginning of 2010. However, emissions resulting from its use as a feedstock, i.e. to produce another chemical, are unregulated, and it is also coproduced during chloroform production and can be coproduced during perchloroethylene production. These CCl_4 sources could explain why global emissions implied by atmospheric observations have been significantly higher than what has been suggested by reported production. Whatever the reason for the concentrations being higher than expected, the uncertainty implies that future trends are also uncertain and that emissions may continue.

Recently, it has been suggested that N_2O could be considered to be an ODS (Ravishankara et al., 2009). While it has been known for over 2 decades that N_2O leads to stratospheric NO_x production, which in turn leads to ozone destruction, N_2O has not been regulated by the Montreal Protocol. Ravishankara et al. (2009) quantified the global ozone depletion potential (ODP) of N_2O and compared the ODP-weighted emissions of N_2O with those of other ODSs. Such a comparison demonstrates that N_2O is an important gas for ozone depletion. N_2O is also a recognized greenhouse gas that was included in the basket of gases regulated under the Kyoto Protocol. Nevertheless, projections suggest that N_2O emissions will remain significant through 2100 even under strongly mitigated climate stabilization scenarios (Clarke et al., 2007).

Equivalent effective stratospheric chlorine (EESC) (Daniel et al., 1995) has been the

tool frequently used to quantify the relative effectiveness of various policy options for reducing ozone depletion (e.g., WMO, 1995, 1999, 2003, 2007). It has been assumed, (but not explicitly quantified) that the integrated EESC decreases from some policy action are related to the integrated ozone increases over the same time period. The EESC approach has been used partly because of the significant computer resources required to evaluate all available options directly using ozone calculated from 2-D or 3-D models. As computer speeds have increased, it has become feasible to perform these calculations with 2-D models.

Here, we consider several of the most important sources of future ODS emissions and how additional restrictions on them could further limit ozone depletion and reduce radiative forcing. Emissions projections that incorporate reductions in these sources, along with the scenarios to which these are compared, are described in Sect. 2. Also in Sect. 2, we describe an approach to incorporate N₂O into the EESC formalism. In section 3, the impacts of the various options for reducing future ODS emissions are calculated in terms of EESC, total column ozone, and radiative forcing. The ozone results are also used to quantify the extent to which the current EESC formulation serves as a suitable metric for approximating integrated ozone changes. Conclusions are presented in Sect. 4.

2 Analysis

Two reference scenarios are used to evaluate the various emission reduction scenarios. One, which we will refer to as the “background” case includes no anthropogenic ODS emissions (including N₂O) in the past or future; it does include observed CO₂ and CH₄ abundances through the present with future mixing ratios prescribed by the Intergovernmental Panel on Climate Change (IPCC) SRES A1B scenario (Nakicenovic et al., 2000). This scenario also does not include the increase from 480 to 550 parts per trillion by volume (pptv) in CH₃Cl during the 20th century (WMO, 2007). This increase may be natural, but it plays a very minor role in the future scenarios. The sec-

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ond, “baseline”, case includes the same CO₂ and CH₄ evolution as in the background case but also includes anthropogenic ODSs (including N₂O). Past ODS concentrations are determined from observations (WMO, 2007). Future concentrations are consistent with the current Montreal Protocol production and consumption limits. They are similar to those in case A1 of WMO (2007) except that they have been updated for more recent atmospheric observations (S. Montzka, personal communication) and/or bank estimates (TEAP, 2009). A few additional changes relative to WMO (2007) include: (1) a reduction in future production of HCFCs to include the faster phaseout approved by the Parties to the Protocol in 2007; (2) a projected slower future decline in CCl₄ production and emissions (5%/yr) to obtain better consistency with the decline in emissions over the last 4 years inferred from global observations; (3) use of CH₃Br being held constant at a level equal to the 2009 critical use exemptions granted by the Parties to the Protocol; and (4) including N₂O as an ODS with future concentrations taken from IPCC SRES A1B. All cases are run through 2100. This end date is chosen partly for the practical reason that scenario A1B and the chlorine- and bromine-containing ODS scenario, A1, are only projected through 2100. We also recognize that it becomes difficult to project market demand and emissions far into the future, particularly for compounds like N₂O that are not currently individually regulated.

We consider seven hypothetical options for reducing future ODS emissions. Some cases involve capture and destruction of the entire 2011 bank (quantities residing in existing equipment or applications), while others include a cessation of future production from 2011 onward. CH₃Br represents an exception in that emissions from gasoline, biomass, and biofuel burning are continued at 2007 levels (Yvon-Lewis et al., 2009) in all cases involving a CH₃Br phaseout. Continuing these burning byproduct emissions leads to a steady state CH₃Br mixing ratio of 6.3 pptv for all CH₃Br phaseout cases rather than the 5.3 pptv attained if these emissions were also eliminated. For N₂O, elimination of all anthropogenic emissions beginning in 2011 is considered; this is accomplished by having the mixing ratio enhancement above the natural background in 2011 decay with a global lifetime of 114 years (WMO, 2007) back toward the back-

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ground level of 275 parts per billion by volume (ppbv) (Denman et al., 2007). Complete elimination of these sources of future emissions is a straightforward way to demonstrate their impact on ozone and climate forcing. However, the feasibility and cost of reducing ODSs varies with compound and application. The effect of smaller reductions can be obtained by simple scaling to the results presented here; scaling is appropriate because the changes are roughly linear with the magnitude of the phaseout as long as the reduction begins around 2011. The specific cases considered and the integrated amounts of ODS emission reduced from 2011-2050 relative to the baseline case are shown in Table 1, along with the impacts on EESC and ozone. The impacts will be discussed in Sect. 3. Feedstock use, as well as by-product emissions of CCl_4 , are not controlled by the Montreal Protocol; emissions resulting from these uses may grow and become increasingly important to future ozone depletion and climate; nevertheless, we will not consider any such growth because of the large uncertainty in their current and future magnitudes.

EESC is calculated assuming a 3-year mean age and an age spectrum width of 1.5 years (Waugh and Hall, 2002) to represent the mean transport time between the troposphere and stratosphere. Relative fractional release values for 3-year-old air from Newman et al. (2007) are assumed for all compounds except for HCFC-141b and -142b, which were characterized by high uncertainty in that analysis. The relative values for these compounds are taken from WMO (2007) and originated from Solomon et al. (1992). There has been discussion of a threshold in EESC below which changes in EESC have little or no impact on O_3 (e.g., (Daniel et al., 1995)). Because globally averaged total column ozone loss continues below this level, no threshold is considered here.

Ozone is calculated using the Goddard Space Flight Center (GSFC) (Fleming et al., 2007; Newman et al., 2009) and the NOCAR interactive 2-D models (Solomon et al., 1998; Portmann et al., 1999) using 2006 Jet Propulsion Laboratory (JPL) rates (Sander et al., 2006). Both models successfully capture the processes important for calculating globally averaged total ozone. The agreement between models both in

ozone depletion and the response of that depletion to ODS emission reductions gives us confidence in the results. Recent 3-D modeling studies have shown the importance of climate change on future stratospheric projections (Eyring et al., 2007). To account for this, the GSFC model parameterizes the long-term changes in surface temperature, latent heating, and tropospheric H₂O based on 3-D simulations from the Goddard Earth Observing System chemistry-climate model (GEOSCCM) (Pawson et al., 2008). The resulting 2-D simulation of the Brewer-Dobson circulation acceleration and decrease in stratospheric age-of-air over 1950–2100 is similar to that of the GEOSCCM. The GSFC 2-D model is also in good agreement with the GEOSCCM in simulating ozone and temperature changes over the 1950–2100 time period.

N₂O has never been included in EESC calculations, perhaps because it has not historically been considered an ODS. There are important complications to including it because it participates in ozone destruction through the NO_x cycle rather than the ClO_x or BrO_x cycles. Increasing NO_x reduces the efficiency of Cl_y and Br_y for ozone destruction by tying up more of these halogens in ClONO₂ and BrONO₂ reservoir species. At elevated chlorine and bromine levels, this offsets some of the impact of an increase in N₂O on ozone depletion. Decreasing Cl_y similarly ties up less NO_y in ClONO₂, increasing the efficiency of N₂O. These interactions imply that the projected future decline in Cl_y and Br_y abundances resulting from the success of the Montreal Protocol should lead to a greater impact of a unit change in N₂O emissions on ozone (Ravishankara et al., 2009). On the other hand since the loss of stratospheric NO_x is inversely related to temperature, the efficiency of N₂O on global ozone depletion is expected to decrease as the upper stratosphere cools from the projected increases in CO₂ (Rosenfield and Douglass, 1998). From the 2-D models considered here, we estimate that by 2100 this process will result in a decrease of 10–20% in the effectiveness of a unit N₂O emission to lead to ozone depletion compared to today. The effect of all of these interactions will potentially lead to a more complicated relationship between EESC and ozone depletion. Nevertheless, we will suggest an approach for including N₂O in EESC and then quantify its success as a metric for integrated ozone depletion under plausible

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perturbations. Future deviations of CO₂ and EESC from the scenarios used here will alter the interactions shown; however, the deviations are not expected to be significant enough to substantively change the results.

Because our focus is on global ozone, we use the N₂O global ODP presented in Ravishankara et al. (2009) of 0.017 calculated for 2000 conditions with the NOCAR model to quantify N₂O's contribution to EESC. Using the GSFC model, we calculate a similar ODP of 0.019 for 2000 conditions. When including N₂O, EESC can be written as

$$EESC(t) = f_{CFC-11} \cdot$$

$$\left\{ \begin{array}{l} \sum_{\text{Cl-containing compounds}} n_i \frac{f_i}{f_{CFC-11}} (\rho_{i,\text{entry}} - \rho_{i(\text{nat}),\text{entry}}) + \alpha \sum_{\text{Br-containing compounds}} n_i \frac{f_i}{f_{CFC-11}} (\rho_{i,\text{entry}} - \rho_{i(\text{nat}),\text{entry}}) \\ + \xi \eta n_{N_2O} \frac{f_{N_2O}}{N_{CFC-11}} (\rho_{N_2O,\text{entry}} - \rho_{N_2O(\text{nat}),\text{entry}}) \end{array} \right\} \quad (1)$$

where α is the relative efficiency of bromine compared with chlorine for destroying total ozone, η is the same factor for nitrogen relative to chlorine when the nitrogen originates from N₂O, ξ is a correction factor for η that is discussed later, n_i is the number of Cl, Br, or N atoms contained in the ODS, f_i is the fraction of the compound dissociated on average in the stratosphere (assumed here to be at the 3-yr-old age-of-air location), and ρ_i is the tropospheric mixing ratio due to anthropogenic emissions. We consider only the anthropogenic contributions of N₂O, CH₃Br, and CH₃Cl by explicitly subtracting the entry mixing ratio of each that arises from natural emissions. All concentrations arising from natural emissions are assumed to be constant in time, so we do not include the small increase in CH₃Cl mixing ratios from WMO (2007). The age spectrum is accounted for in the calculation of ρ .

If we use the semiempirical ODP formula (Solomon et al., 1992)

$$ODP_i = \eta \frac{n_i}{n_{CFC-11}} \frac{f_i}{f_{CFC-11}} \frac{\tau_i}{\tau_{CFC-11}} \frac{M_{CFC-11}}{M_i} \quad (2)$$

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it follows that

$$\eta n_{\text{N}_2\text{O}} \frac{f_{\text{N}_2\text{O}}}{f_{\text{CFC-11}}} = \text{ODP}_{\text{N}_2\text{O}} \eta_{\text{CFC-11}} \frac{\tau_{\text{CFC-11}}}{\tau_{\text{N}_2\text{O}}} \frac{M_{\text{N}_2\text{O}}}{M_{\text{CFC-11}}} = 6.4 \times 10^{-3} \quad (3)$$

Notice that η includes the efficiency of N production from N_2O in all three equations. Levels of ClO_x and BrO_x were shown to significantly affect the N_2O ODP in Ravishankara et al. (2009); at 1959 levels, the ODP was calculated to be 0.026 rather than the 0.017 at 2000 conditions. We will account for this dependence on the N_2O term by applying a correction factor, ξ in Eq. (1). This factor is assumed to be a linear function of the part of EESC arising from chlorine and bromine source gases so that the 1959 EESC level from these gases leads to a value for ξ of 1.53 (0.026/0.017) while 2000 levels of EESC lead to a value of 1.0. The 1959 and 2000 levels of EESC for the baseline scenario are 270 and 1665 pptv, respectively. This factor, along with Eq. (3), is then used in Eq. (1) to calculate N_2O 's contribution to EESC. The EESC/ozone depletion relationship of the N_2O scenarios presented in Sect. 3 are more consistent with the other scenarios when ξ is included in Eq. (1) in this way.

By 2000, increases in CO_2 had already cooled stratospheric temperatures and reduced the $\text{NO}_y/\text{N}_2\text{O}$ ratio. Thus, when calculating ξ using the 1959 and 2000 ODPs, this effect is also included. The temperature effect is expected to scale differently with EESC in the future because EESC is projected to decrease while CO_2 continues to increase in the A1B scenario; thus, it is expected that these interactions should lead to some additional error in the correlation between EESC from N_2O and the associated ozone depletion. However, this error is smaller than the benefit gained from including the EESC dependence.

3 Results and discussion

Figure 1 illustrates the maximum extent to which ODS emission phaseouts can accelerate the recovery of ozone and EESC towards a state defined by the emissions of no

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ODSs at any time. An important result of this study is that even with full and immediate phaseouts of all ODS emissions, except for the three emission sources of CH₃Br discussed in Sect. 2, the recovery to the background case will not have occurred by 2100 because of the long residence times of several of the ODSs. Such a phaseout would, however, lead to ozone levels that exceed ozone in the baseline case by 1.2–1.9% between 2030–2100. Chlorine and bromine emission reductions could affect O₃ relatively quickly, with N₂O playing a larger role by 2100. To put this into perspective, relative to the background case, these models calculate a peak ozone depletion near 2000 of 7–8% and a depletion of about 4% by 2100 for the baseline case. This peak depletion is substantially larger than the 3.5% quoted in WMO (2007) because we are comparing to the higher O₃ level calculated for the background case, which includes increases in CO₂ and CH₄ (and no ODSs), rather than the 1965–1980 observed ozone level used in WMO (2007). It has been estimated that in the absence of the Montreal Protocol and assuming continued growth of ODSs, globally-average total ozone depletion could have reached 17% by 2020 and 67% by 2065 when compared to 1980 levels (Newman et al., 2009). So while options still exist to reduce future ozone depletion, the potential benefits of policy options are substantially reduced compared to what the Montreal Protocol has already achieved.

Figure 1 (panel a) also shows the extent to which increases in CO₂ and CH₄ from the A1B scenario leads to higher calculated column ozone in these two models. Total ozone's return to 1980 levels is known to depend strongly on the future evolution of CO₂ and likely on CH₄ (Portmann and Solomon, 2007; Chipperfield and Feng, 2003; Rosenfield et al., 2002; Randeniya et al., 2002). However, we do not consider CO₂ or CH₄ regulations to be policy options for reducing ozone depletion because these gases are expected to have negative ODPs and their emissions would need to be increased to reduce ozone depletion. Such increases would lead to climate warming, and hence are considered undesirable options.

One metric used in ozone assessments is the year in which EESC drops below the 1980 level. Figure 1 shows that this time associated with EESC does not perfectly

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indicate when total ozone depletion due to ODSs returns to 1980 levels and that the relationship is model dependent. For the 2-D models used here, the evolution of future total ozone depletion due to ODSs is explained well by EESC, but EESC as calculated with a mean age of 3.6 years (NOCAR) and 5.4 years (GSFC), rather than the 3 years typically assumed for midlatitude EESC calculations. The high correlation between normalized EESC using these ages and ozone depletion is shown in Fig. 2. The older ages suggest that while EESC for 3-year-old air remains an acceptable and useful metric, it may not perfectly describe the evolution of globally averaged total column ozone or the time when ozone depletion will reach some target level. It is also important to recognize that the return of global total ozone to some approximately natural level does not imply that the ozone profile, the latitudinal variations, or the radiative forcing associated with the stratospheric ozone distribution will be the same as it was in the unperturbed state (WMO, 2007).

The effects of specific emissions reductions compared to the baseline scenario are quantified in terms of their effect on radiative forcing, EESC, and total ozone in Fig. 3. Table 1 includes the effects on integrated EESC and ozone. Because every case involves an elimination of some future source of ODS emissions, the magnitude of the impact will be dependent on the amount of future emissions projected in the baseline scenario. For example, by 2050 little emission remains in the baseline case for CFCs, halons, CCl₄, and HCFCs, with specific details depending on the compound. This explains the general shape of increasing impacts in the short run and then decreasing for most of the cases. The CH₃Br phaseout leads to a nearly constant change in EESC and ozone because of CH₃Br's short lifetime combined with the assumed continuing critical use exemptions at a constant level in the baseline scenario. The N₂O anthropogenic phaseout leads to increasing impacts on EESC, ozone, and radiative forcing over the time period shown.

This N₂O response represents a fundamentally different behavior compared with the other ODSs. Because of the long lifetime of N₂O and because there is no current regulation that phases out its future emissions, its impact on ozone continues to grow over

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the time period shown and is largely determined by the length of the integration time. Thus, picking a longer time period will generally lead to a greater relative importance of N₂O emissions reductions compared to reductions of other ODSs. To illustrate the importance of the time horizon considered, the integrated impacts in terms of EESC and ozone are shown for two time periods in Table 1. The larger relative impact of the N₂O reduction over the longer period is clear. Of course, there is no scientific reason to stop the integration at 2100 either since ozone depletion will still be occurring relative to a background case. When dealing with a compound like N₂O whose emissions are not limited in the future, but are expected to continue indefinitely, the difficulties in choosing a time horizon for evaluating policy options are similar to those encountered when evaluating the relative impacts of greenhouse gases on radiative forcing and climate. An important distinction is that, unlike with climate change, it is likely that we could return to natural globally averaged total column ozone levels in the next few decades.

An important related question is whether there is a level of global column ozone above which anthropogenic ozone depletion is no longer considered important. For example, if ozone column levels have not risen to the background case levels, but are higher than in 1950, is ozone depletion still a concern? If such a level does exist, policy discussions may need to include the impact of future emissions of CO₂ and CH₄ on ozone. Because of the impact of climate policy on these future emissions, this could represent an important linkage between climate and ozone policy. The year 1980 has frequently been used as a reference year; however, it does not mark the onset of global ozone depletion. If impacts are no longer considered after total EESC returns to 1980 levels, a value judgment is made to neglect longer-term O₃ impacts. Choosing this threshold level and ignoring the contribution of N₂O to EESC and ozone depletion in 1980 as has been typically done in the past, further obscures the relevance of a return to 1980 EESC levels.

Figure 3 and the table also show that the capture and destruction of the CFC bank leads to a greater ozone change than the other chlorine- and bromine-containing ODS cases after about 2045, with an integrated ozone impact slightly larger than that of the

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halon bank case from 2011–2100. Even though the importance of these two banks is thought to be similar, for the US, the Environmental Protection Agency estimates that the fraction of halon banks that are technically accessible for capture and destruction (>95%) is much greater than the fraction of the CFC banks (<10%) (Montzka et al., 2008). Accessibility is an important factor in determining the cost of bank capture. We make this point to emphasize that our calculations only indicate the importance of various emission sources to ozone and climate forcing; we make no estimate of the costs or even relative costs of reducing future emissions.

The complete phaseout of anthropogenic N₂O emissions leads to larger ozone and EESC changes than any other case considered from 2020–2025 onward, and its impact on integrated ozone and EESC from 2011–2100 is larger than all other cases combined. The relative importance of a phaseout in N₂O emissions would become even greater beyond 2100 owing to its long lifetime and continued anthropogenic emissions in the baseline scenario. A phaseout of anthropogenic N₂O emissions also has the greatest impact on radiative forcing (Fig. 3, panel c). By the year 2100, an N₂O phaseout would result in a radiative forcing about 0.23 W/m² less than in the baseline scenario. The capture and destruction of the entire CFC bank would lead to a reduction of about 0.005 W/m², and each of the other options would reduce radiative forcing by less than 0.001 W/m² in 2100. In the shorter term, the HCFC bank and production cases lead to a rate of change in the radiative forcing that is comparable to the N₂O case for about the next 5 and 10 years, respectively. Although an N₂O phaseout currently leads to the largest ozone and radiative forcing impacts of the cases considered, the Montreal Protocol has already resulted in large reductions in emission of chlorine- and bromine-containing compounds. The associated reduction in direct radiative forcing due to the Protocol has been estimated to be 0.20–0.25 W/m² by 2010 compared to a case assuming unregulated growth (Velders et al., 2007). However, some of this benefit could be negated by future increases in hydrofluorocarbons (HFCs) used as replacements of CFCs and HCFCs (Velders et al., 2009).

In past ozone assessments, policy options have been compared using integrated

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EESC, similar to what is shown in Table 1, between either 1980 or the current time and the return of EESC to 1980 levels. It has been assumed that the integrated EESC decrease is proportional to the integrated ozone increase. The results in Table 1, integrated from 2011–2050, are used to evaluate the validity of this assumption in Fig. 4. The individual points, representing fractional EESC changes and fractional ozone changes, are not expected to fall exactly on a line because of known simplifications associated with the EESC formula and values for η , α , and f_i in Eq. (1) that are not perfectly accounted for in models. As seen in Fig. 2, uncertainties in dynamics and resulting transport times can also play a role in the ability of EESC to accurately represent ozone depletion. Two of the largest differences in integrated ozone changes between the two models are for the CH_3Br and halon cases as evident in Fig. 4. The lower impact on ozone depletion in the NOCAR model suggests that the representative α value is somewhat lower than 60 for that model. Daniel et al. (1999) calculated a value of 45 but revised kinetics rates since that study have acted to raise this value some (WMO, 2007). Nevertheless, in spite of all the potential causes of an imperfect relationship between EESC and ozone change, the compact correlation shown in Fig. 4 demonstrates that the relative integrated ozone responses of the cases is represented quite well by the integrated EESC metric.

The information from Table 1 is shown graphically in Fig. 5. The only difference is that the EESC change has been scaled by the slope of the line in the Figure 4 fit to the GSFC results. If EESC were a perfect metric for evaluating ozone depletion in the models shown and all the constants used in Eq. (1) were perfectly accurate, each ozone bar would be expected to be the same size as each EESC bar. The similar sizes of the same-colored bars in Fig. 5 follow directly from Figs. 3 and 4 and demonstrate the degree to which EESC is a good metric for O_3 . The similar sizes of the ozone response bars for the two models demonstrate their good agreement. The ozone bars are slightly smaller, on average, than the EESC bars in the lower panel. However, the relative sizes of the ozone bars are still in good agreement with the relative sizes of the EESC bars, evidence that EESC is a good metric for varying time periods as well.

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Hypothetical reductions of future ODS emissions from several potentially important sources have been analyzed for their impact on EESC, globally averaged total column ozone, and radiative forcing. The potential exists for accelerating future ozone increases and decreasing radiative forcing from ODSs, but these impacts would be substantially smaller than those already accomplished by the Montreal Protocol.

We have presented an approach for including tropospheric concentrations of N₂O arising from anthropogenic emissions into EESC. We have also demonstrated that integrated EESC is an effective proxy for integrated ozone changes for all emission reduction cases considered here, including N₂O cases. Consistent with Ravishankara et al. (2009), we have shown that a complete phaseout of anthropogenic N₂O emissions will have a larger impact on stratospheric ozone recovery than a combined phaseout of all other anthropogenic ODSs if one compares the integrated effect to 2100 and neglects potential future growth in ODS feedstock uses and byproduct emissions. N₂O emission reductions have a relatively larger effect over longer integration times when compared with other ODS reductions because of its long lifetime and projected continuing emissions throughout this century and beyond. This dependence on the time period considered raises the question of the level of concern devoted to ozone depletion if global ozone increases above the natural level in the coming decades, but depletion at some latitudes and altitudes still occurs.

Continuing anthropogenic N₂O emissions assumed in the IPCC A1B scenario also play a larger role in future radiative forcing from about 2030 onward than the combined sources of all the other ODS emissions examined here. An elimination of N₂O emissions beginning in 2011 would reduce radiative forcing in 2100 by 0.23 W/m², while the next most important ODS emission reduction considered, the capture and destruction of the entire CFC bank, would lead to a reduction in radiative forcing of about 0.005 W/m² in 2100. In the short term, the capture and destruction of the HCFC bank in 2010 and the elimination of HCFC production from 2011 onward would lead to a rate

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of change in the radiative forcing comparable to that of the N₂O emission elimination over the next 5 and 10 years, respectively.

In considering future ODS production or emission regulations, additional factors to those emphasized here will likely play a role as well, including for example, the economic cost of various regulations and the potential political tradeoffs of restricting some gases under the Montreal Protocol rather than under a climate agreement.

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Table 1. ODS reduction cases considered and their impact on EESC and globally averaged total column ozone relative to the baseline case. The “Bank” cases assume the entire bank present in 2011 is captured and destroyed, but future production continues as in the baseline case. “Production” cases assume no future production of the compound beginning in 2011, but emissions from existing banks continue. The “N₂O Emission” scenario assumes no additional anthropogenic N₂O emission from 2011 onward. The “Total Emission Reduction” column contains the cumulative emission reduction from 2011–2050 compared to the baseline case. The integrated EESC and O₃ change columns contain values for the reduction in these quantities relative to the baseline scenario. These reductions are shown for the periods 2011–2050 and 2011–2100. The EESC percent changes are generally smaller than what has appeared in past ozone assessments partly because here the change is calculated relative to the entire anthropogenic EESC; in the assessments, it has been calculated relative to EESC in excess of 1980 EESC levels. If compared to EESC in excess of 1980 levels, 2011–2050 percentages should be increased by a factor of 3.4.

Case	Total Emission Reduction (Tg) 2011–2050	Integrated EESC Change Relative to Baseline Scenario (%)		Integrated O ₃ Change Relative to Baseline Scenario (%)	
		2011–2050	2011–2100	2011–2050	2011–2100
N ₂ O Emission (anthropogenic)	455 ¹	–6.1	–16.2	0.35	0.79
CFC Bank	1.32	–2.5	–3.0	0.13	0.14
HCFC Bank	3.44	–1.1	–0.7	0.07	0.03
HCFC Production	9.45	–2.2	–1.6	0.15	0.09
Halon Bank	0.09	–2.6	–2.5	0.14	0.12
CH ₃ Br Production ² (anthropogenic)	0.49	–1.5	–2.0	0.09	0.09
CCl ₄ Production	0.80	–1.9	–1.8	0.09	0.07
All Cl- and Br-Containing ODSs (anthr.)		–12.6	–13.4	0.66	0.56

¹ Determined directly from anthropogenic emissions provided for SRES A1B scenario. Value given in TgN₂O.

² CH₃Br emissions arising from gasoline, biomass, and biofuel burning are assumed to continue in the future at 2007 levels (Yvon-Lewis et al., 2009) in all scenarios except in the background scenario, in which these emissions are never included. If these emissions sources were eliminated, the values for the CH₃Br case in the table would be almost 3 times larger.

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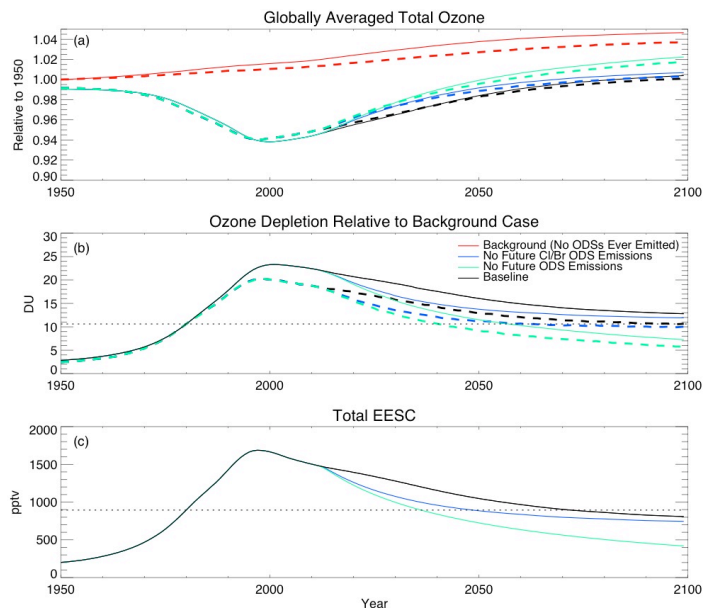


Fig. 1. (a) Globally averaged total column ozone, (b) ozone depletion relative to a case in which no ODSs were or will be emitted (“background” case), and (c) EESC time series. Cases shown are the baseline scenario (black), in which future ODS emissions follow a path consistent with current growth and Montreal Protocol regulations and IPCC scenario A1B for N_2O , CH_4 , and CO_2 , a case in which no anthropogenic chlorine- or bromine-containing ODSs are emitted after 2010 (dark blue), and a case in which no ODSs are emitted (including anthropogenic N_2O) after 2010 (light blue). The ozone time series for the background case is also shown (red). Solid lines are calculations from the GSFC model; dashed are for the NOCAR model. The ozone depletion from the NOCAR model (panel a) is increased by 3% so the 1980 levels of ozone depletion are equal. The dotted lines represent the 1980 benchmark levels that are used in previous ozone assessments and are also often considered in Montreal Protocol discussions.

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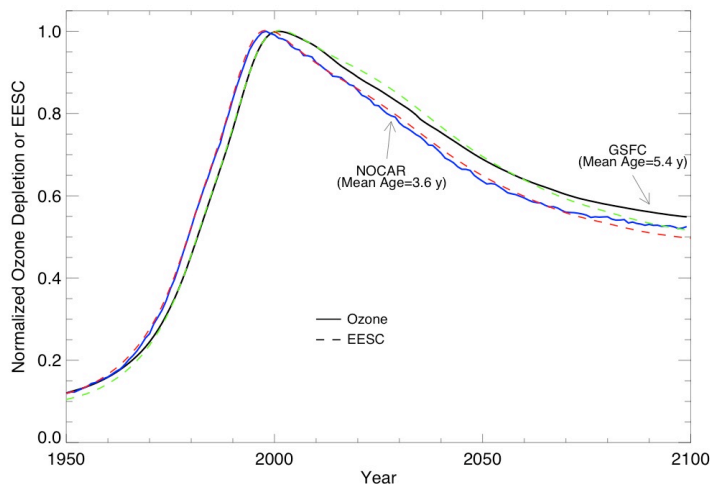


Fig. 2. Comparison of normalized ozone depletion from NOCAR (blue) and GSFC (black) models with EESC (dashed). Ozone depletion from the two models is normalized to the maximum depletion, and EESC is normalized to its peak value. Age spectra used in the EESC calculation were determined by fitting to the ozone time series using a least squares approach. Mean ages derived for the EESC fits are shown. Age spectrum widths were found to be 2.5 years for each model. The older characteristic age for total ozone from the GSFC model compared to the NOCAR model is apparent.

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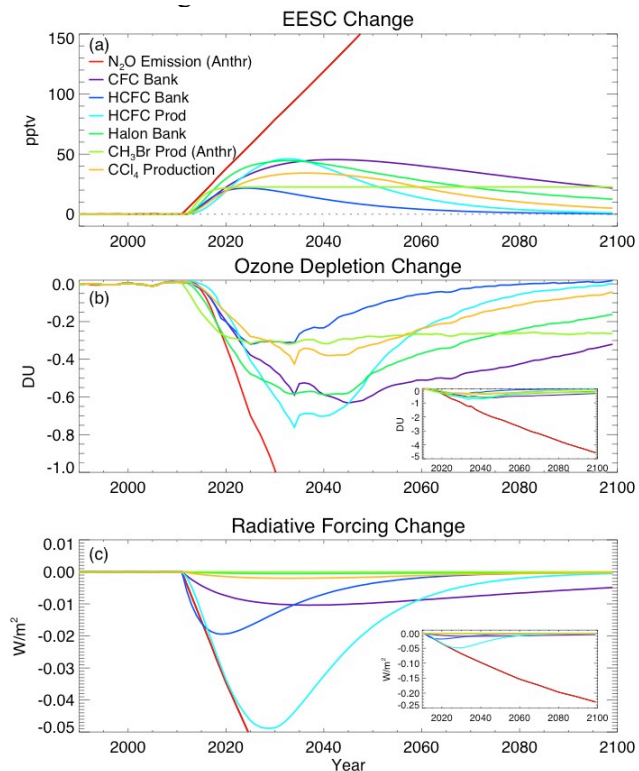


Fig. 3. Changes in **(a)** EESC, **(b)** ozone depletion, and **(c)** radiative forcing resulting from the various ODS reduction cases in Table 1. The responses for the N₂O case (red) appear almost linear in main panels because of its long lifetime and because future anthropogenic N₂O emissions vary little through 2100 in the assumed A1B scenario. The insets in panels (b) and (c) have increased vertical scale ranges so the entire N₂O change in visible through 2100.

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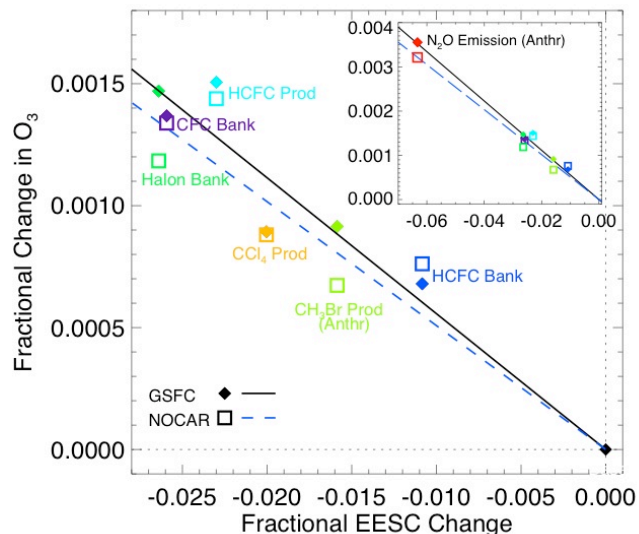


Fig. 4. Correlation of integrated EESC with integrated globally averaged total column ozone over the period 2011–2050. Ozone values are calculated by the GSFC (filled diamonds) and NOCAR (squares) models. The linear fits of the cases shown are also included (solid for GSFC; dashed for NOCAR). These fits are forced to go through the origin and do not include the N_2O case (red symbols) in their calculation. The NOCAR slope (dashed blue) is smaller than the GSFC slope (solid black) primarily due to a smaller ozone change in the NOCAR bromine cases (green squares) than would be expected with an α of 60. The inset shows the same information as the main figure with the scales expanded so the N_2O emission phaseout (red symbols) is visible.

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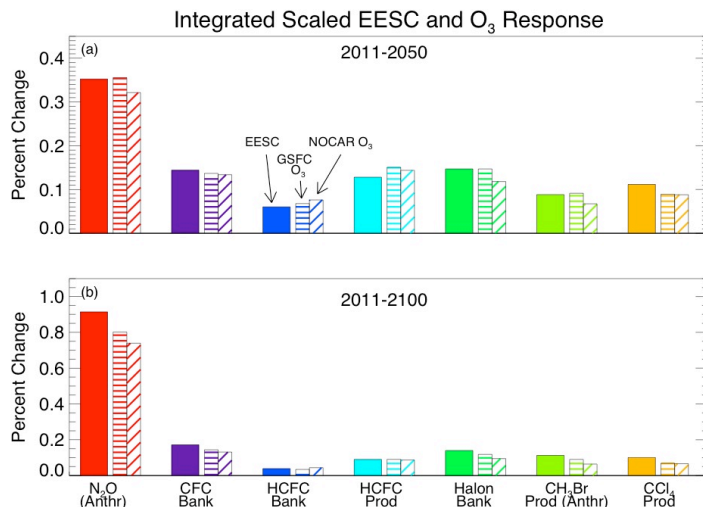


Fig. 5. Impact of the 7 hypothetical emissions reductions shown in Table 1 on integrated EESC (solid bars) and global total column O₃ from GSFC (horizontal hatching) and NOCAR models (angled hatching). Integration periods of **(a)** 2011–2050 and **(b)** 2011–2100 are shown. The extent to which ozone bars of the same color (in the same panel) are the same height as the EESC bars quantifies the success of the EESC parameterization in describing the integrated ozone response. The EESC changes are scaled by the slope of the linear fit to the GSFC calculations (solid black line) shown in Fig. 3.

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