The return to 1980 stratospheric halogen levels: A moving target in ozone assessments from 2006 to 2022

Megan J. Lickley[1,2], John S. Daniel[3], Laura A. McBride[4], Ross J. Salawitch[5,6,7], Guus J.M. Velders[8,9]

[1]Earth Commons, Georgetown University, Washington, DC 20057, USA
[2]Science, Technology, and International Affairs Program, Georgetown University, Washington, DC 20057, USA
[3]Chemical Sciences Laboratory, NOAA, Boulder, CO, 80305-3328, USA
[4]Department of Chemistry and Biochemistry, Albright College, Reading, PA 19612, USA
[5]Department of Chemistry and Biochemistry, University of Maryland College Park, College Park, MD, 20740, USA
[6]Department of Atmospheric and Oceanic Science, University of Maryland College Park, College Park, MD, 20740, USA
[7]Earth System Science Interdisciplinary Center, University of Maryland College Park, College Park, MD, 20740, USA
[8]National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands
[9]Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, the Netherlands

Correspondence to: Megan J. Lickley (megan.lickley@georgetown.edu)

Abstract. The international scientific assessment of ozone depletion is prepared every four years to support decisions made by the Parties to the Montreal Protocol. In each assessment an outlook of ozone recovery time is provided. The year when equivalent effective stratospheric chlorine (EESC) returns to the level found in 1980 is an important metric for the recovery of the ozone layer. Over the past five assessments, the expected date for the return of EESC to the 1980 level, for mid-latitudes, has been delayed, from year 2049 in the 2006 assessment to 2066 in the 2022 assessment, which represents a delay of 17 years over a 16-year assessment period. Here, we quantify the primary drivers that have delayed the expected EESC recovery date between each of these assessments. We find that by using identical EESC formulations the delay between the 2006 and 2022 assessment's expected return of EESC to 1980 levels is shortened to 12.6 years. Of this delay, bank calculation methods account for ~4 years, changes in the assumed atmospheric lifetime for certain ODSs account for ~3.5 years, an under-estimate of the emission of CCl_4 accounts for ~3 years, and updated historical mole fraction estimates of ODSs account for ~1 year. Since some of the underlying causes of these delays are amenable to future controls (e.g. capture of ODSs from banks and limitations on future feedstock emissions), it is important to understand the reasons for the delays in expected recovery date of stratospheric halogens.

1 Introduction

The Montreal Protocol is often lauded as the signature global environmental success story. Since its entry into force in 1989, it has led to large reductions in the production of ozone depleting substances (ODSs) globally and avoided a world with

substantial ozone loss (Morgenstern et al., 2008; Newman et al., 2009). To inform potential policy decisions of the Parties to the Protocol, every 4 years a Scientific Assessment of Ozone Depletion (SAOD) report is prepared by leading international

35 experts in atmospheric science and related fields under the auspices of the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). A key component of each SAOD report is an outlook of the timeline for recovery of the ozone layer. In addition to calculating the return of ozone, itself, return dates to 1980 levels of equivalent effective stratospheric chlorine (EESC) are estimated and provided, given the best scientific understanding of atmospheric processes and the assumption of global compliance with the controls of the Protocol at that time. EESC is a measure of the

40 abundance of stratospheric inorganic chlorine and bromine and is a proxy for the chemical depletion of stratospheric ozone by halogens. While ozone depletion began before 1980, the return of EESC to the amount that had existed in 1980 is an adopted benchmark for the path to recovery. Over the past 16 years, the expected return of EESC to the 1980 level has been pushed back from 2049 in the 2006 SAOD (Daniel and Velders et al. 2007) to 2066 in the 2022 SAOD (Daniel and Reimann et al., 2022), a delay in the expected recovery of stratospheric chlorine and bromine of 17 years over a 16-year assessment period

45 (Fig. 1a). The reasons for this expected delay in the return of stratospheric halogens to the 1980 level have not been fully elucidated although the newer EESC formulation (Engel et al., 2018) may play an important role, as the return to 1980 levels was delayed by more than a decade in the newest SAOD (WMO, 2018; WMO, 2022), which is the first SAOD to adopt the newer EESC formulation.

50 When projections of future mole fractions of ODSs and EESC recovery are updated, the underlying causes of any changes are important to understand. Changes can relate, for example, to a new value of the global lifetime of an ODS, new estimates of the amount of an ODS in banks, more extensive controls on the future production of an ODS, or the detection of the unexpected emission of an ODS. Here, the term "bank" refers to the amount of ODS stored in existing equipment, chemical stockpiles, foams, and other products with the potential of release to the atmosphere. An example of the unexpected emission was

55 described by Montzka et al. (2018), who reported a slowdown in the rate of decline of atmospheric CFC-11 that they attributed to new, unreported production in eastern Asia. This study brought into question the extent to which illicit production of CFC-11, inaccuracies in the assessed emission of CFC-11 from banks, or possibly even inaccuracies in the atmospheric lifetime of CFC-11 were contributing to the delay in the expected decline of the global mean mole fraction of CFC-11 between the projection given in the 2006 SAOD and data presented in the 2014 SAOD. Subsequent studies confirmed the Montzka et al.

60 (2018) findings by identifying emissions of CFC-11 originating from eastern Asia, likely resulting from new production in breach of the Montreal Protocol (Rigby et al., 2019; Benish et al., 2021; Montzka et al., 2021; Park et al., 2021). Furthermore, an upward revision in the magnitude of the bank of ODSs (Lickley et al., 2020; Lickley et al., 2022) led to the recent realization that the return of EESC to the 1980 level would not occur as fast as once expected (Daniel and Reimann et al., 2022). These studies underscore the role that SAOD reports have played in setting expectations for future mole fractions of ODSs.

65 Considering that SAODs are assembled, in part, to provide the Parties with our best knowledge of the effectiveness of current

control measures, and also to set an expectation of the future recovery of the ozone layer, a careful analysis of the drivers changing EESC projections between these past SAODs is warranted.

Here, we quantify the reasons for the delay in the recovery of EESC to the 1980 level given by the five most recent SAOD
70 reports (Daniel and Velders et al., 2007; Daniel and Velders et al., 2011; Harris and Wuebbles et al., 2014; Carpenter and Daniel et al., 2018; Daniel and Reimann et al., 2022). We henceforth refer to these five reports as the 2006; 2010; 2014; 2018; and 2022 SAODs. Specifically, we consider how the delay has been affected by the consistent underestimate of the global production of ODSs (Benish et al., 2021; Lickley et al., 2022; Montzka et al., 2018; Park et al., 2018; Rigby et al., 2019; Montzka et al., 2021; Park et al., 2021; Sherry et al., 2018), as modeled through banks and feedstocks, and observed in part by
75 measured mole fractions following each SAODs publication. In addition, we consider the role of changes in ODS atmospheric lifetime assumptions that affect future atmospheric abundances (SPARC, 2013), and variations in the scientific understanding of the best underlying approach used to compute EESC (Engel et al., 2018; Newman et al., 2007). We quantify the contributions from each of these primary drivers that have delayed the expected return to the 1980 date of EESC between each consecutive SAOD report from 2006 to 2022. To do so, we first re-evaluate each SAOD's historical and future EESC
80 projections using a common formulation for EESC (Engel et al., 2018). We are then able to compare the differences in projections of EESC due to changes in historical and projected atmospheric concentrations alone, rather than confounding the issue with different formulations for the computation of EESC. Next, we identify the primary gases driving each change in the EESC return date between consecutive SAOD reports. We then isolate the effects of four primary gases (CFC-11, CFC-12 and halon-1301 and CCl_4) on EESC, as changing projections of these four compounds explains ~90% of the delay in
85 expected EESC recovery from the 2006 SAOD to the 2022 SAOD. In Section 2, we detail the calculation of EESC given in each SAOD report, including various modeling assumptions. In Section 3, we present our methods for ODS selection and for quantifying each modeling component's contribution to delaying EESC return dates. We present the results of our analysis in Section 4. Finally, we discuss the implications for future assessments in Section 5.

90 ## 2 A review of SAOD calculations for estimating EESC return dates

The modeling approach used in the SAODs from 2006 to 2022 estimates the return of EESC to the 1980 level as a multi-step process. First, this estimate requires knowledge of pre-1980 atmospheric mole fractions of the 16 most abundant ODSs, summarized in Table S1, to establish the 1980 baseline level of EESC. Next, projections of future atmospheric mole fractions
95 require assumptions about expected emissions from future production as well as emissions from existing equipment (termed 'banks'), along with an estimate of the atmospheric lifetime for each gas. Further, four additional years of observations between each assessment has required updating various assumptions, such that the modelled atmospheric concentrations of ODSs are consistent with new observations. Finally, once a historical and future time series of mole fractions has been constructed for each of the 16 primary ODSs, they are aggregated together using a calculation of EESC. Each step in this

modeling process has been updated between various SAOD assessments, reflecting the best scientific knowledge at the time of the publication. A summary of the different modeling assumptions is provided in Table 1, along with the lifetimes of the four most important ODSs with regards to the variations in the return of EESC to the 1980 level across the assessments. In Table 1, the term FRF refers to fractional release factor, a quantity that (as explained below) represents the conversion from organic to inorganic chlorine of each ODS.

Table 1: Summary of key assumptions by Scientific Assessment of Ozone Depletion report

	2006 SAOD	2010 SAOD	2014 SAOD	2018 SAOD	2022 SAOD
EESC Formulation	FRFs: Daniel et al. (1995) Age: 3-yr delta function	FRFs: Newman et al. (2007) Age: 3-yr delta function	FRFs: Newman et al. (2007) Age: Newman (2007) spectrum	**Main text** FRFs: Newman et al. (2007) Age: Newman (2007) spectrum **Appendix**: FRFs: Engel et al. (2018); Age: Engel (2018) spectrum[1]	FRFs: Engel et al. (2018) Age: Engel (2018) spectrum
Lifetimes (yrs)					
CFC-11	45	45	52	52	52
CFC-12	100	100	102	102	102
Halon-1301	65	65	72	72	72
CCl4	26	26	26	32	30
Bank method					
CFC-11	Hybrid model: 2002/2015 ref years	Hybrid model: 2008 ref year	Hybrid model: 2008 ref year	Hybrid model: 2008 ref year	Bayesian model
CFC-12	2002/2015 ref years	2008 ref year	2008 ref year	2008 ref year	Bayesian model
Halon-1301	2002/2015 ref years	2008 ref year	2008 ref year	2008 ref year	Bayesian model

CCl4	Not banked	Not banked	Not banked	Not banked	Not banked
Future production					
CFC-11	Global production ends in 2010	Global production ends in 2010	Global production ends in 2010	Global production ends in 2010	Unexpected production is accounted for up to 2018
CFC-12	Global production ends in 2010	Global production ends in 2010	Global production ends in 2010	Global production ends in 2010	Global production ends in 2010
Halon-1301	Global production ends in 2010	Global production ends in 2010	Global production ends in 2010	Global production ends in 2010	Global production ends in 2010
Future emissions					
CCl4	Linear decline from 2005 top-down derived emissions to zero from 2015 onwards	2009-2050: 6%/year decline 2050 onwards: zero emissions	2013-2100: 6.4%/year decline	2017-2100: 2.5%/year decline	Linear decline from 2020 top-down emissions to 15 Gg/year in 2030. 2030 onwards: 15 Gg/year

[1]The width of the age distribution was taken from Newman et al. (2007).

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Below, we review the calculation of EESC given in each SAOD from 2006 to 2022. We then present the method used for projecting future ODS atmospheric concentrations and review each SAOD's input parameters for these calculations. While pre-1980 concentrations of some of the 16 primary ODSs have been modified at times between assessments, this change represents a small fraction of total change in the EESC recovery time over the entire 16-year period, and is therefore not the
115 focus of the present analysis.

2.1 EESC calculations

Equivalent effective stratospheric chlorine (EESC) is a metric that has been developed to relate the surface level atmospheric abundance of ODSs to inorganic halogen loading in the stratosphere, and thus to stratospheric ozone depletion. Methods for
120 estimating EESC have generally followed the functional form:

$$EESC(t) = a\left(\sum_{Cl} n_i f_i \rho_i + \alpha \sum_{Br} n_i f_i \rho_i\right), \tag{1}$$

where n_i is the number of chlorine or bromine atoms of an ODS, f_i represents the value of the fractional release factor (FRF) of an ODS relative to CFC-11, and ρ_i is the mean stratospheric mole fraction in the location of interest at time t. Values of ρ_i can be related to the surface level mole fraction for gas, i, by

$$\rho_i(t) = \int_{-\infty}^{t} \rho_{i,entry}(t')G(t - t')dt' \tag{2}$$

where $\rho_{i,entry}$ is the mixing ratio of the source gas at the time of entry into the stratosphere (Newman et al., 2007). The quantity α is the efficiency of ozone destruction by bromine radicals relative to the efficiency by chlorine radicals, which is commonly set to 60 for EESC of mid-latitude air and 65 for EESC in polar regions (Sinnhuber et al., 2009). The quantity a represents the fractional release of CFC-11 (Daniel et al., 1995; Newman et al., 2007) in the SAODs from 2010 onward, and it is set to be 1 for the 2006 SAOD. G represents the distribution of time required to be transported from entry into the stratosphere to the region of interest and is referred to as the age spectrum.

The 2006 and 2010 SAOD adopted the Daniel et al., (1995) EESC calculation approach, where G was assumed to be a delta function with a 3-year lag, so ρ_i represented a simple 3-year time lag from surface concentrations (adjusted by the factors described in the previous paragraph). The 2014 and 2018 SAODs adopted the Newman et al. (2007) formulation of EESC, which modified equation (1) such that both f_i and ρ_i were time-weighted averages, reflecting the non-linear dependence of these terms on the age-of-air in the stratosphere. The 2018 SAOD also showed in an appendix the results from using the Engel et al. (2018) approach. The 2022 SAOD has since adopted the Engel et al. (2018) formulation for computation of EESC, which employs slightly different fractional release values and a different age spectrum. The most significant difference introduced by the Engel et al. calculation of EESC is that it attempts to weight the age spectrum by the time when the source gas dissociates, rather than using the Newman et al. (2007) approach (and the delta function approach) in which the age spectrum is identical to the age spectrum of an inert tracer. This change results in effectively higher mean ages, particularly in the midlatitudes, than found using the approach of Newman et al. (2007).

2.2 Projecting ODS concentrations

To calculate values of ρ_i in equations (1) and (2), the SAODs each began with a time series from 1950 to 2100 of surface concentrations for each ODS included in Table 2. The historical range of this period is developed using observed mole fractions, when available. In recent decades, these are highly precise and accurate atmospheric observations from the AGAGE

(Prinn et al., 2018) and NOAA (https://gml.noaa.gov/dv/site/) networks. Before routine and global atmospheric observations were available, there are observations from firn samples that can help constrain prior concentrations for some of the compounds

155 (Butler et al., 1999; Laube et al., 2014), particularly those with strong natural sources such as CH_3Br and CH_3Cl. For the remaining ODSs, historical concentrations between 1950 and 1980 were based on model calculations using the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS, 2001) reported production data, and adjusting calculations to avoid discontinuities between concentration modeled and observed concentrations when observations first began for each compound. The projections of future concentrations generally consider a range of future policy scenarios, where the baseline

160 scenario reflects the current controls. We only consider the baseline scenarios here for comparison across SAOD reports. Baseline projections begin in the year prior to publication of the assessment, t_0, where an initial concentration $[ODS]_{i,t_0}$, for ODS, i, is taken from observed surface concentration values. Each subsequent year, t, is then forward simulated using a 1-box model of the atmosphere following equation (3):

$$[ODS]_{i,t} = exp\left(-\frac{1}{\tau_i}\right) \times [ODS]_{i,t-1} + A_i \times Emiss_{i,t-1} \times \tau_i \times \left(1 - exp\left(-\frac{1}{\tau_i}\right)\right), \tag{3}$$

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where τ_i is the atmospheric lifetime, and A_i is a conversion factor relating emissions, $Emiss_{i,t-1}$, to atmospheric concentrations for gas, i. Values of $Emiss_{i,t}$ are modeled as the sum of emissions from expected production and banks, and are iteratively simulated using equations (4) and (5):

$$Emiss_{i,t} = RF_i \times Bank_{i,t} + DE_i \times Prod_{i,t}, \tag{4}$$

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where RF_i is the yearly release fraction of the bank, $Bank_{i,t}$, and DE_i is the fraction of production, $Prod_{i,t}$, for ODS, i, in year, t, that is emitted in the same year as the production. The size of the bank is then updated;

$$Bank_{i,t+1} = (1 - RF_i) \times Bank_{i,t} + (1 - DE_i) \times Prod_{i,t} \tag{5}$$

175 Therefore, future ODS concentration projections rely on assumptions about global lifetimes, bank sizes, bank release fractions, future production, and direct emissions from production. The different methods across assessments for the values used in equations (1) – (4) are further summarized below.

2.3 Atmospheric Lifetime assumptions

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Atmospheric lifetimes of the ODSs are an important component of the projections of future concentrations. For each SAOD report, an "assessed" best estimate for the lifetime of each compound is presented. Here, lifetime is defined as the global

atmospheric mass, or burden, of a compound divided by the loss rate integrated over the entire atmosphere (SPARC, 2013). These lifetime estimates were calculated using numerous methods, such as analysis of the stratospheric distribution (as a

185   function of altitude and pressure) of long-lived gases (Minschwaner et al., 1993), model inversions with prescribed emissions (Rigby et al., 2013), or the slope of mixing ratio of a particular species versus the mixing ratio of another species with a well-established lifetime (Plumb & Ko, 1992). For gases such as CH_3CCl_3 that undergo removal in the troposphere due to processes such as reaction with OH, the lifetime may be revised due to better knowledge of the rate constant for reaction with OH, the average OH concentration itself, as well as additional years of data from which lifetime is inferred (Montzka et al., 2011; Prinn

190   et al., 2001). A tabulation of the lifetime of the 16 major ODSs, from the five most recent SAOD reports, appears in Supplemental Table S2. Lifetimes most central to our analysis are repeated in Table 1.

2.4 Banks modeling
An ODS bank refers to the quantity of gas contained in equipment or applications that is subject to later release. One approach

195   to estimating the size of an ODS bank in a given year requires knowledge about how much of an ODS has been cumulatively produced and released prior to the year of interest. The difference is assumed to be residing in the bank; this approach is referred to as a top-down approach (e.g. Montzka and Fraser et al., 2003). An alternative method involves estimating the quantity of equipment and/or applications in a given year that contain a particular ODS and how much ODS resides in each piece of equipment/application; this approach is referred to as a bottom-up approach (Ashford et al., 2004, Campbell et al.,

200   2005). Due to uncertainties in data and modeling assumptions, each method yields bank estimates with significant uncertainties.

In earlier assessments (e.g. the 2002 SAOD; Montzka and Fraser et al. 2003), projections of EESC were based on banks found using a top-down approach, where banks were estimated as;

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$$Bank_{i,t+1} = Bank_{i,t} + Prod_{i,t} - Emiss_{i,t} \tag{6}$$

For the 2002 report, the production values, $Prod_{i,t,}$ came from AFEAS (2001) and UNEP's Ozone Secretariat, and emissions, $Emiss_{i,t}$, were derived from observed concentrations by rearranging equation (3). Banks were calculated by starting in the first year of production, with $Bank_{i,t_0}$ equal to zero and iterating forward.

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Due to the inherent large uncertainties associated with this approach, since the bank is a small difference between two large numbers (cumulative production and cumulative emission), and due to the large discrepancies between bank estimates using this top-down approach and other bottom-up accounting methods (Daniel et al., 2007), the 2006 SAOD used a hybrid modeling approach to estimate banks. Bank estimates for 2002 and 2015 were adopted from the Technology and Economic Assessment

215   Panel bank estimate (IPCC/TEAP, 2006), which estimated banks using a careful bottom-up calculation of inventory and

expected release rates by application type. Such bottom-up estimates were not previously available. Equation (5) was then used to solve for RF_i, assuming DE_i equal to RF_i, such that the 2002 and 2015 banks matched the prescribed 2002 and 2015 values, while also accounting for the reported production during this period. After solving for RF_i values, banks and emissions were simulated from 2015 onwards using equations (4) and (5) and assuming RF_i remained constant into the future.

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This method was modified in the 2010, 2014 and 2018 SAODs, which started with a bottom-up estimate for the 2008 bank from a TEAP 2009 report (Kuijpers & Verdonik, 2009). Using equation (6), banks were calculated beginning in 2008 (forward and backward in time if necessary) for the 7 most recent years in which concentration observations were available. Emissions for equation (6) were calculated using equation (3), rearranged to solve for emissions. RF_i was then estimated for each of these

225 years by setting DE_i equal to RF_i in equation (4) and solving for RF_i. For the 2014 and 2018 SAODs, the average RF_i value over these 7 years was then used to forward simulate banks and emissions from 2008 onwards using equations (3) and (4). For the 2010 SAOD, a RF_i that was consistent with the values over the previous 5-10 years, depending on compound, was used.

230 The 2022 SAOD bank estimates followed a Bayesian bank estimation method from Lickley et al. (2020, 2022). This method develops prior distributions of the input parameters to equations (4) to account for uncertainties in production, as well as uncertainties in RF_i and DE_i values. Equations (3 - 5) are then simulated starting in the first year of production for the respective ODS to the end of the observational record, which results in a joint prior distribution of banks, emissions, and atmospheric concentrations. Joint posterior distributions are obtained by updating the prior with available global averaged

235 observed atmospheric concentrations. This approach resulted in larger bank estimates than used in previous assessments, largely due to the allowed possibility that ODS production was higher than reported; this higher posterior production primarily occurs because plausible RF values along with reported production values were inconsistent with atmospheric concentrations, given the model assumptions. Projected ODS concentrations were then estimated using posterior bank and RF_i estimates in 2021 and forward simulating equations (4) and (5), with an assumed production timeseries in line with the controls set by the

240 Parties to the Protocol.

The various bank estimates from the 2006 to 2022 SAODs are shown in Fig. 1.

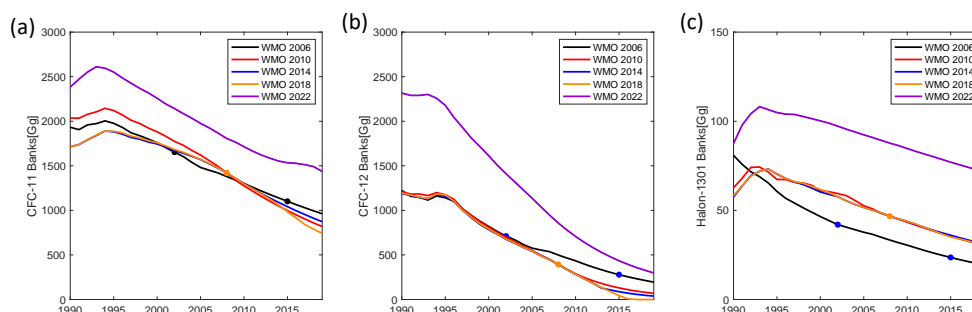



Figure 1. Bank estimates (a) CFC-11 (b) CFC-12 and (c) Halon 1301 for each scientific assessment of ozone depletion from 2006 to 2022, as indicated by the WMO date in the legend. The blue does represent the bottom-up derived banks from IPCC/TEAP (2006) that are adopted as an initial starting point for the WMO (2006) bank assessment. The red dot represents the starting point for the WMO (2010, 2014, 2018) assessments, taken from the 2009 TEAP report (Kuijpers & Verdonik, 2009). The shaded region for WMO (2022) represents the 5th and 95th percentile confidence bounds around the median bank estimate

2.5 CCl4 modeling

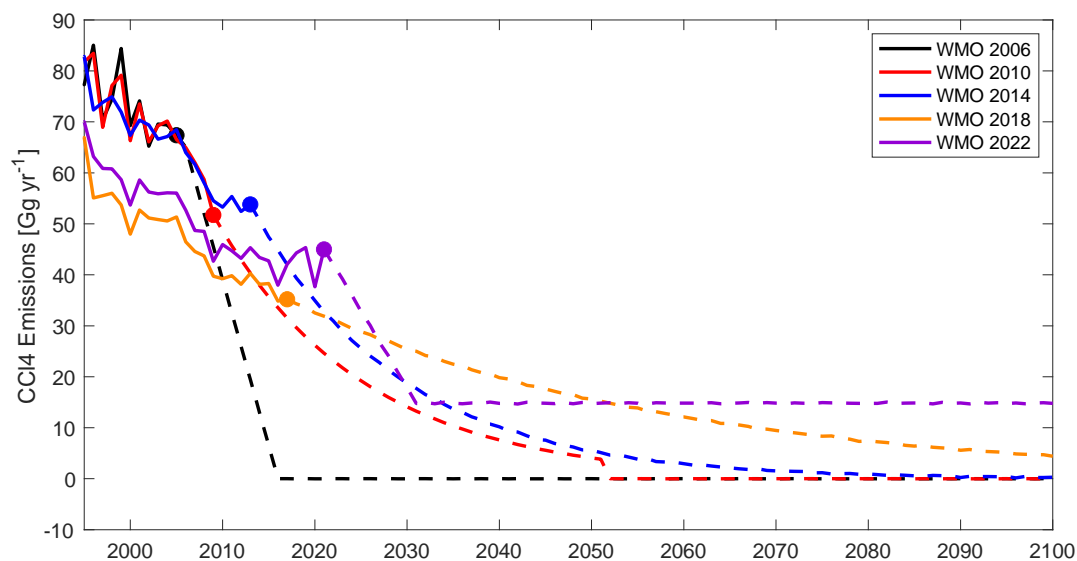
The CCl$_4$ budget remains an area of substantial uncertainty (SPARC, 2016), as noted in each SAOD report from 2010 to present. Under the Montreal Protocol, CCl$_4$ was scheduled to be phased out of production for dispersive uses by 2010, which was consistent with near-zero country-reported production values from that time onward. Assuming CCl$_4$ global production would follow the scheduled phaseout, the 2006 SAOD adopted a future emissions pathway that began with a linear decrease from top-down derived emissions values in 2005 of 65 Gg/year to zero in 2015 and beyond. However, the expected rate of decline was not observed to be as quick as in the 2006 SAOD, which led to adjustments in CCl$_4$ projections in subsequent SAODs. The emission estimates for CCl$_4$ used in the 2010 SAOD report, and the subsequent three reports, is shown in Fig. 2.

260

Figure 2. Emissions estimates from each scientific assessment of ozone depletion (SAOD) from 2006 to 2022, as indicated by the WMO date in the legend. Solid lines represent observationally-derived emissions using the assumed lifetime from the corresponding SAOD. The dashed line represents the emissions projection estimates from each SAOD and the dots indicate the year of each publication, which separates the observationally-derived from projected emissions.

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The 2010 and 2014 SAOD developed CCl_4 emissions projections by extrapolating the top-down derived CCl_4 emissions trend from the previous five years, equivalent to 6%/year and 6.4%/year, respectively. The 2010 SAOD assumed zero emissions following 2050, whereas the 2014 SAOD assumed the continued 6.4%/year decrease in emissions, which was near zero by 2050. However, observationally-derived emissions values from 2000 – 2012, after accounting for updated atmospheric lifetime

270 estimates, again did not reflect this assumed decline in emissions but rather were estimated to be relatively stable at 39^{45}_{34} Gg/year (Liang et al., 2014), highlighting the gap in understanding of emissions sources.

This projection assumption was again updated in the 2018 SAOD to better match top-down derived emissions, which were declining slower than expected at a rate of 2.5%/year over the previous two decades. This slower than expected decline was

275 only partially explained from adjusted estimates in atmospheric lifetimes between the 2014 and 2018 SAODs (Table 1). Additional discrepancies were documented in the SPARC (2016) special report on the "mystery" of CCl_4 which pointed to previously unaccounted for by-product emissions during chloromethane and perchlorethylene (PCE) production, feedstock emissions for hydrofluocarbons (HFCs) and PCEs, legacy emissions including from contaminated soils and landfills, and unreported emissions (Sherry et al., 2018, SPARC, 2016). Sherry et al. (2018) estimated bottom-up emissions in 2014 that

280   included ~15 Gg/year from unreported non-feedstock and fugitive emissions and ~10 Gg/year of legacy emissions from chloro-alkali plants.

The 2022 SAOD thus adopted a hybrid CCl_4 emissions projection that began with top-down derived emissions equal to 45 Gg/year in 2020 and assumed a linear decrease in emissions from 2020 to 2030, with a constant emissions of 15 Gg/year from

285   2030 onwards. The emissions pathway reflects an assumption that legacy emissions will decline linearly until their cessation in 2030, and an assumption of continued constant emission from, for example, feedstock sources. New knowledge of pathways of atmospheric emission of CCl_4 continue to emerge (Li et al., 2024), which will likely result in further adjustments to future emissions in subsequent SAOD reports.

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3 Quantifying drivers of delayed EESC return dates

Here we explain the various steps that underlie our process for quantifying the contribution of updated modeling assumptions in delaying the return of EESC to the value found for January, 1980. We use the beginning of 1980 as a marker for the return

295   of EESC, since the return of EESC and atmospheric levels of ozone to the "pre-1980 value" is a commonly adopted metric for assessing the recovery of the ozone layer in the SAOD reports to the Parties of the Montreal Protocol.

Step 1: Update EESC calculation method to that used in WMO (2022).
We recalculate the EESC time series for each assessment by applying the Engel et al. (2018) formulation, using each SAOD's

300   original time series of atmospheric concentration for the 16 major ODSs given in Table 1. This is performed first so changes in the EESC calculation method do not confound changes in ODS projections.

Step 2: Identify the primary gases delaying EESC return dates
We then identify the primary ODSs that have driven the delay in EESC return dates. This identification is done by beginning

305   with the original assessment's time series for all ODSs. One gas at a time with replacement, we substitute in the subsequent assessment's time series and re-calculate EESC and its expected 1980 return date. The ODSs that dominate the delay in EESC and are also subject to banking (that is, CFC-11, CFC-12, halon-1301) are then considered in Steps 3 – 5. CCl_4, which is the most critical ODS in delaying expected EESC return dates between SAODs and is not assumed to be significantly banked, is then considered in Step 6.

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Step 3: Update Lifetime assumptions to 2022 SAOD for most important banked gases
For CFC-11, CFC-12 and halon-1301, we adopt the 2022 SAOD atmospheric lifetimes, and recalculate emissions and banks following each assessment's original bank calculation method described earlier. We then use the updated bank and release

fractions, along with the new atmospheric lifetimes to project mole fractions to 2100. See Supplementary Table S2 for a

315   summary of the atmospheric lifetimes adopted for each SAOD.

Step 4: Update mole fraction observations to WMO (2022) for most important banked gases

We recalculate atmospheric concentrations by updating the bank and emissions calculations based on observed mole fractions out to 2021, while retaining the approaches of the respective SAODs. This is done to evaluate the extent to which differences

320   in the projected mole fractions from 2006-2021 would have impacted the EESC return date using the original bank and emissions estimation methods.

Step 5: Update banks to WMO (2022) for most important banked gases

After updating mole fractions and lifetimes, bank emissions are the only remaining discrepancy for CFC-11, CFC-12 and

325   halon-1301. Therefore, we next update the entire projection time series using the 2022 SAOD projected time series to account for the outstanding update, which is the updated bank values and approach. This allows us to quantify the new estimated bank contributions to differences in the expected return of EESC to the 1980 level for these three gases.

Step 6: Update CCl_4 lifetimes and emissions projections

330   We update the time series for CCl_4 as follows. First, we update the lifetime of CCl_4 to match the 2022 SAOD assumed lifetime of 30 years, and we then re-calculate all future emissions based on the same approaches in each of the respective SAODs. This adjustment impacts future projected concentrations of CCl_4 due to the rate of atmospheric decline and also impacts observationally-derived emissions that are used to inform the projected emissions. Next, we update the timeseries of observed mole fractions out to 2021, as is done in Step 4, to reflect how the original projection methods from each SAOD would be

335   impacted by the actual observed concentrations, had this projection method been used in the 2022 assessment. The final part of the modified CCl_4 projection involves updating the future emissions projection method to what was used in the 2022 SAOD, which brings both historical and future CCl_4 mole fraction time series to the timeseries used in the 2022 SAOD. We refer to this final part as accounting for future feedstock emissions, though the 15 Gg/year of continued emission was meant to comprise all potential emissions, including those that are unreported. This gas is treated separately from CFC-11, 12 and

340   Halon-1301 because CCl_4 is not a banked ODS, and also because the manufacturing of the gas and its feedstock-related emissions are relatively poorly understood (Liang et al., 2014; SPARC, 2016).

Step 7: Update all other gases to WMO (2022) values

For the final step in quantifying contributions to expected delays in EESC, we update the time series for the abundance of the

345   remaining 12 ODSs to the values given in the 2022 SAOD.

4 Results

350   The various formulations of EESC used in the past five SAOD reports have resulted in substantial differences in the 1980 return date reported in these assessments (Fig. 3). There are relatively large differences in the magnitude of EESC given in the 2006 SAOD compared to all subsequent SAOD reports (Fig. 3a). The larger EESC magnitude in the 2006 report is due to the use of FRFs for ODSs relative to the FRF of CFC-11, rather than the actual values of FRFs used in subsequent reports. The 2006 SAOD formulation results in a simple scaling of a factor of 2.13 relative to the other SAODs and updating the 2006

355   SAOD with absolute FRF values does not affect the return date of EESC to the 1980 value or the EESC shape at all. The EESC return dates as reported in the assessments do not meaningfully change between the 2006 SAOD and the subsequent three SAODs. EESC values for the 2006 to 2018 SAODs yield a return to 1980 date between 2046 and 2050. In contrast, the 2022 SAOD provides an estimated return date of 2066. This disparity is due in part to the use of the Engel et al. (2018) formulation of EESC in the 2022 report, which effectively uses a higher age of air spectrum relative to the Newman et al. (2007) approach

360   that impacts the FRFs of ODSs (see Section 2.1), resulting in a rightward shift in the EESC timeseries. Consequently, the 1980 level of EESC is reduced, delaying 1980 return date for EESC relative to the previous assessments (Fig. 3a). Various other counteracting changes in the formulation of EESC for the 2006 to 2018 SAOD reports resulted in near constancy of the return to 1980 level for EESC. As the year of the SAOD report advanced, there was a tendency for the surface mixing ratios of ODSs other than HCFC-22 to return to their 1980 levels at later dates, which all else being equal would have led to incremental

365   delays in the return to 1980 date of EESC. However, as the year each SAOD report advanced, there were incremental changes in the approach used to compute EESC that largely counteracted these incremental delays. It is therefore instructive to examine the return to 1980 EESC levels for the assessed time series of the 16 principal ODSs of each SAOD report using an identical formulation for EESC.
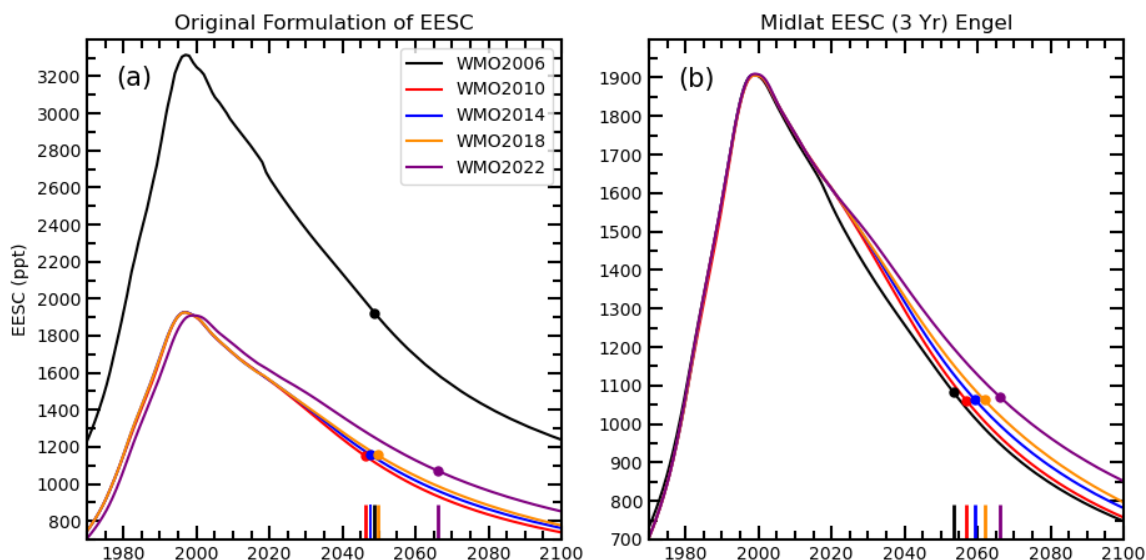
Figure 3. EESC calculations applied to WMO assessment's atmospheric concentrations. (a) EESC formulation as it appears in the original assessments, where WMO (2006) follows the Daniel et al. (1995) formulation, WMO (2010, 2014, 2018) follows the Newman et al. (2007) formulation, and WMO (2022) follows the Engel et al. (2018) formulation. (b) Engel et al. (2018) EESC calculation applied to the original assessment's atmospheric concentrations. Dots and vertical lines on the x-axis refer to the first month in which EESC returns to below 1980 levels for the respective WMO assessment.

Using the Engel et al. (2018) formulation for EESC applied to the time series of ODS abundance given in the past five SAOD reports, we see a near consistent delay in return to 1980 dates between reports (Fig. 3b). For each consecutive SAOD, the return to 1980 date lags that given in the prior report by about 2 to 4 years. Further, using the identical formulation for EESC (Engel et al. 2018) shortens the difference in the 1980 return date between the 2006 and 2022 SAOD reports from 17 to 12.6 years, which we investigate below. Note that the value of EESC in 1980 (that is, the return to 1980 target) does not perfectly align, despite the use of an identical formulation for the calculation of EESC (Fig. 3b). These slight shifts are a result of updating historical atmospheric concentrations of ODSs between assessments, with the most significant change arising from the hindcasting of CH_3Br (Table 2).

Table 2: Independent incremental change (in yrs) between assessments by gas for mid-latitude EESC return date using the Engel et al. (2018) formulation. Gases are ordered by total contribution to change in EESC return date between 2006 and 2022.

	WMO 2006	WMO 2010	WMO 2014	WMO 2018
Initial EESC return date Engel et al. (2018)	2053.5	2056.9	2059.4	2061.9
	Difference from 2006 to 2010 (yrs)	Difference from 2010 to 2014 (yrs)	Difference from 2014 to 2018 (yrs)	Difference from 2018 to 2022 (yrs)
CFC-11	0.55	1.82	0.15	2.42
CCl4	1.76	0.67	3.3	-0.83
halon-1301	0.53	0.2	0.04	0.6
CFC-12	0.02	0.12	0.04	0.64
CH3Br	2.15*	-0.43	-1.02	0.01
CFC-113	0.06	0.17	0.03	0.21
halon-2402	0.27	0.53	-0.02	-0.43
HCFC-142b	0.16	-0.03	0	0.09
CH3CCl3	0.02	0	0	0.06
CFC-114	-0.01	0	0.01	0.05
CFC-115	0	0	0	0
halon-1202	0	-0.01	0	0
halon-1211	-0.31	-0.07	-0.01	0.37
HCFC-141b	0	-0.09	-0.02	0.03
CH3Cl	0.03	-0.43	0	0
HCFC-22	-1.89	-0.05	0.06	0.74
Sum	3.34	2.40	2.56	3.96

*Updating EESC values from changes in CH3Br between WMO (2006) and WMO (2010) leads to a large decrease in EESC
390 1980 values from 1082 ppt to 1060 ppt.

The role of the choice of EESC formulation in delaying return dates is further explored in Fig. 4. The SAOD reports provide estimates of EESC for both midlatitude (assumed to be 3-year old air) and polar (5.5-year old air) stratospheric regions, which

395 are used in many papers (and the assessments) as proxies for the recovery of midlatitude and polar ozone to perturbations caused by anthropogenic halogens. By normalizing the original formulations of EESC to their 1980 values, the 2022 SAOD is a notable outlier for EESC of midlatitude regions (Fig. 4a). Identical formulations of EESC, using either the Engel et al. (2018) or Newman et al. (2007) method, result in consistent delays in the return 1980 dates for midlatitude EESC, as the year of the various SAOD reports advances (Fig. 4b and 4c). However, there are large differences in return dates *between* these

400 two formulations, with return dates of midlatitude EESC found using Engel et al. (2018) lagging those of Newman et al. (2007) by over a decade. Relative to the 2014 SAOD report, the earlier return to 1980 date of midlatitude EESC in 2010 SAOD is more apparent once an age of air spectrum is applied. Similarly, updating the 2006 SAOD EESC formulation with the 2010 SAOD's FRF values advances the 2006 SAOD projected by over 5 years. These shifts illustrate the role that the age-of-air spectrum approach and FRF values collective play in delaying the return of EESC relative to their earlier specifications. While

405 the Newman et al. (2007) and Engel et al. (2018) formulations result in large differences in EESC for midlatitude regions, these two formulations result in similar EESC return dates for polar regions (Fig. 4 e and f). This difference is due to the Engel et al. (2018) EESC formulation attempting to weight the age of air by the timing of source gas dissociation, which leads to differences in estimated concentrations of active (inorganic) halogens in midlatitudes, as photolysis largely occurs in the tropical stratosphere. The formulations give similar estimates of EESC for polar regions because the transit through the

410 stratosphere from injection (in the tropics) to polar descent results in nearly complete loss of most ODSs, due to longer residence time in the stratosphere and most importantly exposure to a more intense ultraviolet radiation environment than seen for most 3-year old, midlatitude air parcels.
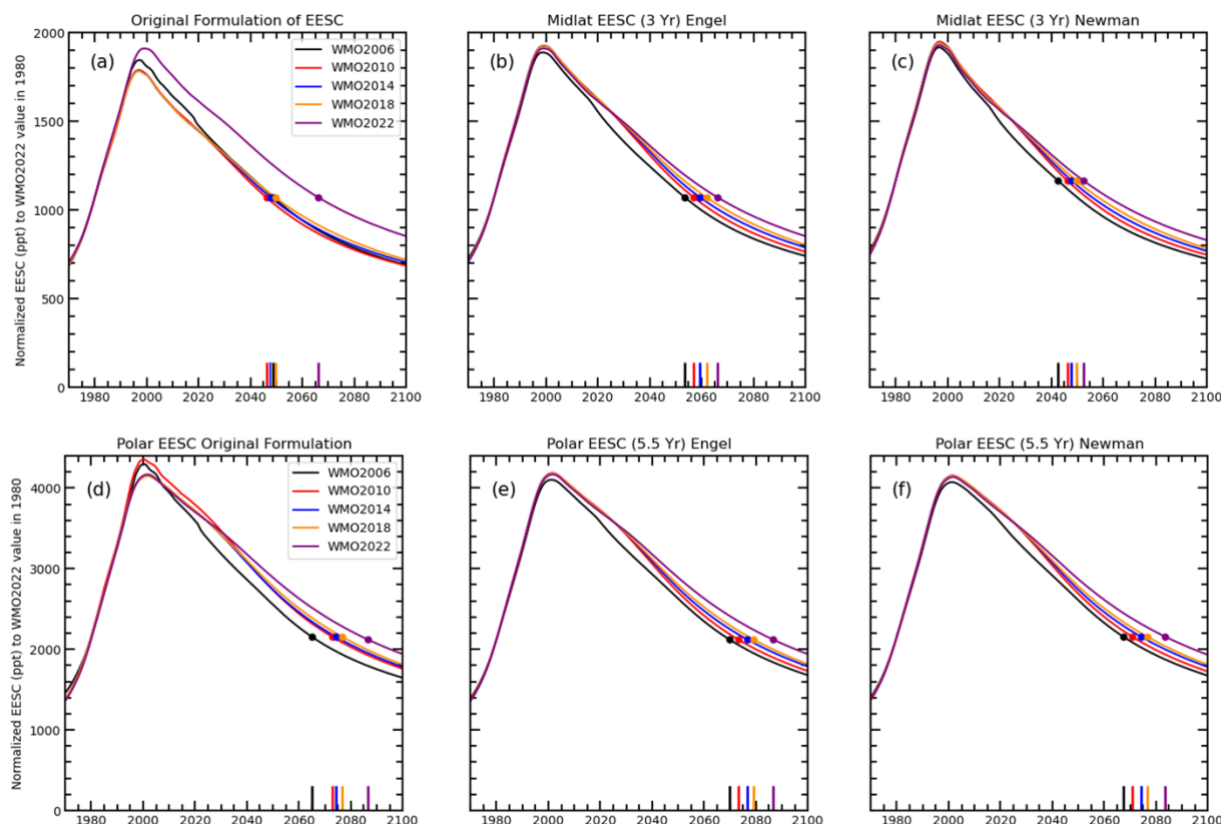
Figure 4. EESC calculations applied to each WMO assessment's atmospheric concentrations. (a) The original assessment's mid-latitude EESC formulations normalized to the WMO (2022) 1980 EESC value. (b) mid-latitude EESC estimates for each WMO assessment's atmospheric concentrations using the Engel et al. (2018) formulation. (c) as in (b) but using the Newman et al. (2007) formulation. (d)-(f) as in (a)-(c) but for polar EESC calculations. Dots and vertical lines on the x-axis refer to the first month in which EESC returns to below 1980 levels for the respective WMO assessment.

Table 2 provides the calculated contribution of each ODS to the delay in the return to 1980 of EESC. CFC-11 and CCl$_4$ account for the largest delays in EESC recovery between the 2006 and 2022 SAOD reports, each delaying cumulative recovery over this period by ~ 4.9 years. Halon-1301 and CFC-12 contribute the third and fourth most substantial delays of 1.4 and 0.8 years, respectively. Note that the impacts on the 1980 return date shown in Table 2 are calculated for each ODS independently. The return to 1980 date for EESC is affected by past and future changes of all ODSs in a non-linear manner such that the sum of the independent impacts across all ODSs (Table 2), when all are changed simultaneously, is not equal to the cumulative sum of the impacts on return date when all ODSs are changed individually (Table S1).

430

Of the four ODSs contributing to the largest delays in ozone recovery, CFC-11, CFC-12 and Halon-1301 are subject to banking. We further investigate the role of each change in modeling assumption for these three ODSs in Fig. 5. Since 2006, projected concentrations of HCFC-22 have decreased by a greater amount than had once been projected. However, the effect on EESC of a faster decline in the atmospheric abundance of HCFC-22 than had once been forecast has been offset by increases in
435 atmospheric abundances of the other aggregated 11 ODSs (that is, the other 15 ODSs excluding the top 4 [CFC-11, CCl_4, halon-1301, and CFC-12]). The implications of HCFC-22 relative to other ODSs are further explored in Fig. 6. Between the 2006 SAOD and 2010 SAOD, updates in CH_3Br delayed the EESC return date by ~2 years. This change is a result of updates in pre-1980 CH_3Br concentrations, which lowered the 1980 EESC baseline value between the 2006 and 2010 assessments (Fig. 3b).

440

The primary results of this analysis are shown in Fig. 5 and Table S1, which quantify the contribution of each modeling assumption to the delay in EESC return dates that is found for midlatitude air for the past 5 SAOD reports. Updating the atmospheric lifetime for CFC-11 from the 45-year value used in the 2006 and 2010 SAOD reports to the 52-year value used in the 2014 to 2022 reports results in a 2.2-year delay in EESC return date. This delay is due to the projected atmospheric
445 mole fractions declining more quickly in the earlier assessments with the shorter assumed CFC-11 lifetime, and also a result of the impact of lifetimes on earlier bank estimation methods. In the 2010 SAOD, for example, the shorter lifetime leads to higher inferred emissions during the time when atmospheric concentration observations were available, and because production was fixed, these higher emissions were modeled as bank emissions. Therefore, banks were estimated to deplete more quickly and were thus projected to be smaller when found using the lower atmospheric lifetime.

450

Updates in observed atmospheric concentrations do not substantially impact our EESC return date estimates for banked gases, relative to the other factors. One initially counter-intuitive result is the impact of observed concentrations of CFC-11 on the 1980 return date, for each SAOD from 2006 to 2018 (Fig. 5). When observed concentrations were higher than had been expected, this finding accelerated the estimated return date using each SAOD's respective projection method. The higher
455 concentrations were assumed to be due to higher-than-expected emissions from banks, which was achieved by increasing the release fractions from banks. This led to estimated bank values decreasing more quickly as the date of each SAOD report advanced, thus being a smaller source of future emission which in turn moved up the return date for EESC. This result is in part due to the assumption in SAODs from 2006 to 2018 that the global production of these banked gases was well known, and that the uncertain parameters controlling bottom-up emissions were in bank release rates, not industrial production. This
460 assumption regarding highly certain production values was relaxed in the bank modeling approach used in 2022 SAOD report, which has led to bank release rates being less sensitive to observed mole fractions.

Updating the bank methodology to the 2022 SAOD report results in notable delays in EESC return dates for all three gases, though most substantially for CFC-11. Bank estimates using the 2022 SAOD methodology result in significantly larger bank
465   estimates (Fig. 1), primarily driven by accounting for the uncertainty in the values of production of ODSs. By relaxing the assumption of full compliance with the controls of the Montreal Protocol, higher atmospheric concentrations and inferred emissions of ODSs may result in higher posterior production estimates, which in turn accumulate into higher bank estimates. This was the case with unexpected emissions of CFC-11 after 2012 (Benish et al., 2021; Lickley et al., 2020; Montzka et al., 2018; Park et al., 2018; Rigby et al., 2019), where allowing for production uncertainty in the banks modeling framework over
470   this time period resulted in posterior production estimates that were non-zero following 2010, and larger posterior bank values than what was inferred by assuming zero production uncertainty and full compliance with the Protocol following 2010.

Changes in understanding of the processes impacting CCl_4 have led to nearly consistent delays in expected EESC return dates (Fig. 5). Updating the atmospheric lifetime from 26 years, which was used in the 2006, 2010, and 2014 SAOD reports to the
475   30-year value used in the 2022 SAOD had two competing effects on EESC return date. The longer lifetime results in lower inferred emissions during the time atmospheric concentration observations were available; however, it also implies a slower decay of the gas in the atmosphere, resulting in a 0.9 year delay in EESC return date. Likewise, the higher-than-projected observed mole fractions of CCl_4 compared with earlier projections contributed an additional 1-year delay in the EESC return date. Because CCl_4 is not a banked chemical, there is no compensating emission source to explain these higher-than-expected
480   mole fractions in earlier SAODs, so the higher-than-expected inferred emissions would be modeled strictly as an emission source from new production of CCl_4. Finally, the additional assumption in the 2022 SAOD report of a long-term, continuous feedstock emissions of 15 Gg/year, which was not accounted for in the projections used in any of the earlier SAODs (Fig. 2), contributes an addition 3.1 years to the delay in EESC from the 2006 compared to the 2022 SAOD report. Overall, updated modeling assumptions for CCl_4 between the 2006 and 2022 SAODs delays the expected EESC return date by a total of 5 years.
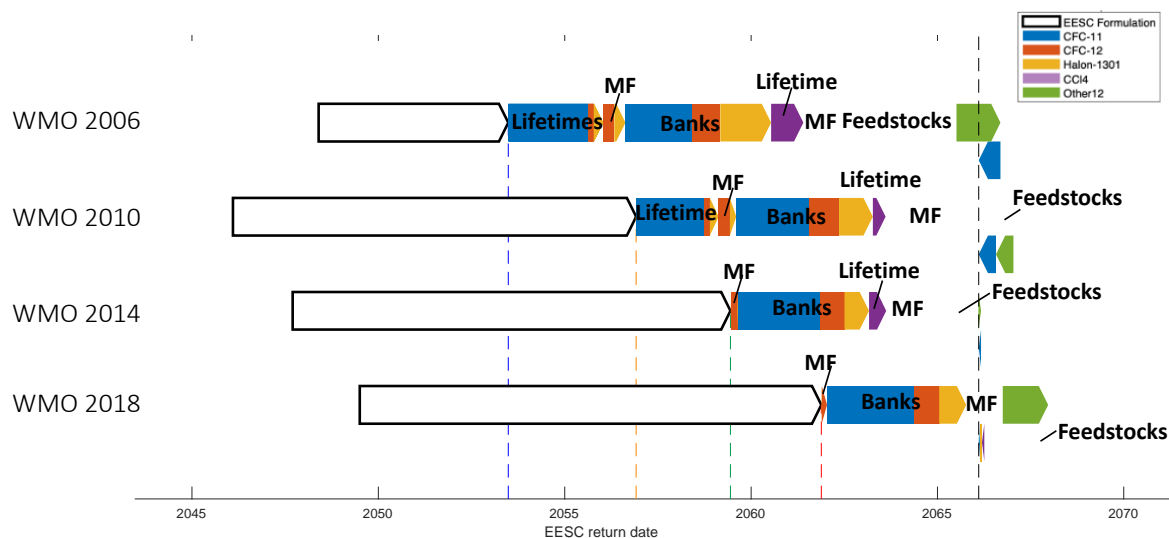
Figure 5. EESC return dates to 1980 levels for each sequential update to the original assessment's methods. The vertical dashed lines correspond to the return date that is estimated after applying the identical (Engel et al. (2018)) EESC formulation to each of the original WMO atmospheric concentration time series for the 16 most prominent ozone depleting substances (ODSs). The corresponding change resulting from the EESC formulation update is shown by the white arrows. The next update corresponds to updating atmospheric lifetime assumptions for the three most prominent bank gases responsible for delaying EESC return date (CFC-11, CFC-12, and halon-1301). The next update corresponds to the update in observed mole fractions since publication of each assessment until 2022, indicated by MF, followed by the banks update. The contribution of projections of CCl$_4$ to delaying EESC return dates is shown in purple for the lifetime updates (dark purple), the observed mole fraction updates (medium purple) and the future feedstock emissions projections (light purple). The remaining 12 gases are shown in green. If the update corresponds to a delay in EESC return date, then the arrow is pointing to the right. If updated assumptions accelerate the return date, the arrow points to the left.

Much of this work focuses on ODSs and their role in estimating EESC, which is an estimate of active (inorganic) halogens in the stratosphere. Because stratospheric halogens originate from organic compounds that are accurately measured in the troposphere, the equivalent effective tropospheric chlorine (EECl) is often considered in parallel with EESC when reporting trends in ODSs. We evaluate the historical and projected values of EECl for each SAOD report considered in this analysis, for the 16 principal ODSs (Fig. 6a). We find that the 1980 return date of EECl, for SAODs from 2006 to 2018 are all clustered together around 2046/2047, whereas for the 2022 SAOD report the1980 return date of EECl is around 2054. Repeating this calculation and excluding HCFC-22 (Fig. 6b), we find that the EECl return dates are more evenly delayed between various SAODs. Between the 2006 and 2010 SAODs, the projected emissions of HCFC-22 dropped by a factor of ~ 2, reflecting the 2007 decision by the Parties to accelerate the phase-out of HCFCs (Montzka et al., 2015). Despite the earlier phase-out of

HCFC-22, the estimated EECl return date was not advanced due to increases in the projections of other compounds. This is important information if one is relying solely on EECl as an indicator of expected ozone recovery. While the drop in HCFC-22 makes a large contribution to EECl, there is only a small effect on EESC because most of the loss of HCFC-22 occurs in the troposphere.

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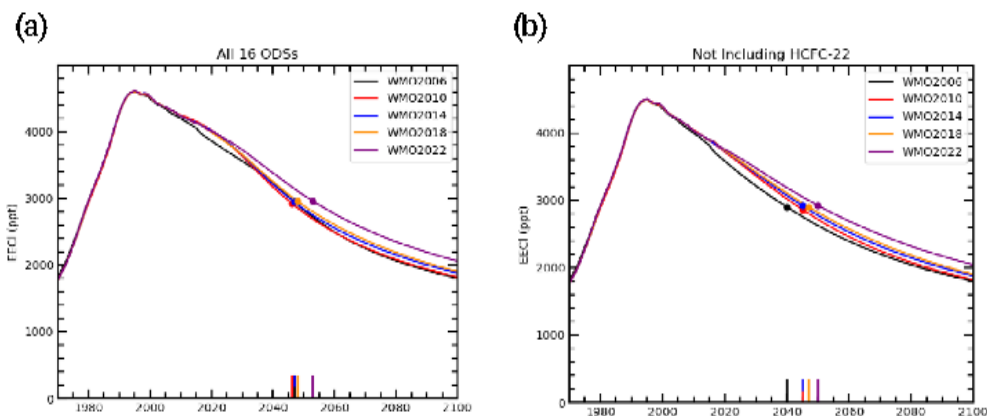
Figure 6. Equivalent effective tropospheric chlorine (EECl) estimates for each WMO assessment ODS atmospheric concentrations. (a) EECl calculated using all 16 ODSs and (b) EECl calculations excluding HCFC-22. Dots and vertical lines on the x-axis refer to the first month in which EECl returns to below 1980 levels for the respective WMO assessment.

515

5 Discussion and Conclusions

520 Between the 2006 and the 2022 SAOD reports, the expected year for which EESC of midlatitude (3-year old air) returns to the value of EESC at the start of 1980 has been delayed by ~17 years. This change suggests, all else being equal, an approximate 17-year delay in the recovery of midlatitude ozone column with respect to the value that occurred in 1980. Reported EESC recovery dates were relatively consistent between the 2006 and 2018 SAOD reports, with the value given in the 2022 report appearing to be an outlier. However, applying identical formulations to the computation of EESC to projections of the 16 525 principal ODSs of each SAOD report indicates, as shown above, that the EESC recovery time has been consistently delayed by 2 to 4 years between each successive SAOD report. Thus, the changing formulation of EESC between the 2006 and 2018 SAOD reports has obscured the fact that the assessed projections of the atmospheric abundances of ODSs have been consistently updated to higher values, on average, between consecutive reports. Applying an identical formulation for EESC (Engel et al., 2018) to the projections of ODSs from each SAOD report results in a delay of 12.6 years, between the 2006 and 530 2022 SAOD reports, for the recovery of EESC of midlatitude air to the value found for the start of 1980. Lifetime assumptions in the earlier assessments for CFC-11 and other ODSs were lower than the current best estimates, providing an earlier expected

return date for EESC than found using lifetimes in the 2022 SAOD report. Since the 2006 SAOD, changes in atmospheric lifetime estimates can explain approximately ~3.5 years of the difference between the 2006 and 2022 SAOD projected return dates. Higher than expected mole fractions of ODSs explain ~1 year of the difference, largely due to observed mole fractions

535   of CCl_4, which contributed a higher baseline and slower rate of decline in future emissions projections. Changes in bank estimates account for another ~4 years of the difference in EESC return date, and updated future emissions projections of CCl_4, largely due to assumed continued feedstock emissions, account for ~3 years of the difference. The remaining ~1 year discrepancy between SAOD is accounted for by the remaining 12 ODS mole fraction projection updates.

540   An important update in the 2022 SAOD pertains to the assumption that historical production of ODSs were in compliance with the Montreal Protocol. In earlier SAODs, it was assumed that there was no unreported production and therefore unexpected emissions were accounted for by higher release rates from banks. For the 2022 SAOD report, new production of controlled substances not in compliance with the Montreal Protocol was considered; this new production is included implicitly through increases to both atmospheric concentrations and explicitly through the bank size of the affected ODS.   These updates have

545   been made in light of evidence of unreported production of halocarbons in recent years (Benish et al., 2021; Lickley et al., 2022; Montzka et al., 2018; Park et al., 2018; Rigby et al., 2019; Montzka et al., 2021; Park et al., 2021; Sherry et al., 2018) as well as during the 1980s in the Soviet Union at an amount that accounted for ~20% of global production of CFC-11 (Gamlen et al., 1986), suggesting historical production may have been consistently underestimated in earlier SAOD reports. Production of CCl_4 has similarly been consistently underestimated in the SAODs (SPARC, 2016). The CCl_4 budget continues to be a

550   source of uncertainty, as observationally-derived emissions are consistently higher than bottom-up estimates (Daniel and Reimann, 2022). Recent studies have made progress on budget closure (Liang et al., 2014; Park et al., 2018; Sherry et al., 2018 , though bottom-up sources of 15-25 Gg/year (Sherry et al., 2018) are still not within the top-down global emissions range of 34 - 45 Gg/year (Liang et al., 2014). Li et al. (2024) found current atmospheric emissions of CCl_4 from numerous industrial sources such as the manufacture of general-purpose machinery, raw chemical materials, and chemical products.

555   Currently, the use of CCl_4 and other ODSs used as feedstock in the manufacturing process is exempt from control under the Montreal Protocol, likely due to an assumption that the associated atmospheric releases would remain small. The findings of Li et al. (2024), coupled with the continued tendency of atmospheric mole fractions of CCl_4 to lie above prior projections, suggests a portion of the slower than expected decline of EESC is caused by inadvertent atmospheric releases of CCl_4 from a wide range of industrial activities.

560

Following the publication of the 2022 SAOD, further evidence has emerged of increasing concentrations of CFCs from 2010 to 2020 (Western et al., 2023), thought to be driven in part by feedstock-related emissions, and reports have emerged of unreported feedstock emissions at chemical plants (EIA, 2023). The apparent leakage from feedstock activity may warrant increasing controls on their production processes (Andersen et al., 2021; Lickley et al., 2021). Banks represent another

565   opportunity for reducing future halocarbon emissions. While the CFC-11 bank resides largely in foams, which is difficult to

recover, CFC-12 used in refrigeration, and the use of halon-1301 as a fire suppressant may be more accessible for bank collection and subsequent destruction. Full recovery of CFC-12 and halon-1301 banks would accelerate estimated ozone recovery by ~ 3 years, with total bank collection representing an opportunity for accelerating ozone recovery ~6 years of delay (Lickley et al. 2020, 2022). Unexpected emissions and additional controls on ODSs, such as the ones described above, would

570   all impact future SAOD EESC recovery estimates.

In addition to changes in controls on feedstock and bank emissions, updates in the representation of atmospheric processes may also result in changes in expected EESC recovery time in future SAODs. This may include changes in estimate ODS atmospheric residence times resulting from updates in estimates of the Brewer-Dobson circulation (Fleming et al., 2011;

575   Prather et al., 2023), ocean exchanges, and changes in the hydroxyl radical (Wang et al., 2023). There is emerging evidence that very short-lived (VSL) chlorine compounds, which are largely anthropogenic and are not controlled by the Montreal Protocol, might be responsible for the slower than expected decline of HCl in the upper stratosphere (Bednarz et al., 2022; Hossaini et al., 2015; Hossaini et al., 2019). If so, then VSL chlorine compounds might need to be considered for future formulations of EESC.

580

EESC baseline projections serve two important purposes for policy makers. First, they are designed to reflect how the current controls in place under the Montreal Protocol are expected to impact stratospheric halogens, and hence the recovery of the ozone layer, as well as radiative forcing of climate by ODSs. Parties can use this information to identify which additional restrictions could potentially be considered for safeguarding the ozone layer and climate system. Second, the baseline

585   concentration projections used to calculate EESC sets expectations with regards to future abundances of ODSs. These projections have been proven valuable in identifying new and illicit production of banned substances in breach of the Protocol (e.g. Montzka et al. 2018). While global compliance has not been absolute, the effectiveness of the Protocol is clearly evidenced by the current declines in EESC values along with initial signs of the recovery of the ozone layer (Solomon et al., 2016; Dhomse et al., 2018; Weber et al., 2022). The present study shows that consistent delays in the EESC return dates is

590   partially due to unreported production of banned ODSs, and partially driven by scientific uncertainty in atmospheric lifetimes. We would expect updates in the modeling of atmospheric processes to both accelerate or delay expected EESC return dates in the future, and it could be valuable for future SAODs to consider including uncertainty quantifications in their baseline projections to account for the uncertainty in current scientific understanding (for e.g. the uncertainty of atmospheric lifetimes of ODSs). However, changes in EESC return dates resulting mainly in delays are not likely a result of atmospheric

595   uncertainties, but rather suggest the potential for either breaches in the Protocol or significant emissions resulting from the use of ODSs as feedstock, which are not controlled by the Protocol. A continued trend of delayed EESC return dates in future SAODs will require careful consideration by the Parties of the Montreal Protocol regarding current reporting and monitoring procedures and by scientists regarding our understanding of ODS lifetimes and how to best characterize emissions over time.

Expanded monitoring networks and increased transparency from industry, for example, could aid in more rapid detection of

600   illicit emissions in the future and limit further delays in ozone recovery.

Author Contributions

605   All authors designed the methodology. M.J.L., J.S.D, and R.J.S. conducted the analysis. M.J.L and L.A.M. created the figures. All authors contributed to the writing and editing of the manuscript.

Data Availability

All data will be placed in a public repository upon acceptance.

610

Code Availability

All Code will be placed in a public repository upon acceptance.

Competing Interests

615   The authors declare that they have no conflict of interest.

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