

## When will the Antarctic Ozone Hole Recover?

### Popular Summary

Scientists had previously estimated that the Antarctic ozone hole would recover in approximately 2050. New findings now show that the Antarctic ozone hole will fully recover 18 year later in approximately 2068.

The Antarctic ozone hole is a massive loss of ozone that occurs each spring in the Southern Hemisphere. The ozone hole is caused by chlorine and bromine gases in the stratosphere that destroys ozone in a cyclic process known as a catalytic cycle. The chlorine and bromine gases come from human-produced chemicals such as chlorofluorocarbons (CFCs). The Montreal Protocol was ratified in 1987 to limit the production of these ozone-depleting substances. Subsequent agreements completely eliminated production of ozone-depleting substances. Surface observations now show that ozone-depleting substances are declining in our atmosphere, but these substances have very long atmospheric lifetimes (up to 100 years). Because of this slow decline of ozone depleting substances, computer models have predicted that the ozone hole should soon start to diminish and will be fully recovered by 2050.

We have developed a new model that is based upon estimates of chlorine and bromine levels over Antarctica and the temperature of the Antarctic stratosphere in late spring. We have then used future projections of ozone-depleting substances to predict ozone hole recovery. We find that recovery to 1980 levels will occur in approximately 2068, 18 years later than the current estimate of 2050. We also show that the ozone hole is very slowly declining at present, meaning that we should expect large ozone holes until approximately 2018. We further show that nominal Antarctic stratospheric greenhouse gas forced climate change will have a small impact on the ozone hole.

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**Abstract:** The Antarctic ozone hole demonstrates large-scale, man-made effects on our atmosphere. Surface observations now show that human produced ozone depleting substances (ODSs) are declining. The ozone hole should soon start to diminish because of this decline. Herein we demonstrate an ozone hole parametric model. This model is based upon: 1) a new algorithm for estimating Cl and Br levels over Antarctica and 2) late-spring Antarctic stratospheric temperatures. This parametric model explains 95% of the ozone hole area's variance. We use future ODS levels to predict ozone hole recovery. Full recovery to 1980 levels will occur in approximately 2068. The ozone hole area will very slowly decline over the next 2 decades. Detection of a statistically significant decrease of area will not occur until approximately 2024. We further show that nominal Antarctic stratospheric greenhouse gas forced temperature change should have a small impact on the ozone hole.

### Introduction:

As ozone-depleting substances (ODSs) decline, ozone hole recovery has been predicted to occur in approximately 2050 (Hofmann et al., 1997; WMO, 2003). Hofmann et al. (1997) fit ozone with ODS amounts over the 12–20 km layer mean to estimate the recovery date. In WMO (2003) recovery was estimated based upon an ensemble of 3-dimensional models. Ozone recovery will occur in 3 phases: 1) a cessation of ozone decline, 2) a turnaround phase where ozone begins to increase, and 3) full recovery to 1980 levels of ozone. In this paper, for the ozone hole, phase 1 is defined as a cessation of the growth of the ozone hole area, phase 2 is defined as the year of peak area, and phase 3 is defined as the date when the ozone hole has zero area.

Recent analyses have shown that the ozone hole has entered this first stage of recovery because it is no longer growing (Newman et al., 2004; Huck et al., 2005; Yang et al., 2005). These analyses are based upon empirical fits of ozone hole diagnostics to effective equivalent stratospheric chlorine (EESC) and stratospheric temperatures. EESC is a convenient measure of ozone depleting stratospheric chlorine and bromine levels that is estimated from ground-based measurements of halocarbons with assumptions about transit times into the stratosphere (Prather and Watson, 1990; Daniel et al., 1995; Montzka et al., 1996, 1999; WMO, 1999).

This paper describes an estimate of the ozone hole's future based upon a parametric fit of the ozone hole's area to Cl and Br abundances and stratospheric temperature during the past 25 years. Section 2 describes the data sources. Section 3 describes how we estimate

the levels of ODSs over Antarctica used in this parametric fit. Section 4 describes the parametric fit of temperature and ODSs to the ozone hole's area. Section 5 contains both ozone hole recovery dates and uncertainties. Section 6 describes the effects of changing temperatures and ODSs on recovery.

### **Ozone Hole Area**

The ozone hole expanded rapidly during the 1980s, but that expansion slowed in the early 1990s, and appears to have stopped in the last few years. Figure 1 shows TOMS observed average ozone hole area (grey line). The area is determined from version 8 TOMS data between September 21-30 for 1979-2004 (TOMS was not operational in 1985) and OMI in 2005. The area is contained by the 220-DU contour in the Antarctic region. Values below 220 DU represent anthropogenic ozone losses over Antarctica (Newman et al., 2004). The ozone hole peak period is during Sept. 21–30 period, prior to the late spring break-up when Antarctica is fully illuminated. Large area variations result from variations of stratospheric dynamics. The 2002 hole was substantially smaller as a result of the first observed major stratospheric warming in the southern hemisphere, while 2003 was the largest hole observed for this late September period. At present, there is no clear indication that the ozone hole area is decreasing.

The ozone hole area and variation is determined by chemical losses in the vortex collar and meteorological fluctuations that drive collar temperatures (Newman et al., 2004). Vortex collar ozone losses are driven by Cl and Br species derived from ODSs (Anderson et al., 1991). The ODS levels primarily determine the area of the ozone hole. The temperature of the polar vortex collar region has a secondary impact on area (Newman et al., 2004). While Antarctic meteorological analyses are observationally derived, multi-year observations of ODSs, and inorganic Cl and Br levels over Antarctica are unavailable. Therefore, it is necessary to estimate Cl and Br inside the stratospheric polar vortex from trace-gas measurements at Earth's surface and consideration of atmospheric mixing. Newman et al. (2004) fit the area using polar vortex collar temperature and an estimate of effective equivalent stratospheric chlorine (EESC) with a 6-year time lag to account for the delay in time for ODSs and their products to arrive over Antarctica. They showed that the ozone hole is decreasing quite slowly because of the slow decrease of ODSs.

### **Estimates of Inorganic Chlorine and Bromine Abundances in the Stratosphere**

The gases that cause the ozone hole are released as CFCs and other compounds at Earth's surface, and are then carried from the troposphere into the stratosphere in the tropics. These compounds are transported by the Brewer-Dobson circulation, upward through the stratosphere and mesosphere in the tropics and subtropics and then downward over the polar regions. Air that is carried very high in the stratosphere (> 40 km) has a 5–6 year transit time from tropical tropopause to a point inside the polar vortex in the Austral spring (Waugh and Hall, 2002). Over a 5-year period, 95% of  $\text{CFCl}_3$  (CFC-11) is photolyzed from its organic form (Schauffler et al., 2003). This CFC's chlorine is transported downward from the upper stratosphere and mesosphere into the Antarctic

polar vortex near 20 km during the SH winter. Br has a similar pathway, but virtually 100% of the brominated compounds are converted to inorganic forms.

ODSs are not regularly measured in the Antarctic stratosphere, requiring us to estimate their abundances and changes over time. Stratospheric ozone assessments (e.g., WMO, 2003) have estimated halogen levels using EESC from ground-based measurements of halocarbons (Prather and Watson, 1990; Daniel et al., 1995; Montzka et al., 1996, 1999; WMO, 1999). EESC is estimated by using observed surface halogen trends, a lag time for transport to the stratosphere, and rates of ODS degradation for Cl and Br release during this transport. WMO (2003) calculated EESC using halogen values from WMO (2003) Table 1-16 and the following parameters:  $\tau = 45$ , F-11 normalization = 0.8397, and fractional release factors in Table 1-4, second column (from Schauffler et al., 2003 and WMO, 1999) for gases not addressed in Schauffler et al., (2003). Because Br is a more efficient halogen for ozone loss, Cl and Br are combined by scaling Br by the  $\tau$  factor. The F-11 normalization and fractional release values try to account for the partial release of halogens from organic to inorganic Cl and Br species.

Current EESC estimates have three problems. First, EESC is estimated with a time lag of 3 years. This is a reasonable midlatitude time lag at 20 km, but is inappropriate for the Antarctic lower stratosphere. Second, EESC is not estimated using age-of-air spectrum estimates. Third, EESC is not estimated with release rates appropriate for the Antarctic stratosphere. For example, while about 84% of CFC-11 has been converted from organic form after 3 years in the stratosphere, the fraction is closer to 100% after 6 years. Hence, the age-of-air is crucial to correctly estimate total inorganic chlorine ( $Cl_y$ ) and bromine ( $Br_y$ ) in the Antarctic stratosphere (as well as other parts of the stratosphere). The EESC used in Newman et al. (2004) had a 6-year time lag, but used fractional release rates that were not exactly appropriate for the Antarctic stratosphere.

We have reformulated the EESC to more appropriately estimate Antarctic  $Cl_y$  and  $Br_y$  levels. This reformulation uses an appropriate age spectrum for air transported over Antarctica, and ODS fractional release rates that are dependent on the mean age-of-air. We summarize the calculation of equivalent effective Antarctic stratospheric chlorine (EEASC) below. Auxiliary material (<http://code916.gsfc.nasa.gov/People/Newman/AuxSection.pdf>) contains a detailed discussion of this new algorithm for estimating EESC in various regions of the stratosphere.

The degraded products or released fractions of ODSs have been calculated from aircraft observations by Schauffler et al. (1999, 2003). We first use the time series of surface observations from Prinn et al. (2000) to calculate the levels of total Cl and Br over Antarctica convolved with our age-of-air spectrum. Following Schauffler et al. (1999, 2003), we calculate fractional release rates for all species. This technique provides ODS fractional release for mean age-of-air up to about 6 years. Thus, given a mean age-of-air, we can estimate  $Cl_y$  and  $Br_y$  in the stratosphere from the ground observations

Age-of-air over Antarctica has been estimated from both models and limited observations. Waugh and Hall (2002) estimated a 6-year age-of-air to explain globally-averaged HALOE HCl observations at 55 km. Since air is advected downward from the upper stratosphere into the core of the vortex over the course of the Antarctic winter, we estimate age-of-air inside the lower stratospheric polar vortex to be approximately 5–6 years. Andrews et al. (2001) have calculated age-of-air in the Antarctic vortex edge as approximately 5 years in the Austral spring using aircraft observations of CO<sub>2</sub> at the edge of the Antarctic polar vortex. Mean age-of-air in the Arctic lower stratosphere is approximately 5 years, a lower bound on the Antarctic value because of the more dynamically mixed nature of the Arctic (Waugh and Hall, 2002). To generate our estimate of EEASC we use a 5.5 year mean age-of-air with a 2.75-year width to the age spectrum (see Waugh and Hall, 2002), and an  $\tau = 50$  (Chipperfield and Pyle, 1998).

### Parametric model of the ozone hole

The Antarctic ozone long-term trend is well explained by ODS trends. Year-to-year variability can be mainly explained by temperature variability of the collar. We use EEASC and temperature to create a multi-variate regression against the observed area of the ozone hole (grey line in Figure 1). Temperatures are from the NCEP/NCAR data. Temperatures are averaged over 60°–75°S for September 11–30 at 50 hPa (approximately 20 km in altitude). The EEASC and temperature are regressed as quadratic functions against the area constrained by the maximum area occurring at maximum EEASC:

$A = aE + bE^2 + cT + dT^2$ , where  $b = -a/(2E_{\max})$ . In this equation, E is EEASC, T is temperature, and  $E_{\max}$  is the maximum value of EEASC.

The regression of these variables explains 95.6% of the area's variance (correlation of 0.978). The residual standard deviation ( $1\sigma$ ) is estimated as 1.8 million km<sup>2</sup> (indicated by the cyan bar in Figure 1). The blue points in Figure 1 show the area with the temperature terms removed ( $A_i - cT_i - dT_i^2$ ) and black line shows the area fit to the EEASC ( $A = aE + bE^2$ ).

Figure 1 shows that the ozone hole reached a peak value in the early 1990s, but has varied considerably over the last decade. Peak EEASC occurred in 2001 for the 5.5 year mean age. Because of the peak in EEASC, the “fit” area also peaks in 2001. The rapid late 1980s growth and the small increases of area in the mid 1990s occurred as EEASC steadily increased. This implies that the ozone losses in the vortex edge had saturated in the 1990–2004 period (Newman et al., 2004).

The remaining area variability of 1.8 million km<sup>2</sup> has various sources. The large deviation in 1992 resulted from enhancements of stratospheric sulfate aerosols by Mt. Pinatubo (Hofmann et al., 1997). From our temperature regression, a deviation of 1 million km<sup>2</sup> is equivalent to about a temperature uncertainty of 1 K. Comparisons of monthly mean radiosonde and 100-hPa temperatures show good agreement to about 1 K with some pronounced biases in October and November (Marshall, 2002). The gradient of ozone near the 220-DU level is approximately 0.121 million km<sup>2</sup>/DU (Newman et al., 2004). Hence, the 5-DU year-to-year ozone measurement uncertainty in the 220-DU value (R.

McPeters, private communication) is equivalent to a 0.6 million km<sup>2</sup> year-to-year area error. The residual areas are probably a combination of sulfate aerosol impact on chemistry, mis-estimates of H<sub>2</sub>O levels, dehydration and PSC interannual variability, errors from both TOMS and the temperatures, and mis-estimates of the EEASC over Antarctica.

### **Parametric model estimates of ozone hole recovery**

We use future ODS scenarios in our parametric model to predict future ozone hole behavior. The parametric model prediction (black line) is shown in Figure 1 versus year using Scenario Ab from WMO (2003). Again, we have used a 5.5 year mean age-of-air and a 2.75-year age spectrum width in this estimate. The area remains large for at least the next decade. By 2017 the area begins to decrease. This plateau period of relatively unchanged area contrasts with the sharper peak of EESC that has been calculated from surface observations (WMO, 2003). The plateau results from the insensitivity of ozone losses over Antarctica to Cl and Br levels (i.e., loss saturation) plus the slow ODS recovery. Area decrease will not occur until EEASC has substantially fallen over Antarctica. While the ozone hole turnaround occurred in approximately 2001 (based upon our EEASC), this slow decline will not be immediately detectable.

Full ozone hole recovery to a zero area is projected to occur in 2068. This is 18 years later than the current WMO (2003) recovery estimate. A statistically significant area decline from the turnaround and the plateau period will not be detectable until about 2024. We define the year of this statistically significant decrease as the “first detection” year. We estimate this year by calculating the linear downward trend calculated for each year from 2003 and using our estimated  $\sigma = 1.8$  million km<sup>2</sup> with a Student’s T-distribution. Up to 2017 the trend is near zero and progressively becomes more negative each year beyond 2017. The 2024 “first detection” year occurs after the ozone hole has decreased in area by approximately 3–4 million km<sup>2</sup> (1–2  $\sigma$ ) from the 23.7 million km<sup>2</sup> mean peak.

Uncertainty in our area fits arise from uncertainties in age-of-air, age spectrum width, and EEASC. This uncertainty is calculated by performing Monte Carlo simulations of the EEASC and by using a bootstrap technique on the area estimate. Simulated 1979-2005 area time series are created by adding the area fit (black line in Figure 1) plus a resampling of the residual errors (deviations of the blue points from the black line). The EEASC time series is calculated by using a Monte Carlo technique on the mean age-of-air ( $\sigma=0.5$  years) and age spectrum width ( $\sigma=0.5$  years), and then adding 80 pptv of random variations to the EEASC to account for transport variations. The 80 pptv is estimated from interannual variability in the GSFC chemical transport model (Kawa et al., 2002). This 80 pptv variability results from interannual variability of vertical advection and mixing that affects Cl<sub>y</sub>, Br<sub>y</sub>, and age-of-air estimates. We then use these simulated time series to re-compute the regression of ozone area against EEASC. A total of 8500 simulations were computed. The 95% uncertainty in final recovery is from 2053–2084 (horizontal magenta bar in Figure 1), while the 95% uncertainty in 1st detection is 2018–2030 (horizontal red bar). The largest uncertainty in recovery results

from our estimate of mean age-of-air and the consequent fractional release rates of ODSs. A mean age-of-air of 5 years (width=2.5 years) results in a recovery date of 2058, while a 6-year age (width=3 years) has a recovery of 2074.

In addition to this linear technique, we have used the CUSUM technique (Yang et al., 2004) to estimate the 1<sup>st</sup> detection of turnaround date. In the CUSUM technique, we simulate the ozone hole from 2003-2040 using the black line in Figure 1 with resampled residual errors for each year from our residual deviations. We do 10,000 simulations and calculate the CUSUM for each simulation. We find that 95% of the CUSUMs are negative after 2024, consistent with the 1<sup>st</sup> detection discussed above.

Our full recovery times are later than Hofmann et al. (1997). The EEASC used in their study was taken from ODS measurements from WMO (1995), had a 3-year time lag with respect to the surface observations, no age spectrum, a Br amplification factor of 40, and fractional release rates from Daniel et al. (1995). They concluded that the hole would show first signs of recovery in the 2008–2010 period with a 2050 full recovery. In contrast, our results have a 5.5 year age spectrum, updated ODS levels from WMO (2003), a Br amplification factor of 50, and updated fractional release rates. The main differences with the Hofmann et al. (1997) study is the longer age, and additional constraints supplied from the longer observational records.

We have also estimated recovery from October monthly mean minimum and 65-75°S zonal-mean ozone. We choose an initial point as the average of the two-year 1979–1980 value, consistent with the area estimate. From the October minimum and the zonal mean we obtain a recovery date of 2063, reasonably consistent with the area recovery date of 2068. The first detection of recovery is estimated to be 2023 for the October minimum and 2025 for the zonal mean, again consistent with the area-based estimate of 2024.

### **Future scenarios**

The ozone hole area is strongly related to temperature. Climate assessment models estimate an Antarctic lower stratosphere cooling of approximately -0.25 K/decade (IPCC, 2001). This cooling would increase the hole by approximately 0.2 million km<sup>2</sup>/decade using our temperature regression coefficients. During the 2020–2030 period, the area will be decreasing by 3–5 million km<sup>2</sup>/decade, so the climate change cooling will have small impact and will modestly delay the 1st detection by approximately 1-2 years. We estimate that the cooling will delay full recovery by approximately 4 years. This small delay is uncertain because of: 1) the uncertain magnitude of the cooling estimate, 2) the impact of climate change on the stratospheric circulation and age-of-air, 3) the assumption that the influence of temperature on ozone loss rates in the past is representative of future loss rates, and 4) uncertain predictions of future stratospheric water vapor and their influence on PSCs.

This parametric model can be used to test future scenarios of ozone hole recovery. As an example, we have modified methyl bromide (CH<sub>3</sub>Br, a natural compound and also an agricultural fumigant) in WMO (2003) scenario Ab. Current levels of CH<sub>3</sub>Br are

specified in their scenario to maximize in 1999 at 9.5 pptv and fall to a fixed level of about 8.2 pptv by 2016 because of production phase out. CH<sub>3</sub>Br has a short life-time of only 0.7 years. If we permanently fix CH<sub>3</sub>Br at 9.5 pptv and adjust the EEASC into the future, we estimate the ozone hole full recovery is increased by 3.7 years.

## Conclusions

In this paper we estimate Antarctic ozone hole recovery using the ozone hole's area as our prognostic variable. Newman et al. (2004) showed that: 1) the area was primarily controlled by Cl<sub>y</sub>, Br<sub>y</sub>, and temperature, 2) the area was no longer strongly increasing, 3) the ozone hole was decreasing at a very slow rate of approximately 1% per year based upon the slow decrease of Cl<sub>y</sub> and Br<sub>y</sub> estimates, and 4) the slow decrease would be masked by year-to-year variability. This paper extends the ozone hole area estimates into the future using Cl<sub>y</sub> and Br<sub>y</sub> projected values to 2100.

We have recalculated EEASC over Antarctica using a new algorithm that uses an age-of-air spectrum with a 5.5-year mean age and an age that is consistent with ODS fractional release rates. The Cl<sub>y</sub> estimate over Antarctica shows reasonable agreement with HALOE HCl observations (see auxiliary material at <http://code916.gsfc.nasa.gov/People/Newman/AuxSection.pdf>). Because of the 5.5-year mean age, previous studies that used a 3-year shift of EESC (e.g., WMO, 2003) over Antarctica had EESC peaking in 1997, at least 2–3 years earlier than would be expected and with a stronger EESC decrease in the 1998–2004 period.

Based upon our new estimates of EEASC, we estimate that the Antarctic ozone hole will fully recover in about 2068, 18 years later than the current WMO (2003) estimate. Using a conventional linear analysis, the turnaround of the ozone hole's area will not be statistically detectable until about 2024 (after removal of temperature effects). In contrast to the Newman et al. (2004) estimate of a 1% per year decrease of ozone hole area, we now estimate that the ozone hole is decreasing in area by less than 0.3% per year until about 2010 with recovery accelerating after this slow decrease period.

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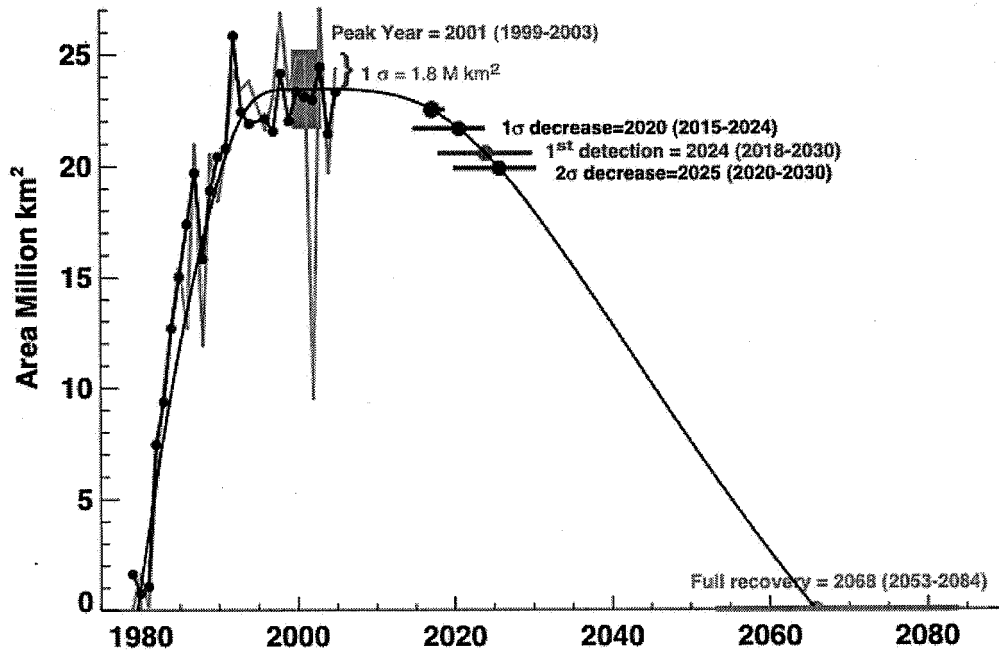


Figure 1. Ozone hole area versus time. Grey line shows ozone hole area averaged from Sept. 21-30 daily values. Blue line is from area values (grey line) corrected for temperature. Black line shows area fit to EEASC for the 1979-2005 period extrapolated using WMO (2003) scenario Ab. The horizontal bars show uncertainties in date estimates (see text for details).