

Options to Accelerate Ozone Recovery: Ozone and Climate Benefits

J. S. Daniel, E. L. Fleming, R. W. Portmann, G. J. M. Velders, C. H. Jackman, and A. R. Ravishankara

Brief, Popular Summary of the Paper:

The humankind or anthropogenic influence on ozone primarily originated from the chlorofluorocarbons and halons (chlorine and bromine). Representatives from governments have met periodically over the years to establish international regulations starting with the Montreal Protocol in 1987, which greatly limited the release of these ozone-depleting substances (ODSs). Two global models have been used to investigate the impact of hypothetical reductions in future emissions of ODSs on total column ozone. The investigations primarily focused on chlorine- and bromine-containing gases, but some computations also included nitrous oxide (N₂O). The Montreal Protocol with ODS controls have been so successful that further regulations of chlorine- and bromine-containing gases could 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. Chlorine- and bromine-containing gases and nitrous oxide are also greenhouse gases and lead to warming of the troposphere. Elimination of N₂O emissions would result in a reduction of radiative forcing of 0.23 W/m² in 2100 than presently computed and destruction of the CFC bank would produce a reduction in radiative forcing of 0.005 W/m² in 2100. This paper provides a quantitative way to consider future regulations of the CFC bank and N₂O emissions.

1 **Options to Accelerate Ozone Recovery: Ozone and Climate Benefits**

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4 J.S. Daniel¹, E.L. Fleming^{2,3}, R.W. Portmann¹, G.J.M. Velders⁴, C.H. Jackman², and A.R.
5 Ravishankara¹

6
7 ¹National Oceanic and Atmospheric Administration, Earth System Research Laboratory,
8 Chemical Sciences Division, Boulder, CO 80305 USA

9 ²NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771 USA

10 ³Science Systems and Applications, Inc., Lanham, MD 20706 USA

11 ⁴Netherlands Environmental Assessment Agency, NL-3720 AH Bilthoven, Netherlands

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13 Corresponding author: J.S. Daniel (john.s.daniel@noaa.gov)
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16 **Abstract**

17
18 Hypothetical reductions in future emissions of ozone-depleting substances
19 (ODSs), including N₂O, are evaluated in terms of effects on radiative forcing, equivalent
20 effective stratospheric chlorine (EESC), and globally-averaged total column ozone
21 through 2100. Due to the established success of the Montreal Protocol, these actions can
22 have only a fraction of the impact that regulations already in force have had. If all
23 anthropogenic ODS emissions were halted beginning in 2011, ozone is calculated to be
24 higher by about 1-2% during the period 2030-2100 compared to a case of no additional
25 ODS restrictions. Radiative forcing by 2100 would be about 0.23 W/m² lower due to the
26 elimination of N₂O emissions and about 0.005 W/m² lower due to destruction of the CFC
27 bank. The ability of EESC to be a suitable metric for total ozone is also quantified.
28 Responding to the recent suggestion that N₂O should be considered an ODS, we provide
29 an approach to incorporate N₂O into the EESC formulation.

30
31 **1. Introduction**

32
33 The Montreal Protocol on Substances that Deplete the Ozone Layer and its
34 amendments and adjustments have been successful in halting the increasing trend in
35 stratospheric ozone depletion (WMO, 2007); these actions have also reduced climate
36 forcing over the last 2 decades (Velders et al., 2007), and have thus presumably reduced
37 the rate of climate change over this period compared to what would have otherwise
38 occurred. The production and consumption of many of the most important chlorine- and
39 bromine-containing ozone-depleting substances (ODSs) are already phased out. Most of
40 the others are controlled, with schedules in place to phase out their production and
41 consumption in the next few decades.

42 However, the Protocol does not limit some types of ODS production and
43 consumption and does not directly regulate ODS emissions at all. Several activities
44 involving ODSs are thus expected to continue to lead to atmospheric emissions.
45 Restricting these sources represents an opportunity to accelerate ozone recovery. For
46 example, because the Montreal Protocol regulates production and consumption rather
47 than emissions, it does not limit the release of ODSs already produced and currently

48 residing in existing equipment or applications, such as firefighting equipment, air
49 conditioners, refrigerators, and foams. Production of HCFCs and CH₃Br also continues.
50 Production of HCFCs is to be virtually phased out globally by 2030 with stepwise
51 reductions in place in the intervening time under the current Protocol. CH₃Br use for
52 quarantine and preshipment purposes is unrestricted and critical use exemptions have
53 been granted every year since 2005. Production of CCl₄ for non-feedstock use has been
54 globally phased out since the beginning of 2010. However, emissions resulting from its
55 use as a feedstock, i.e. to produce another chemical, are unregulated, and it is also
56 coproduced with chloroform production and can be coproduced with perchloroethylene
57 production (add Sherry reference). These sources could explain why global emissions
58 implied by atmospheric observations have been significantly higher than what has been
59 suggested by reported production. Whatever the reason for the higher concentrations
60 than expected, the uncertainty implies that future trends are also uncertain and that
61 emissions may continue.

62 Recently, it has been suggested that N₂O could be considered to be an ODS
63 (Ravishankara et al., 2009). While it has been known for over 2 decades that N₂O leads
64 to stratospheric NO_x production, which in turn leads to ozone destruction, N₂O has not
65 been regulated by the Montreal Protocol. Ravishankara et al. (2009) quantified the global
66 ozone depletion potential (ODP) of N₂O and compared the ODP-weighted emissions of
67 N₂O with those of other ODSs. Such a comparison demonstrates that N₂O is an
68 important gas for ozone depletion. N₂O is also a recognized greenhouse gas that was
69 included in the basket of gases regulated under the Kyoto Protocol. Nevertheless,
70 projections suggest that N₂O emissions will remain significant through 2100 even under
71 strongly mitigated climate stabilization scenarios (Clarke et al., 2007).

72 Equivalent effective stratospheric chlorine (EESC) (Daniel et al., 1995) has been
73 the tool frequently used to quantify the relative effectiveness of various policy options for
74 reducing ozone depletion (e.g., (WMO, 1995, 1999, 2003, 2007)). It has been assumed,
75 (but not explicitly quantified) that the integrated EESC changes from some policy action
76 are related to the integrated ozone depletion over the same time period. The EESC
77 approach has been used partly because of the significant computer resources required to
78 evaluate all available options directly using ozone calculated from 2-D or 3-D models.

79 As computer speeds have increased, it has become feasible to perform these calculations
80 with 2-D models.

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

91

92 **2. Analysis**

93

94 Two reference scenarios are used to evaluate the various emissions reductions.
95 One, which we will refer to as the “background” case includes no anthropogenic ODS
96 emissions (including N₂O) in the past or future; it does include observed CO₂ and CH₄
97 abundances through the present with future values prescribed by the IPCC SRES A1B
98 scenario (Nakicenovic et al., 2000). This provides a time series of ozone unaffected by
99 anthropogenic ODS emissions. The second, “baseline” case includes the same CO₂ and
100 CH₄ evolution as in the background case but also includes anthropogenic ODSs
101 (including N₂O). Past ODS concentrations are determined from observations (WMO,
102 2007). Future concentrations are consistent with the current Montreal Protocol
103 production and consumption limits. They are similar to those in case A1 of WMO (2007)
104 except that they have been updated for more recent atmospheric observations (S.
105 Montzka, personal communication) and/or bank estimates (TEAP, 2009). A few
106 additional changes relative to WMO (2007) include: (1) a reduction in future production
107 of HCFCs to include the faster phaseout approved by the Parties to the Protocol in 2007;
108 (2) a projected slower future decline in CCl₄ production and emissions (5%/yr) to obtain
109 better consistency with the decline in emissions over the last 4 years inferred from global

110 observations; (3) holding use of CH₃Br fixed at a level equal to the 2009 critical use
111 exemptions granted by the Parties to the Protocol; and (4) including N₂O as an ODS with
112 future concentrations taken from IPCC SRES A1B. All cases are run through 2100. This
113 end date is picked partly for the practical reason that scenario A1B and the chlorine- and
114 bromine-containing ODS scenario, A1, are only projected through 2100. We also
115 recognize that it becomes difficult to project market demand and emissions far into the
116 future, particularly for compounds like N₂O that are not currently individually regulated.

117 We consider seven hypothetical options for reducing future ODS emissions. Some
118 cases involve capture and destruction of the 2011 bank (quantities residing in existing
119 equipment), while others include a cessation of future production from 2011 onward. For
120 N₂O, elimination of all anthropogenic emissions beginning in 2011 is considered; this is
121 accomplished by having the mixing ratio enhancement above the natural background in
122 2011 decay with a global lifetime of 114 years (WMO, 2007) back to the background
123 level of 275 ppb (Denman et al., 2007). Complete elimination of these contributions to
124 future emissions is a straightforward way to demonstrate their impact on ozone and
125 climate forcing. However, the feasibility and cost of reducing ODSs varies with
126 compound and application. The effect of smaller reductions can be obtained by simple
127 scaling to the results presented here and can be used because the changes are roughly
128 linear with the magnitude of the phaseout as long as the reduction begins around 2011.
129 The specific cases considered and the integrated amounts of ODS emission reduced from
130 2011-2050 relative to the baseline case are shown in Table 1, along with the impacts on
131 EESC and ozone. The impacts will be discussed in Section 3. Feedstock use, as well as
132 by-product emissions of CCl₄, are not controlled by the Montreal Protocol; emissions
133 resulting from these uses may grow and become increasingly important to future ozone
134 depletion and climate; nevertheless, we will not consider any such growth because of the
135 large uncertainty in their current and future magnitudes.

136 EESC is calculated assuming a 3-year mean age and an age spectrum width of 1.5
137 years (Waugh and Hall, 2002) to represent the mean transport time between the
138 troposphere and stratosphere. Relative fractional release values for 3-year-old air from
139 Newman et al. (2007) are assumed for all compounds except for HCFC-141b and -142b,
140 which were characterized by high uncertainty in that analysis. The relative values for

141 these compounds are taken from WMO (2007) and originated from Solomon et al.
142 (1992). There has been discussion of a threshold in EESC below which changes in EESC
143 have little or no impact on O₃ (e.g., (Daniel et al., 1995)). Because globally averaged total
144 column ozone loss continues below this level, no threshold is considered here.

145 Ozone is calculated using the GSFC (Fleming et al., 2007; Newman et al., 2009)
146 and the NOCAR interactive 2-D models (Solomon et al., 1998; Portmann et al., 1999)
147 using 2006 JPL rates (Sander et al., 2006). Both models successfully capture the
148 processes important for calculating globally averaged total ozone. The agreement
149 between models both in ozone depletion and the response of that depletion to ODS
150 emission reductions gives us confidence in the results. Recent 3-D modeling studies have
151 shown the importance of climate change on future stratospheric projections (Eyring et al.,
152 2007). To account for this, the GSFC model parameterizes the long-term changes in
153 surface temperature, latent heating, and tropospheric H₂O based on 3-D simulations from
154 the Goddard Earth Observing System chemistry-climate model (GEOSCCM) (Pawson et
155 al., 2008). The resulting 2-D simulation of the Brewer-Dobson circulation acceleration
156 and decrease in stratospheric age-of-air over 1950-2100 is similar to that of the
157 GEOSCCM. The GSFC 2-D model is also in good agreement with the GEOSCCM in
158 simulating ozone and temperature changes over the 1950-2100 time period.

159 N₂O has never been included in EESC calculations, perhaps because it has not
160 historically been considered an ODS. There are important complications to including it
161 because it participates in ozone destruction through the NO_x cycle rather than the ClO_x or
162 BrO_x cycles. For example, increasing NO_x reduces the efficiency of Cl_y and Br_y for
163 ozone destruction by tying up more of these halogens in ClONO₂ and BrONO₂ reservoir
164 species. At elevated chlorine and bromine levels, this offsets some of the impact of an
165 increase in N₂O on ozone depletion. Decreasing Cl_y similarly ties up less NO_y in
166 ClONO₂, increasing the efficiency of N₂O. These interactions imply that the projected
167 future decline in Cl_y and Br_y abundances resulting from the success of the Montreal
168 Protocol should lead to a greater impact of a unit change in N₂O emissions on ozone
169 (Ravishankara et al., 2009). On the other hand since the loss of stratospheric NO_x is
170 inversely related to temperature, the efficiency of N₂O on global ozone depletion is
171 expected to decrease as the upper stratosphere cools from the projected increases in CO₂

172 (Rosenfield and Douglass, 1998). From the 2-D models considered here, we estimate
 173 that by 2100 this process will result in a decrease of 10-20% in the effectiveness of a unit
 174 N₂O emission to lead to ozone depletion compared to today. The effect of all of these
 175 interactions will potentially lead to a non-unique relationship between EESC and ozone
 176 depletion. Nevertheless, we will suggest an approach for including N₂O in EESC and
 177 then quantify its success as a metric for integrated ozone depletion under plausible
 178 perturbations. Future deviations of CO₂ and EESC from the scenarios used here will alter
 179 the interactions shown; however, the deviations are not expected to be significant enough
 180 to substantively change the results.

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

$$\begin{aligned}
 EESC(t) = f_{CFC-11} \times & \\
 \left[\sum_{\substack{Cl- \\ \text{containing} \\ \text{compounds}}} n_i \frac{f_i}{f_{CFC-11}} (\rho_{i,entry} - \rho_{i(nat),entry}) + \alpha \sum_{\substack{Br- \\ \text{containing} \\ \text{compounds}}} n_i \frac{f_i}{f_{CFC-11}} (\rho_{i,entry} - \rho_{i(nat),entry}) \right] & \\
 + \xi \eta n_{N_2O} \frac{f_{N_2O}}{f_{CFC-11}} (\rho_{N_2O,entry} - \rho_{N_2O(nat),entry}) & \quad (1)
 \end{aligned}$$

186 where α is the relative efficiency of bromine compared with chlorine for destroying total
 187 ozone, η is the same factor for nitrogen relative to chlorine, n_i is the number of Cl, Br, or
 188 N atoms contained in the ODS, f_i is the fraction of the compound dissociated on average
 189 in the stratosphere (assumed here to be at the 3-yr-old age-of-air location), and ρ_i is the
 190 tropospheric mixing ratio due to anthropogenic emissions. The age spectrum is
 191 accounted for in the calculation of ρ . In equation (1) we do not consider concentrations
 192 arising from natural emissions. We subtract the entry mixing ratio of N₂O, CH₃Br, and
 193 CH₃Cl arising from natural emissions, so that we only consider the mixing ratios from
 194 anthropogenic emissions. We do include the small increase in CH₃Cl mixing ratios from
 195 WMO (2007)

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

197
$$ODP_i = \eta \frac{n_i}{n_{CFC-11}} \frac{f_i}{f_{CFC-11}} \frac{\tau_i}{\tau_{CFC-11}} \frac{M_{CFC-11}}{M_i}$$
 (2)

198 it follows that

199
$$\eta n_{N_2O} \frac{f_{N_2O}}{f_{CFC-11}} = ODP_{N_2O} n_{CFC-11} \frac{\tau_{CFC-11}}{\tau_{N_2O}} \frac{M_{N_2O}}{M_{CFC-11}} = 6.4 \times 10^{-3}$$
 (3)

200 Levels of ClO_x and BrO_x were shown to significantly affect the N₂O ODP in
 201 Ravishankara et al. (2009); at 1959 levels, the ODP was calculated to be 0.026 rather than
 202 the 0.017 at 2000 conditions. We will account for this dependence by applying a
 203 correction factor to (3). This factor, ξ , is assumed to be a linear function of the part of
 204 EESC arising from chlorine and bromine source gases so that the 1959 EESC level from
 205 these gases leads to a value for ξ of 1.53 (0.026/0.017) while 2000 levels of EESC lead to
 206 a value of 1.0. The 1959 and 2000 levels of EESC for the baseline scenario are 270 and
 207 1665 ppt, respectively. This factor, along with (3), is then used in equation (1) to
 208 calculate N₂O's contribution to EESC. The EESC/ozone depletion relationship of the
 209 N₂O scenarios presented in Section 3 are more consistent with the other scenarios when ξ
 210 is included in (1) in this way.

211 When calculating ξ using the 1959 and 2000 ODPs, in addition to the EESC
 212 dependence, there is some effect from the change in stratospheric temperature in the
 213 NO_y/N₂O ratio owing to the higher levels of CO₂ by 2000. This temperature effect is
 214 expected to scale differently with EESC in the future because EESC is projected to
 215 decrease while CO₂ continues to increase in the A1B scenario; thus, it is expected that
 216 these interactions should lead to some additional error in the correlation between EESC
 217 from N₂O and the associated ozone depletion. However, this error is smaller than the
 218 benefit gained from including the EESC dependence.

219

220 **3. Results and Discussion**

221

222 Figure 1 illustrates the maximum extent to which ODS emission phaseouts can
 223 accelerate the recovery of ozone and EESC towards a state defined by the emissions of
 224 no ODSs at any time. A key result of this study is the even with full and immediate
 225 phaseouts of all ODS emissions, the recovery to the background case will not have

226 occurred by 2100 because of the long residence times of many of the ODSs. Such a
227 phaseout would lead to ozone levels that exceed ozone in the baseline case by 1.2-1.9%
228 between 2030-2100. Chlorine and bromine emission reductions could affect O₃ relatively
229 quickly, with N₂O playing a larger role by 2100. To put this into perspective, these
230 models calculate a peak ozone depletion near 2000 of 7-8% relative to the background
231 case and a depletion of about 2% by 2100. This peak depletion is substantially larger
232 than the 3.5% quoted in *WMO* (2007) because we are comparing to the higher O₃ level
233 calculated for the background case, which includes increases in CO₂ and CH₄ (and no
234 ODSs), rather than the 1965-1980 observed ozone level used in *WMO* (2007). It has
235 been estimated that in the absence of the Montreal Protocol and assuming continued
236 growth of ODSs, globally-average total ozone depletion could have reached 17% by 2020
237 and 67% by 2065 when compared to 1980 levels (Newman et al., 2009). So while
238 options still exist to reduce future ozone depletion, the potential benefits of policy options
239 are substantially reduced compared to what the Montreal Protocol has already achieved.

240 Figure 1 (panel a) also shows the extent to which increases in CO₂ and CH₄ from
241 the A1B scenario leads to higher calculated column ozone in these two models. Total
242 ozone's return to 1980 levels is known to depend strongly on the future evolution of CO₂
243 and likely on CH₄ (Portmann and Solomon, 2007; Chipperfield and Feng,
244 2003; Rosenfield et al., 2002; Randeniya et al., 2002). However, we do not consider CO₂
245 or CH₄ regulations to be policy options for reducing ozone depletion because it is
246 believed that they have negative ODPs and their emissions would need to be increased to
247 reduce ozone depletion. Such increases would lead to climate warming, and hence are
248 considered undesirable options.

249 One metric used in ozone assessments is the year in which EESC drops below the
250 1980 level. Figure 1 shows that this time associated with EESC does not perfectly
251 indicate when total ozone depletion due to ODSs returns to 1980 levels and that the
252 relationship is model dependent. For the 2-D models used here, the evolution of future
253 total ozone depletion due to ODSs is explained well by EESC, but EESC as calculated
254 with a mean age of 3.6 years (NOCAR) and 5.4 years (GSFC), rather than the 3 years
255 typically assumed for midlatitude EESC calculations. The high correlation between
256 normalized EESC using these ages and ozone depletion is shown in Figure 2. The older

257 ages suggest that while EESC for 3-year-old air remains an acceptable and useful metric,
258 it may not perfectly describe the evolution of globally averaged total column ozone or the
259 time when ozone depletion will pass some target level. It is also important to recognize
260 that the return of global total ozone to some approximately natural level does not imply
261 that the ozone profile, the latitudinal variations, or the radiative forcing associated with
262 the stratospheric ozone distribution will be the same as it was in the unperturbed state
263 (WMO, 2007).

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

276 This N₂O response represents a fundamentally different behavior compared with
277 the other ODSs. Because of the long lifetime of N₂O and because there is no current
278 regulation that phases out its future emissions, its impact on ozone continues to grow
279 over the time period shown and is largely determined by the length of the integration
280 time. Thus, picking a longer time period will generally lead to a greater relative
281 importance of N₂O emissions reductions compared to reductions of other ODSs. To
282 illustrate the importance of the integration time considered, the integrated impacts in
283 terms of EESC and ozone are shown for two time periods in Table 1. The larger relative
284 impact of the N₂O reduction over the longer period is clear. Of course, there is no
285 scientific reason to stop the integration at 2100 either since ozone depletion will still be
286 occurring relative to a background case. When dealing with a compound like N₂O whose
287 emissions are not limited in the future, but are expected to continue indefinitely, the

288 difficulties in choosing an integration time for evaluating policy options are similar to
289 those encountered when evaluating the relative impacts of greenhouse gases on radiative
290 forcing and climate. An important distinction is that, unlike with climate change, it is
291 likely that we could return to natural globally averaged total column ozone levels in the
292 next few decades.

293 An important related question is whether there is a level of global column ozone
294 above which anthropogenic ozone depletion is no longer considered important. For
295 example, if ozone column levels have not risen to the background case levels, but are
296 higher than in 1950, is ozone depletion still a concern? If such a level does exist, policy
297 discussions may need to include the impact of future emissions of CO₂ and CH₄ on
298 ozone. Because of the impact of climate policy on these future emissions, this could
299 represent an important linkage between climate and ozone policy. The year 1980 has
300 frequently been used as a reference year; however, it does not mark the onset of global
301 ozone depletion. If impacts are no longer considered after total EESC returns to 1980
302 levels, a value judgment is made to neglect longer-term O₃ impacts. Choosing this
303 threshold level and ignoring the contribution of N₂O to EESC and ozone depletion in
304 1980 as has been typically done in the past, further obscures the relevance of recovery to
305 1980 EESC levels.

306 Figure 3 and the table also show that the capture and destruction of the CFC bank
307 leads to a greater ozone change than the other chlorine- and bromine-containing ODS
308 cases after about 2045, with an integrated ozone impact slightly larger than that of the
309 halon bank case from 2011-2100. Even though the importance of these two banks is
310 thought to be similar, for the U.S. the Environmental Protection Agency estimates that
311 the fraction of halon banks that are technically accessible for capture and destruction
312 (>95%) is much greater than the fraction of the CFC banks (<10%) (Montzka et al.,
313 2008). Accessibility is an important factor in determining the cost of bank capture. We
314 make this point to emphasize that our calculations only indicate the importance of various
315 emission sources to ozone and climate forcing; we make no estimate of the costs or even
316 relative costs of reducing future emissions.

317 The complete phaseout of anthropogenic N₂O emissions leads to larger ozone and
318 EESC changes than any other case considered from 2020-2025 onward, and its impact on

319 integrated ozone and EESC from 2011-2100 is larger than all other cases combined. A
320 phaseout of anthropogenic N₂O emissions also has the greatest impact on radiative
321 forcing (Figure 3, panel c). By the year 2100, an N₂O phaseout would result in a
322 radiative forcing about 0.23 W/m² less than in the baseline scenario. The capture and
323 destruction of the entire CFC bank would lead to a reduction of about 0.005 W/m², and
324 each of the other options would reduce radiative forcing by less than 0.001 W/m² in
325 2100. In the shorter term, the HCFC bank and production cases lead to a rate of change
326 in the radiative forcing that is comparable to the N₂O case for about the next 5 and 10
327 years, respectively. Although an N₂O phaseout currently leads to the largest ozone and
328 radiative forcing impacts of the cases considered, the Montreal Protocol has already
329 resulted in large reductions in emission of chlorine- and bromine-containing compounds.
330 The associated reduction in direct radiative forcing due to the protocol has been estimated
331 to be 0.20-0.25 W/m² by 2010 compared to a case assuming unregulated growth (Velders
332 et al., 2007). However, some of this benefit could be negated by future increases in
333 HFCs used as replacements of CFCs and HCFCs (Velders et al., 2009).

334 In past ozone assessments, policy options have been compared using integrated
335 EESC, similar to what is shown in Table 1, between either 1980 or the current time and
336 the return of EESC to 1980 levels. It has been assumed that the integrated EESC change
337 is proportional to the integrated ozone impact. The results in Table 1, integrated from
338 2011-2050, are used to evaluate the validity of this assumption in Figure 4. The
339 individual points, representing fractional EESC changes and fractional ozone changes,
340 are not expected to fall exactly on a line because of known simplifications associated
341 with the EESC formula and values for η , α , and f_i in equation (1) that differ among
342 models and between observations and models. As seen in Figure 2, uncertainties in
343 dynamics and resulting transport times can also play a role in the ability of EESC to
344 accurately represent ozone depletion. Evident in Figure 4, two of the largest differences
345 in integrated ozone changes between the two models are for the CH₃Br and halon cases.
346 The lower impact on ozone depletion in the NOCAR model suggests that the
347 representative α value is somewhat lower than 60 for that model. Daniel et al. (1999)
348 calculated a value of 45 but revised kinetics rates since that study have acted to raise this
349 value some (WMO, 2007). Nevertheless, in spite of all the potential causes of an

350 imperfect relationship between EESC and ozone change, the compact correlation shown
351 in Figure 4 demonstrates that the relative integrated ozone responses of the cases is
352 explained quite well by the integrated EESC metric.

353 The information from Table 1 is shown graphically in Figure 5. The only
354 difference is that the EESC change has been scaled by the slope of the line in Figure 4 fit
355 to the GSFC results. If EESC were a perfect metric for evaluating ozone depletion in the
356 models shown and all the constants used in equation (1) were perfectly accurate, each
357 ozone bar would be expected to be the same size as each EESC bar. The similar sizes of
358 the same-colored bars in Figure 5 follow directly from Figure 3 and demonstrate the
359 degree to which EESC is a good metric for O₃ in a different manner. The similar sizes of
360 the ozone response bars for the two models demonstrate their good agreement. The
361 ozone bars are slightly smaller, on average, than the EESC bars in the lower panel.
362 However, the relative sizes of the ozone bars are still in good agreement with the relative
363 sizes of the EESC bars, evidence that EESC is a good metric for varying time periods as
364 well.

365

366 **4. Conclusions**

367

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

373 We have presented an approach for including tropospheric concentrations of N₂O
374 arising from anthropogenic emissions into EESC. We have also demonstrated that
375 integrated EESC is an effective proxy for integrated ozone changes for all emission
376 reduction cases considered here, including N₂O. Consistent with Ravishankara et al.
377 (2009), we have shown that a complete phaseout of anthropogenic N₂O emissions will
378 have a larger impact on stratospheric ozone recovery than a combined phaseout of all
379 other anthropogenic ODSs if one compares the integrated effect to 2100 and neglects
380 potential future growth in ODS feedstock uses and byproduct emissions. N₂O emission

381 reductions have a relatively larger effect over longer integration times when compared
382 with other ODS reductions because of its long lifetime and projected continuing
383 emissions throughout this century and beyond. This dependence on the time period
384 considered raises the question of the level of concern devoted to ozone depletion if global
385 ozone increases above the natural level in the coming decades, but depletion at some
386 latitudes and altitudes still occurs.

387 Continuing anthropogenic N₂O emissions assumed in the IPCC A1B scenario also
388 play a larger role in future radiative forcing from about 2030 onward than the combined
389 causes of all the other ODS emissions examined here. An elimination of N₂O emissions
390 beginning in 2011 would reduce radiative forcing in 2100 by 0.23 W/m², while the next
391 most important ODS emission reduction considered, the capture and destruction of the
392 entire CFC bank, would lead to a reduction in radiative forcing of about 0.005 W/m².
393 The capture and destruction of the HCFC bank in 2010 and the elimination of HCFC
394 production from 2011 onward would lead to a rate of change in the radiative forcing
395 comparable to that of the N₂O emission elimination over the next 5 and 10 years,
396 respectively.

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

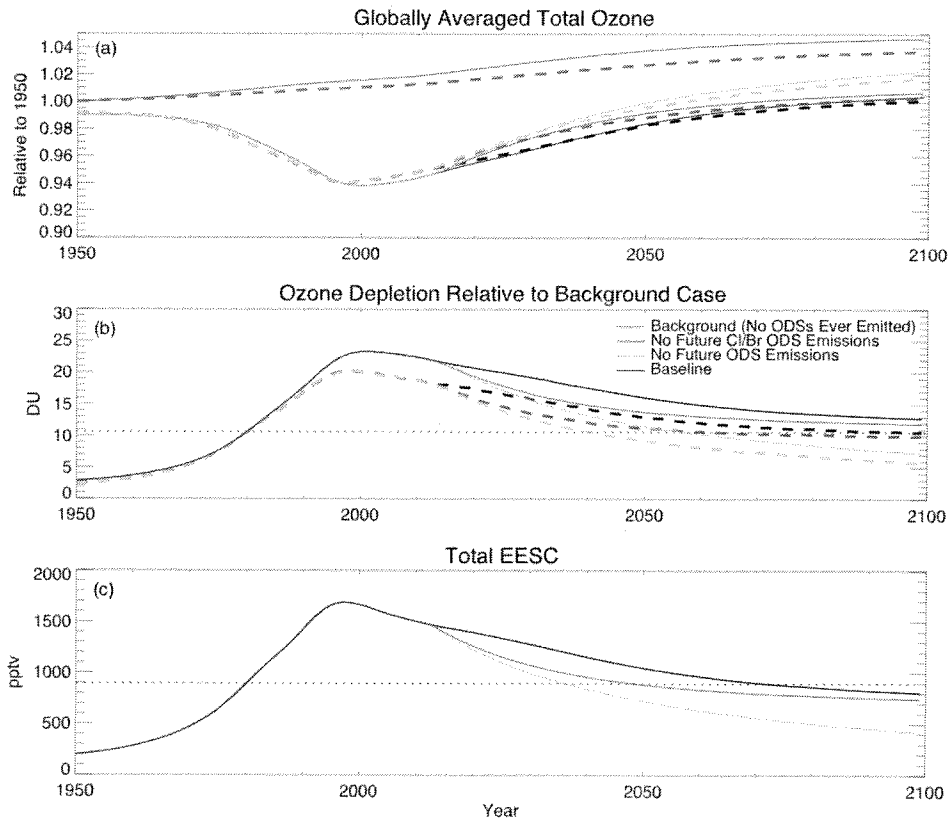
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405 **Figures**

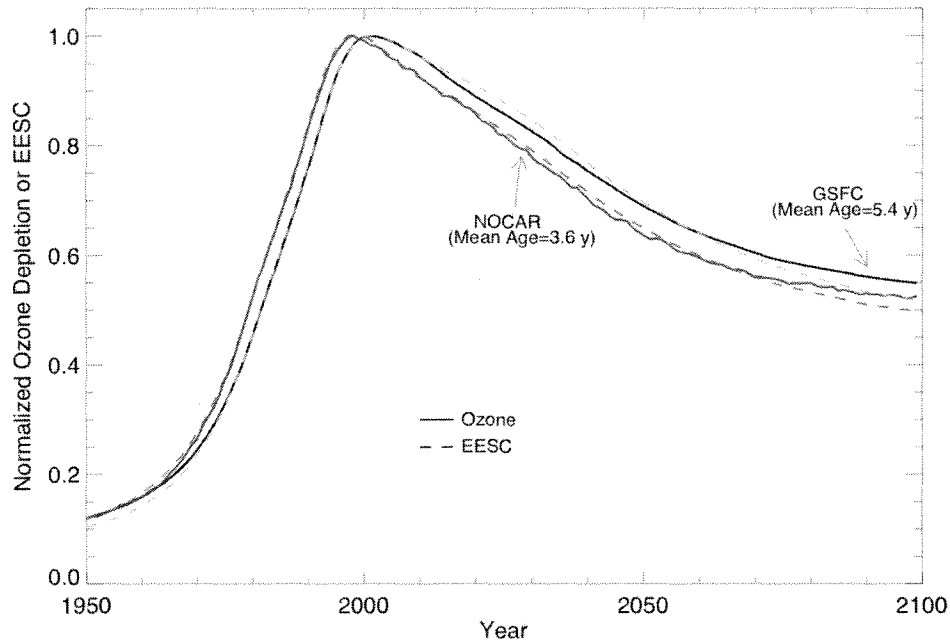
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407 Figure 1. (a) Globally averaged total column ozone, (b) ozone depletion relative to a case
408 in which no ODSs were or will be emitted (“background” case), and (c) EESC time
409 series. Cases shown are the baseline scenario, in which future ODS emissions follow a
410 path consistent with current growth and Montreal Protocol regulations and IPCC scenario
411 A1B for N₂O, CH₄, and CO₂, a case in which no chlorine- or bromine-containing ODSs
412 are emitted after 2010, and a case in which no ODSs are emitted (including
413 anthropogenic N₂O) after 2010. The ozone time series for the background case is also
414 shown. Solid lines are calculations from the GSFC model; dashed are for the NOCAR
415 model. The ozone depletion from the NOCAR model (middle panel) is increased by 3%
416 so the 1980 levels of ozone depletion are equal. The dotted line represents the 1980
417 benchmark levels that are used in previous ozone assessments and are also often used in
418 Montreal Protocol discussions.



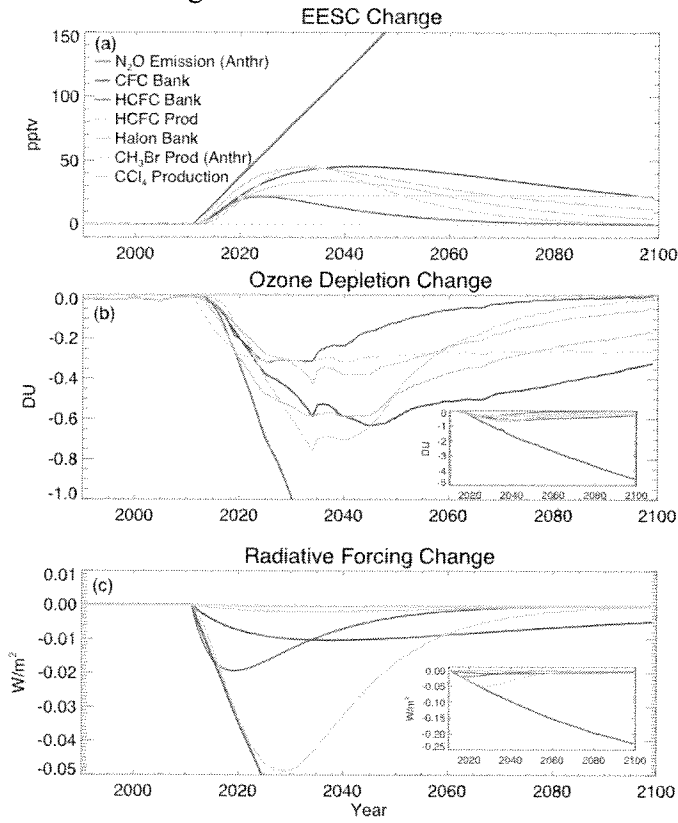
419

420 Figure 2. Comparison of normalized ozone depletion (solid) and EESC (dashed) for
421 NOCAR and GSFC models. Ozone depletion from the two models is normalized to the
422 maximum depletion, and EESC is normalized to its peak value. Age spectra used in the
423 EESC calculation were determined by fitting to the ozone time series using a least
424 squares approach. Mean ages derived for the EESC fits are shown. Age spectrum widths
425 were found to be 2.5 years for each model. The older characteristic age for total ozone
426 from the GSFC model compared to the NOCAR model is apparent.
427



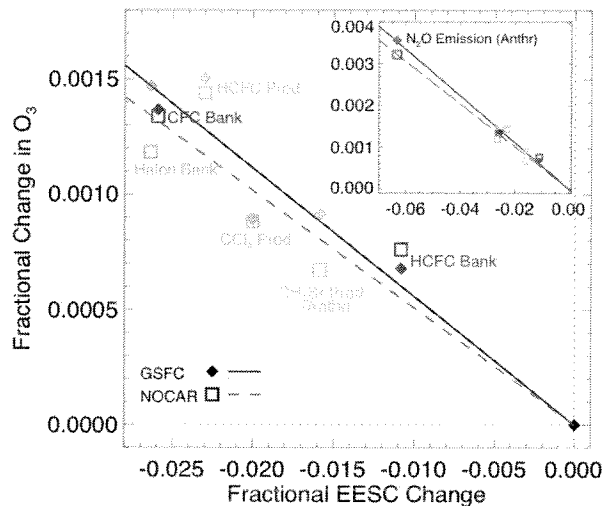
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429 Figure 3. Changes in (a) EESC, (b) ozone depletion, and (c) radiative forcing resulting
430 from the various ODS reduction cases in Table 1. The responses for the N₂O case
431 appears almost linear in main panels because of its long lifetime and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



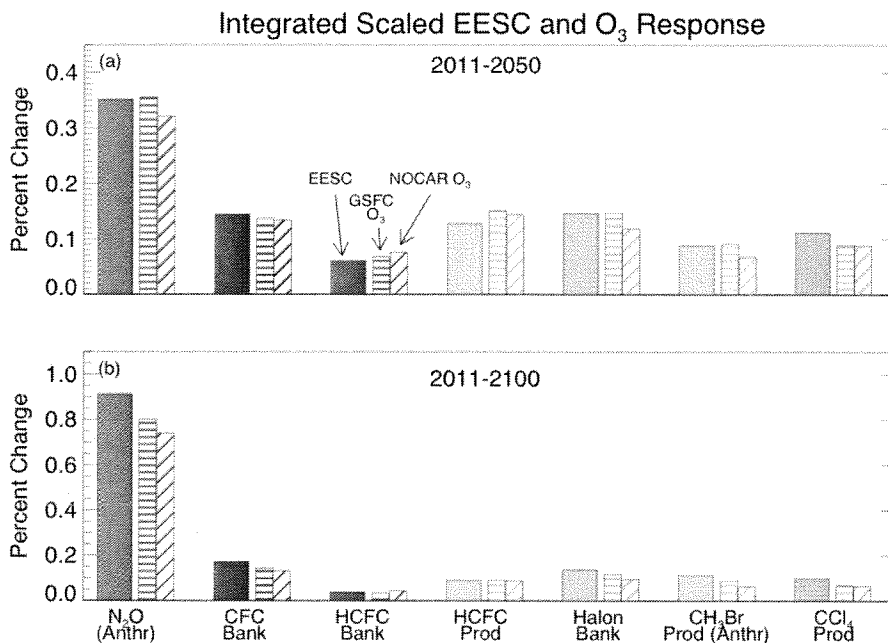
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436 Figure 4. Correlation of integrated EESC with integrated globally averaged total column
437 ozone over the period 2011-2050. Ozone values are calculated by the GSFC (diamonds)
438 and NOCAR models (squares) models. The linear fits of the cases shown are also
439 included (black for GSFC; purple for NOCAR). These fits are forced to go through
440 the origin and do not include the N₂O case in their calculation. The NOCAR slope is smaller
441 than the GSFC slope primarily due to a smaller ozone change in the NOCAR bromine
442 cases than would be expected with an α of 60. The inset shows the same information as
443 the main figure with the scales expanded so the N₂O emission phaseout is visible.
444



445
446

446 Figure 5. Impact of the 7 hypothetical emissions reductions shown in Table 1 on
 447 integrated EESC (solid bars) and global total column O₃ from GSFC (horizontal
 448 hatching) and NOCAR models (angled hatching). Integration periods of (a) 2011-2050
 449 and (b) 2011-2100 are shown. The extent to which ozone bars of the same color (in the
 450 same panel) are the same height as the EESC bars quantifies the success of the EESC
 451 parameterization in describing the integrated ozone response. The ozone values are
 452 scaled by the slope of the linear fit to the GSFC calculations shown in Figure 3.
 453
 454



455
 456

456 **Tables**

457 Table 1. ODS reduction cases considered and their impact on EESC and globally
 458 averaged total column ozone relative to the baseline case. The “Bank” cases assume the
 459 entire bank present in 2011 is captured and destroyed, but future production continues as
 460 in the baseline case. “Production” cases assume no future production of the compound
 461 beginning in 2011, but emissions from existing banks continue. The “N₂O Emission”
 462 scenario assumes no additional anthropogenic N₂O emission from 2011 onward. The
 463 “Total Emission Reduction” column contains the cumulative emission reduction from
 464 2011-2050 compared to the baseline case. The integrated EESC and O₃ change columns
 465 contain values for the reduction in these quantities relative to the baseline scenario. These
 466 reductions are shown for the periods 2011-2050 and 2011-2100. The EESC percent
 467 changes are generally smaller than what has appeared in past ozone assessments partly
 468 because here the change is calculated relative to the entire anthropogenic EESC; in the
 469 assessments, it has been calculated relative to EESC in excess of 1980 EESC levels. If
 470 compared to EESC in excess of 1980 levels, 2011-2050 percentages should be increased
 471 by a factor of 3.4.
 472

Case	Total Emission	Integrated EESC Change		Integrated O ₃ Change	
	Reduction	Relative to Baseline		Relative to Baseline	
	(Tg)	Scenario (%)		Scenario (%)	
	2011-2050	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 (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

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

475
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477

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