On the size of the Antarctic ozone hole

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[1] A primary estimate of the severity of the Antarctic ozone hole is its size. The size is calculated from the area contained by total column ozone values less than 220 Dobson Units (DU) during September–October. The 220-DU value is used because it is lower than pre-1980 observed ozone values, and because it is in the strong ozone gradient region. We quantitatively show that the ozone hole size is primarily sensitive to effective stratospheric chlorine trends, and secondarily to the year-to-year variations in temperatures near the edge of the polar vortex. Temperatures are in turn sensitive to variations in tropospheric planetary wave forcing of the Southern Hemisphere stratosphere. Currently the average hole size reaches approximately 25 million km^2 each spring. Slow decreases of ozone depleting substances will only result in a decrease of about 1 million km^2 by 2015. This slow size decrease will be obscured by large dynamically forced year-to-year variations of 4 million km^2 (1σ), and possibly delayed by greenhouse gas cooling of the Antarctic stratosphere. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334). **Citation:** Newman, P. A., S. R. Kawa, and E. R. Nash (2004), On the size of the Antarctic ozone hole, *Geophys. Res. Lett.*, *31*, L21104, doi:10.1029/2004GL020596.

1. Introduction

[2] The geographical size of the Antarctic ozone hole is used as a primary diagnostic of its severity [e.g., *World Meteorological Organization* (*WMO*), 2003]. The size is primarily controlled by catalytic ozone losses in reaction with chlorine (Cl) and bromine (Br). Modeling studies have shown that growth in size from pre-1979 to the present is consistent with photochemical destruction and trends in Cl and Br [*Butchart and Austin*, 1996; *Schoeberl et al.*, 1996]. New coupled chemistry climate models have also modeled size over the last few decades and into the future. These studies predict recovery of ozone by about 2050 [*Austin et al.*, 2003]. Year-to-year ozone hole size variations are approximately 10–20%. These variations have been qualitatively related to stratospheric temperatures and dynamics [*Newman and Nash*, 2000; *Schoeberl et al.*, 1996].

[3] The 2002 hole is an interesting case study. It was the smallest observed since 1988 [*Stolarski et al.*, 2004]. Total Cl and Br levels did not significantly change [*WMO*, 2003], but temperatures were warmer than average. *Sinnhuber et al.* [2003], *Newman and Nash* [2004], and others concluded that unusual dynamics was the primary factor in this small hole. However, a quantitative relationship between hole size and dynamics has not been established. In fact, hole size is not directly related to polar vortex size as defined by circumpolar winds [*Bodeker et al.*, 2002].

[4] The goals of this paper are: 1) discuss this size diagnostic, 2) use observations to quantify the connection of stratospheric dynamics to this size, and 3) use a simple model to test sensitivity of size to temperature and chemistry.

2. Data

[5] Total Ozone Mapping Spectrometer (TOMS) data used here are 1° latitude × 1.25° longitude gridded data from Nimbus 7, Meteor 3, and Earth Probe satellites [*McPeters and Labow*, 1996]. Ozone hole area is calculated by integrating the area south of 40°S with values less than 220 DU (see section 3 for the rationale for choosing the 220-DU value). For solar zenith angles greater than 80°, caution needs to be exercised. For this analysis polar night area is filled with values interpolated into the interior using a Barnes analysis of edge observations, effectively partitioning the polar night area amongst the daylight values. If all of the values around the polar night region are less than 220 DU, then the entire region is included in the 220-DU size estimate.

[6] In August and early September, values in polar night near South Pole may be above 220 DU while surrounded by values less than 220 DU. However, it is the area contained by the 220-DU value near the vortex edge that is most important, rather than the area sum less than 220 DU. Because ozone loss requires sunlight, the edge region is most sensitive to variability of halogens and temperatures. Further, polar night area is still effectively part of the hole because its ozone will almost immediately decrease to less than 220 DU on exposure to sunlight. Hence area “contained” by the 220-DU contour is used to measure hole size.

[7] Meteorological data are from the reanalyses of the National Centers for Environmental Prediction and National Center for Atmospheric Research [*Kalnay et al.*, 1996]. Trajectories are calculated using United Kingdom Meteorological Office (UKMO) data [*Swinbank and O’Neill*, 1994].

3. Estimating the Size of the Ozone Hole

[8] Figure 1 displays the ozone hole on 28 September 2001 (the thick black line is the 220-DU contour). The size is 24.5 million km^2, slightly larger than the surface area of the North American continent.

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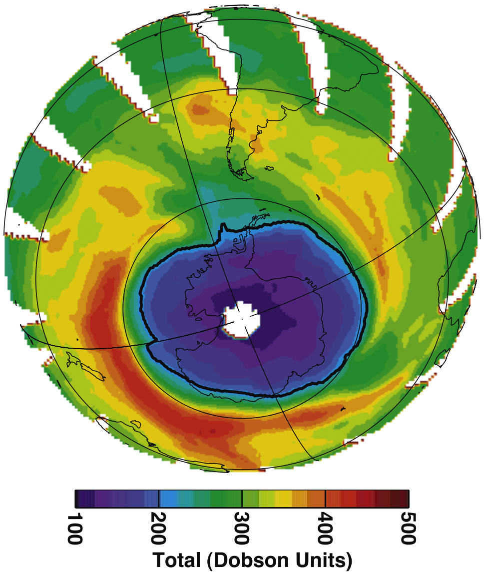

Figure 1. Total column ozone for 28 September 2001 from the Earth Probe TOMS satellite instrument. White areas show data voids, while the thick black line shows the 220-DU contour.

[9] The 220-DU contour is chosen as the edge value because the edge should be lower than measurements prior to the first appearance of the ozone hole in the 1980s. We use observations from Halley Bay, Syowa, and Amundsen-Scott stations to calculate probability distributions during the SH spring going back to 1956 (not shown herein). Prior to 1979, there are very few instances of values below 220 DU, while after 1979 numerous observations are less than 220 DU. In addition the edge value should be located in the region of strong ozone gradient. As seen in Figure 1, the maximum horizontal gradient in this region can be more than 20 DU per degree of latitude. We choose our edge value in this strong gradient region to reduce sensitivity to instrument calibration. Typically, the largest ozone gradient is found for values in the range of 220–270 DU. Size estimates based on values less than 200 DU are much more sensitive to potential calibration and offset effects.

[10] Average size and ranges for 1990–2001 have recently been shown by *Stolarski et al.* [2004, Figure 3]. The size reaches a maximum by the second week of September, and drops off in October. We average daily size estimates for 7 September–13 October. Figure 2 displays these averages for each year of 1979–2003. Vertical bars show the daily range for 7 September–13 October. The upper and lower dashed lines show size estimates based upon the 200- and 240-DU contours, respectively. A 20 DU or 9% difference is equivalent to a size difference of 2–3 million km^2. Since TOMS has an uncertainty of about 3%, the size uncertainty is approximately 1 million km^2. Size growth has slowed in the 1990s, with a precipitous drop in 2002, and the largest value in 2003. The single largest daily value reached nearly 30 million km^2 on 20 September 2000.

4. Dynamical Variations

[11] For constant seasonal conditions, hole size is most sensitive to inorganic chlorine (Cl_y) and bromine (Br_y) abundances in the polar vortex. We estimate Cl_y and Br_y levels by calculating the effective equivalent stratospheric chlorine (EESC) at the surface from *WMO* [2003] with a 6-year time lag to compensate for the time lag between emission and arrival over Antarctica [*Waugh et al.*, 2001], where EESC = Cl_y + 50 Br_y [*WMO*, 2003]. Since not all Cl in the lower stratosphere has been converted to inorganic in the lower stratosphere, this value is multiplied by 0.8 using an empirical relationship between Cl_y and nitrous oxide [*Schauffler et al.*, 2003]. EESC peaks in 1999 at 3.0 ppbv. We quadratically fit average size to September EESC values for the 1979–2003. We then subtract the fit to obtain a residual hole size. For the size fit, we use the 21–30 September average (denoted in Figure 2 by stars) since this is a period when the hole is well developed, and TOMS observations extend to the pole.

[12] The hole size residuals have year-to-year variations of 4 million km^2 (1σ). Figure 3 displays size residual as the black line. *Kawa et al.* [1997] have used aircraft observations in the vortex edge to show that reactive Cl is very sensitive to temperatures near 195 K. Midwinter temperatures at the vortex edge (60°S) are about 200 K, while the vortex center (80°–90°S) typically has temperatures below 190 K. A zonally symmetric ozone hole of 25 million km^2 would be at 64.4°S. *Lee et al.* [2001] have shown that the polar vortex at 480 K is separated into a well-mixed zone in the equivalent latitude range of 70°–90°S, and a weakly mixed zone of approximately 60°–70°S. The hole edge is most sensitive to temperature and chemistry in this "weakly" mixed region.

[13] During the early years of the hole (1975–1982), the 220-DU contour is sometimes found deep in the vortex core and not at the edge. In these early years the 220-DU value does not reflect processes occurring in the edge region. However, using zonal mean total ozone residuals in the vortex, we still see an excellent relationship to temperature.

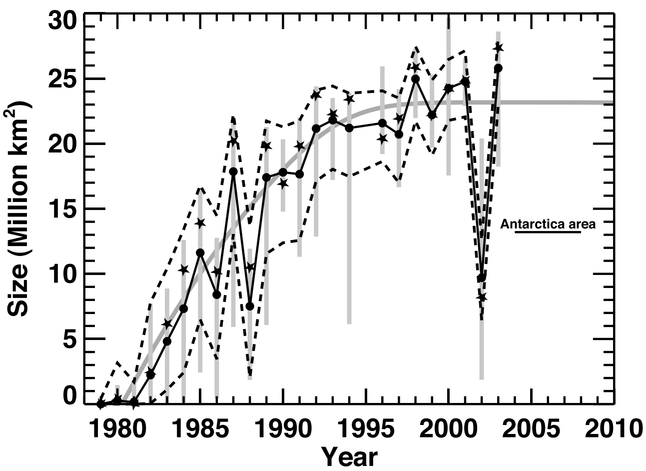

Figure 2. Size of the ozone hole for 1979–2003 averaged from daily total ozone area contained by the 220-DU value for 7 September–13 October (solid line with circles) (updated from *WMO* [2003, Figures 3–7]). Vertical gray bars show the range of those values, and the lower and upper dashed lines show the area contained by the 200- and 240-DU contours, respectively. Stars indicate area averaged from daily values for 21–30 September, the peak hole period. The smoothed gray line is discussed in the text.

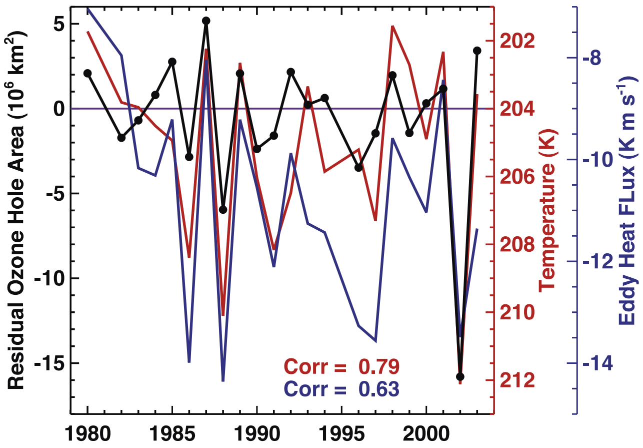

Figure 3. Residual of hole size calculated from hole size averaged for 21–30 September (black line with circles), zonal-mean average (55°–75°S) of 50-hPa temperature for 11–20 September (red line, note reversed scale), and zonal-mean average (45°–65°S) of 100-hPa eddy heat flux for 1 July–10 September.

[14] While high EESC levels are necessary for large ozone loss, warmer temperatures lessen the surface area and decrease the reactivity of swollen sulfate aerosol cloud particles, reducing reactive Cl, resulting in decreased loss. Figure 3 shows (red line) the 55°–75°S zonal-mean temperature at 50 hPa for 11–20 September (immediately preceding the size estimate). Residual size correlates with temperature at $r = -0.79$. Interannual variability of temperature in the collar is 2.7 K. Hence to first order, temperature in the vortex collar strongly modulates the size. A temperature decrease of 1 K in the collar leads to an increase in size of 1.1 million km^2.

[15] Temperature variability depends on tropospheric wave driving of the stratosphere [*Newman et al.*, 2001]. Figure 3 includes a measure of the wave driving: 100 hPa meridional eddy heat flux (blue line). Eddy heat flux is proportional to vertical flux of wave energy into the stratosphere and temperature is correlated with wave driving. Wave driving through midwinter and fall (July to early September in Figure 3) warms the stratosphere by mid September. Warmer temperature leads to a smaller size. Increased wave driving also increases vertical advection of ozone into the polar lower stratosphere. Typically, this Antarctic vertical advection is weak in late winter [*Rosenfield et al.*, 1994].

[16] We have also fitted the hole to the size of the polar vortex using the criteria of *Nash et al.* [1996] using potential vorticity on the 465 K isentropic surface. In agreement with *Bodeker et al.* [2002] we find an insignificant correlation of 0.1 between vortex and ozone hole size. This non-relationship appears to be caused by warm temperatures near the vortex collar. While temperatures are quite cold in the vortex core, temperature increases above the PSC formation temperature inside the vortex as the edge is approached from the core. Therefore, the hole is always somewhat smaller than the stratospheric polar vortex. Further, vortex size has small year-to-year variability of 1°–2°, and this variability is not highly correlated with interannual temperature variability.

[17] The fit of hole size to EESC further reveals that the growth rate of the hole slows as EESC increases above 2.6 ppbv in 1993. EESC increases after 1993 by about 0.4 ppbv (14%), but size only modestly increases in this period. This suggests that for very large ozone holes, size has almost reached a threshold that is constrained by warmer temperatures in the vortex collar.

5. Trajectory and Chemistry Modeling

[18] Following *Schoeberl et al.* [1996], we use a simple trajectory model to estimate the impact of temperature and EESC on size in late September. While they used three isentropic levels, we have used ozonesonde observations (hereafter referred to as sondes) at the hole's edge to show that total ozone is correlated with ozone mixing ratio at the 465 K isentropic level ($r = 0.85$). Again from the sonde analysis, an ozone mixing ratio of 1.44 ppmv corresponds to a 220 DU column ozone value. With sondes alone, prior to 1985 we find no column less than 220 DU or mixing ratio less than 1.5 ppmv. We conclude that a single layer diabatic model can adequately represent the hole's evolution.

[19] We choose 38 parcel trajectories initialized from Syowa, Marambio, and Neumayer sondes near the vortex edge after 1991 during September. These stations are chosen because their observations were made in the *Lee et al.* [2001] "weakly" mixed region. The 50-day diabatic trajectories are run using UKMO analyses. The trajectory model is described by *Schoeberl et al.* [1996] and the chemistry package is described by *Kawa et al.* [1997]. Overhead ozone is determined from an empirical fit to sondes as a function of date and pressure. Nitric acid and water are initialized from UARS data, while ozone is initialized with a temporal fit to sondes that start with a value of 2.85 ppmv on 1 August. A base case run shows a 50% ozone loss in the vortex edge by mid September, in good agreement with September sondes.

[20] We test sensitivity of hole size to temperature variations by uniformly adding ±2 K to each trajectory in our ensemble. Colder temperatures lead to greater loss in the air parcels. From these trajectory temperature perturbations, we find an additional ozone loss of −54 ppbv for a 1 K decrease of temperature ($\partial\chi/\partial T = -54$ ppbv K^{-1}). Using $\partial A/\partial T = \partial A/\partial\Omega \; \partial\Omega/\partial\chi \; \partial\chi/\partial T$, we can calculate area sensitivity to temperature. Here A is ozone hole size, T is temperature, Ω is total ozone, and χ is ozone mixing ratio at 465 K. We calculate $\partial A/\partial\Omega$ as 0.121 million km^2 DU^{-1} from the late-September TOMS data during the mid 1990s, and $\partial\Omega/\partial\chi$ is 56 DU $ppmv^{-1}$ from sondes. Combining this with our trajectory sensitivity yields a $\partial A/\partial T$ of −0.37 million km^2 K^{-1}, while the fit to the 1980–2001 data yields a value of -0.66 ± 0.19 million km^2 K^{-1}. Hence our trajectory model is less sensitive to temperature than the estimate from the size residual and temperature analyses. This model underestimate is partially a result of the absence of vertical advection, but could also result from an underestimate of model ozone loss. Nevertheless, the trajectory model is generally consistent with observations.

[21] We test sensitivity of hole size to EESC change by uniformly adjusting EESC in trajectory parcels by ±25%. Greater EESC leads to more ozone loss and an earlier appearance of the 220-DU contour. We estimate from the parcel ensemble that ozone loss is 1.0 ppmv per ppbv

of EESC. Again, using partial derivatives, this yields 6.9 million km^2 per ppbv of EESC, which compares to 4.9 million km^2 per ppbv of EESC from the observed hole size fit. This EESC sensitivity is consistent with *Schoeberl et al.* [1996] and *Butchart and Austin* [1996], and current coupled-chemistry modeled size [*Austin et al.*, 2003]. In addition to the effect of EESC on hole size, higher levels of EESC result in an earlier appearance of the hole during the spring. A 25% increase of EESC from the basic state shifts the appearance of the hole 10 days earlier, while a 25% decrease of EESC shifts it 14 days later.

6. Discussion

[22] In this paper we have shown estimates of ozone hole size. We have also shown from empirical fits that size is mainly controlled by stratospheric Cl and Br and secondarily by temperature in the polar vortex collar. We have used a simple trajectory model to show that these empirical fits are consistent with our theoretical calculations.

[23] Effective equivalent stratospheric chlorine is currently decreasing at a rate of about 1% yr^{-1} since 1999 [*WMO*, 2003]. The size fit to EESC is shown as the thick grey line in Figure 2 with temperature variations removed, and an extrapolation to 2010 based upon EESC projections. From this empirical fit of EESC we can estimate that the hole size is decreasing at a slow rate of less than 0.1 million km^2 yr^{-1} (0.4% yr^{-1}). Only a few per cent decrease from maximum size will have occurred by 2015 solely as a result of decreasing halogens (see Figure 2). The reduction of EESC will also lead to a later appearance in spring of the hole by approximately 0.6 d yr^{-1}. This very slow recovery results from both a slow decline of halogens and near saturation of ozone loss in the polar vortex collar.

[24] The year-to-year variation of temperatures in the polar vortex collar causes hole size variations of a few million square kilometers. Antarctic ozone recovery due to decline of Cl and Br compounds will be masked by ozone interannual variability caused by temperature and dynamics.

[25] Cooling of the stratosphere by well-mixed greenhouse gases has been predicted in a number of climate simulations. *Butchart et al.* [2000] predict a cooling of 0.5–1.5 K by 2010 over the Antarctic region in comparison to a 1992–2001 model average. This would lead to an increase of hole size by 0.33–1.00 million km^2 by 2010, offsetting the decrease of size from decreasing Cl_y and Br_y.

[26] In addition to direct cooling effects of greenhouse gases, an indirect effect of climate change is modification of tropospheric wave energy propagating into the stratosphere. At present, chemistry-climate model simulations of these wave driving changes are uncertain [*Austin et al.*, 2003]. A wave-driving reduction: 1) decreases temperatures and thereby increases ozone destruction via Cl_y and Br_y reactions, and 2) reduces advection of ozone into the polar vortex collar. A 10% decrease of wave driving leads to a 1.2 million km^2 increase of hole size. As Cl and Br recover to pre-1980 levels, losses due to direct cooling will also decrease [*WMO*, 2003]. However, decreases or increases of ozone advection due to changed wave driving are not impacted by Cl_y and Br_y levels. Hence a climate shift that produces a decrease of wave driving will also produce a consequent decrease of ozone.

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