

Interannual variability in Antarctic ozone depletion controlled by planetary waves and polar temperature

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[1] The dependence of Antarctic ozone depletion on midlatitude planetary wave activity and South Pole temperatures was examined from 1979–2003 using NCEP/NCAR reanalyses and column ozone data. The annual severity of Antarctic ozone depletion was quantified using the seasonal mean of daily ozone mass deficit (OMD). The dependence of annual mean OMD on effective equivalent stratospheric chlorine (EESC) was removed to produce an anomaly time series (OMD'). Similar anomaly time series for 100 hPa South Pole temperatures (T') and 20 hPa, 60°S midlatitude planetary wave activity (PWA') were calculated. Regression of OMD' against T' and PWA' shows that most of the interannual variability in Antarctic ozone depletion can be explained by variability in midlatitude planetary wave activity and South Pole temperatures. To estimate how future changes in South Pole temperatures, midlatitude wave activity and EESC will affect Antarctic ozone depletion, the regression model was applied to T' and PWA' values from a chemistry-climate model run (1975–2019). **Citation:** Huck, P. E., A. J. McDonald, G. E. Bodeker, and H. Struthers (2005), Interannual variability in Antarctic ozone depletion controlled by planetary waves and polar temperature, *Geophys. Res. Lett.*, 32, L13819, doi:10.1029/2005GL022943.

1. Introduction

[2] Previous analyses based on measurements [Bodeker and Scourfield, 1995] and modeling [Shindell *et al.*, 1997] have shown that interannual differences in the severity of Antarctic ozone depletion are anti-correlated with southern hemisphere midlatitude planetary wave activity. Waves can affect the total column ozone distribution directly through meridional and vertical transport of ozone or indirectly through heat transport or displacement and/or elongation of the Antarctic polar vortex. Heat transport induced by upward propagating planetary waves [Schoeberl and Hartmann, 1991] warms the vortex which reduces the occurrence of polar stratospheric clouds (PSCs), a key prerequisite for the heterogeneous chemistry that depletes ozone. Displacement away from the pole or elongation of the vortex perturbs the polar photochemistry [Solomon *et al.*, 1993] and can initiate earlier ozone destruction than would have occurred in the undisturbed circumpolar flow [Austin and Butchart, 1992]. An example of how midlatitude planetary waves perturb the Antarctic ozone hole was

the wave induced sudden stratospheric warming in 2002, the first since observations began, which split the polar vortex and lead to the smallest ozone hole since 1988 [Hoppel *et al.*, 2003; Sinnhuber *et al.*, 2003].

[3] There are a number of metrics which can be used to quantify the severity of Antarctic ozone depletion. Most often ozone hole size, OHS [Newman *et al.*, 2004; Alvarez-Madrigo and Pérez-Peraza, 2005], or ozone minima over Antarctica [World Meteorological Organization (WMO), 2003] are used. OHS, however, suffers from saturation, showing little growth over the 1990s and relative insensitivity to future stratospheric halogen loading [Newman *et al.*, 2004]. Ozone minima have also shown little change since 1990 [WMO, 2003]. In contrast, ozone mass deficit (OMD), which combines the effects of changes in ozone hole area and depth, almost doubles during the 1990s and is more sensitive to future changes in stratospheric halogen loading than OHS [Bodeker *et al.*, 2005]. Therefore, in this study we have used OMD as the metric for the severity of Antarctic ozone depletion. Interannual variability in OHS is affected primarily by variability in the vortex collar (55°S–75°S) temperature [Newman *et al.*, 2004]. In this study we have examined the combined effects of polar temperatures and midlatitude planetary wave activity on OMD. It should be noted that the wave driving also affects polar temperatures and that the two influences are coupled.

[4] To investigate the dependence of OMD on polar temperatures (T) and midlatitude planetary wave activity (PWA), OMD anomalies (OMD') are regressed against temperature anomalies (T') and wave activity anomalies (PWA') as detailed in section 2. The correlations and dependencies derived from the regression are presented in section 3 together with an estimate of how the future evolution of Antarctic ozone depletion may depend on polar temperatures and wave activity. The results are discussed and conclusions drawn in section 4.

2. Method

[5] Global ozone fields from version 2 of the NIWA assimilated total column ozone data base [Bodeker *et al.*, 2005] were used to calculate daily ozone mass deficits [Bodeker and Scourfield, 1995]. To relate our results to those from previous studies [Newman and Nash, 2005], and to compare the attributes of different measures of Antarctic ozone depletion, daily measures of the OHS were derived from the same data base. For both measures a threshold of $O_3 < 220$ Dobson Units (DU; $1 \text{ DU} = 2.69 \times 10^{16} \text{ molecules/cm}^2$)

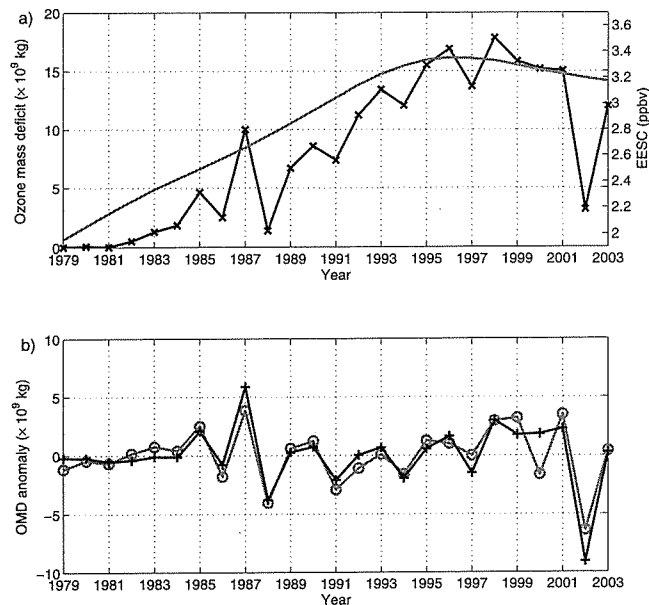


Figure 1. (a) Annual mean OMD plotted against the left ordinate (black) and EESC plotted against the right ordinate (shaded). (b) Measurement based OMD anomalies (black) and OMD anomalies from the regression model (shaded).

south of 40°S was used. The OMD in kg within a given TOMS cell (1.25° longitude × 1° latitude) is given by:

$$\text{OMD} = (220 \text{ DU} - x) \times 2.11 \times 10^{-5} \times A, \quad (1)$$

where x is the total column ozone in DU and A is the area in m^2 of the TOMS cell. These values were summed to produce daily OMDs, which were then averaged over the Antarctic vortex period (AVP; 18 July to 30 November) to produce annual mean OMD values.

[6] The primary driver of long-term changes in OMD is changes in halogen loading of the stratosphere. Therefore annual mean OMD values were first regressed against effective equivalent stratospheric chlorine (EESC) and replaced with their regression residuals (OMD') to produce an anomaly time series independent of stratospheric chlorine and bromine concentrations. The EESC is calculated by combining all ozone depleting substances in the troposphere and adding a time lag for their transport to the stratosphere [Daniel *et al.*, 1995]. EESC data used here were obtained from the European Environment Agency web page at <http://dataservice.eea.eu.int/dataservice/>. Theoretically, ozone loss rates depend on the square of the ClO concentration [Salawitch *et al.*, 1993]. However, complete destruction of ozone within the polar lower stratosphere [Kröger *et al.*, 2003] causes saturation of the ozone destruction chemistry and hence a lower than second order dependence on ClO. Therefore OMD' values were calculated as:

$$\text{OMD}' = \text{OMD} - (a \times \text{EESC}^2 + b \times \text{EESC} + c). \quad (2)$$

Using this equation, it was found that EESC describes ~82% of the variance in OMD. The same equation was used to derive OHS' values. This high correlation is to be expected because of the importance of chlorine and bromine

in driving polar ozone depletion [Solomon, 1999, and references therein].

[7] Two different measures for daily polar stratospheric temperatures were extracted from the NCEP/NCAR reanalyses, viz.: the primary measure of South Pole temperatures at 100 hPa and a secondary measure of zonal mean temperature between 55°S and 75°S equivalent latitude [Butchart and Remsburg, 1986], on the 450 K isentropic surface. Several pressure levels for the stratospheric South Pole temperature were considered, and the values at the 100 hPa level were found to produce the best results. Newman *et al.* [2004] calculated collar temperatures at 50 hPa between 55°S and 75°S geographical latitude. Calculation of zonal mean temperature by geographical latitude when the vortex is distorted away from zonal symmetry, blurs the steep meridional temperature gradient. Therefore we have calculated collar temperatures by equivalent latitude. Daily temperature anomalies were calculated by subtracting the mean annual cycle (1979–2003), and were then averaged over the AVP to provide annual temperature anomalies (T').

[8] Two different measures for daily planetary wave activity were also derived from the NCEP/NCAR reanalyses. The first is wave power (WP) calculated by applying a discrete Fourier transform to the geopotential heights at 60°S and 20 hPa and then taking the root sum of squares of the amplitudes of the first 6 wave modes. Planetary wave energy entering the lower stratosphere can also be specified by the vertical component of the Eliassen-Palm flux [Fusco and Salby, 1999]. Within the quasi-geostrophic approximation, this can be approximated as the zonally averaged eddy heat flux (EHF), $\sqrt{v'T'}$ [Andrews *et al.*, 1987]. The second measure was therefore the EHF calculated at 60°S and 20 hPa. Similar to the polar temperature data, daily WP and EHF anomalies were calculated by subtracting the mean annual cycle (1979–2003), and were then averaged over the AVP to provide annual PWA anomalies (WP' and EHF').

[9] A linear least squares regression model was used to relate OMD' and OHS' to T' and PWA', noting that two different measures for T' and for PWA' are used. The variance explained by the four resultant regression models for each ozone measure provides an indication of which anomaly time series provide the best predictors of the interannual variability in the severity of Antarctic ozone depletion. Assuming that the linear dependencies between OMD', T' and PWA' will not change in the future, the regression coefficients from this empirical model can be applied to T' and PWA' time series extracted from a global climate model or from a chemistry-climate model. This provides an indication of how future trends and interannual variability in T' and/or PWA' may affect the future evolution of Antarctic ozone depletion. To this end, T' and PWA' time series were extracted from a multidecadal run of the Unified Model with Eulerian Transport and Chemistry (UMETRAC [Austin and Butchart, 2003]) chemistry-climate model and used as the basis functions within the statistical model derived above.

3. Results and Discussion

[10] The ozone mass deficits averaged over the Antarctic vortex period are shown together with the EESC in Figure 1a. While the long-term evolution of the OMD follows the halogen loading, there is higher frequency

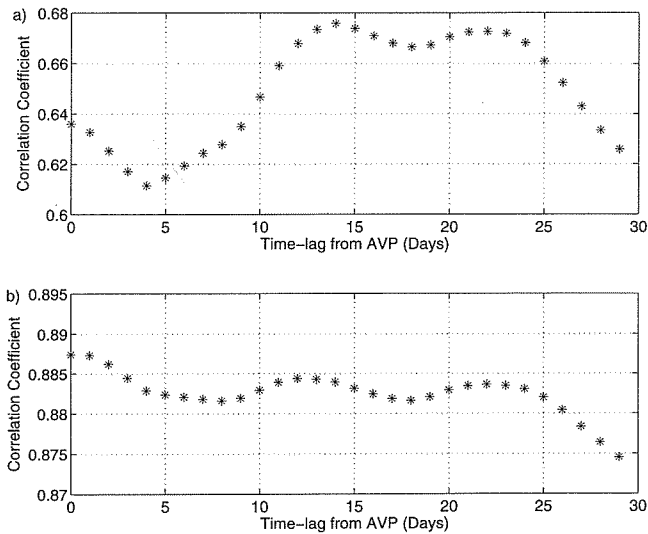


Figure 2. (a) Correlation coefficients (r values) for OMD' correlated against EHF' for lags of 0–30 days applied to the period over which the daily EHF anomalies were averaged. (b) Correlation coefficients (r values) for OMD' correlated against EHF' and T' for lags of 0–30 days applied to the period over which the daily EHF anomalies were averaged.

year-to-year variability where years with anomalously high wave activity (1988 and 2002 [Newman *et al.*, 1990; Newman and Nash, 2005]) show weak Antarctic ozone depletion, and years with suppressed wave activity (1987 [Newman *et al.*, 1990]) show severe ozone depletion.

[11] While the differences in variance explained by the four regression models tested were not large, the model using South Pole temperature anomalies and eddy heat flux anomalies was found to be the best and, unless otherwise stated, it is the results from this model that are reported below. In an earlier study [Newman *et al.*, 2004], vortex collar temperatures were found to strongly modulate interannual variability in OHS. In our study, regression of OMD' against the two temperature anomaly series alone (ignoring the wave activity) suggested that South Pole temperature anomalies (T') are a better predictor of interannual variability in OMD than collar temperatures. Furthermore, it was found that T' can explain more of the interannual variability in OMD' than EHF'. However, our results indicate that addition of EHF' to T' as an explanatory variable produces the best model for explaining interannual variability in OMD'. The measured and modeled OMD' values are plotted in Figure 1b. The good agreement ($r = 0.89$) between the two time series, and in particular the ability of the simple statistical model to capture the anomalous 2002 ozone hole, confirms that most of the interannual variability in Antarctic ozone depletion can be explained by polar temperature and midlatitude eddy heat flux anomalies. Closer examination of the 2000 ozone hole reveals that the polar vortex was strongly distorted during August and September. This could be a reason why the model underestimates the ozone depletion for this year.

[12] Similar analyses using OHS as the measure of Antarctic ozone depletion indicate that South Pole temperature anomalies are a better predictor of OMD' compared to

collar temperature anomalies as a predictor of OHS', if temperature alone is used as an explanatory variable. Furthermore, if both meteorological variables are used as predictors, then EHF' and T' are better predictors of interannual variability in OHS' than EHF' and collar temperature anomalies, but that EHF' and T' explain more of the variance in OMD' than EHF' and T' explain in OHS'.

[13] So far, in this study annual mean values were calculated over the 136 day period from 18 July to 30 November. This however ignores any intraseasonal temporal lags between dynamical drivers and their effect on ozone depletion, for example, anomalous wave activity is expected to influence ozone depletion with some time lag [Shindell *et al.*, 1997; Newman *et al.*, 2004]. To test whether such lags need to be considered, the variance in OMD' explained by the regression model was calculated with increasing time lags (0–30 days) applied to the period over which T' and EHF' were averaged. Correlation coefficients (r values) for the regression model with only EHF' as the explanatory variable, and with lags applied to the EHF' averaging period, are shown in Figure 2a. Lag 1 shows the correlation coefficient between unlagged OMD' and EHF' averaged over 17 July to 29 November, those at 2 are for values averaged over 16 July to 28 November, etc. The highest correlation is found for a lag of two weeks (a similar result was found if WP' was used as the measure of wave activity). Therefore, if only wave activity is to be used as a predictor of variability in Antarctic ozone depletion, a lag of 2 weeks applied to the wave activity metric provides the highest correlation. If temperature alone is used as the predictor the highest correlation is achieved with zero lag. If both EHF' and T' are used as explanatory variables, with lags applied only to EHF', then again the highest correlation is achieved with zero lag (Figure 2b) since the temperature dominates the eddy heat flux in explaining the interannual variability in the ozone depletion (as detailed above).

[14] Using chemistry-climate models (CCMs) to investigate whether recovery of Antarctic ozone is likely to be delayed or accelerated by climate change, is complicated by the fact that there is significant disagreement between different models [WMO, 2003]. Temperature biases within CCMs, and their parameterizations dependent on temperature, for example, PSC formation processes, result in inaccurate representation of the Antarctic ozone hole. However, by using only the year-to-year temperature and wave activity anomalies from a CCM run as the explanatory variables in our regression model, many of these complicating factors are avoided. To this end, time series of WP and T were extracted from the last 20 years of a 1975–2019 run of the UMETRAC chemistry-climate model. Annual mean anomalies of the UMETRAC output were calculated by averaging the daily anomalies (derived in the same way as the NCEP/NCAR anomalies) from 18 July to 30 November. The regression model coefficients derived above, were then applied to the annual mean anomalies to indicate how future changes in OMD' may be driven by future trends in stratospheric temperature and planetary wave activity anomalies, which in turn are likely to be affected by climate change [Butchart and Scaife, 2001]. The resultant OMD' values calculated using the UMETRAC output are compared with those derived from the measurements in Figure 3. The UMETRAC values show higher interannual variability

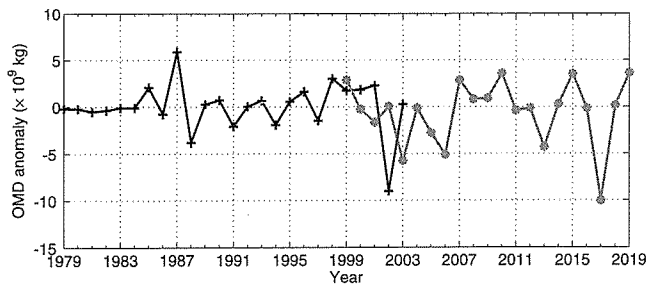


Figure 3. Measurement based OMD anomalies (black, 1979–2003) compared with OMD anomalies derived by applying the regression model to T' and WP' anomalies calculated from UMETRAC output (shaded, 1999–2019).

than the measurements. This is not surprising since it is well-known that UMETRAC displays excess year-to-year variability over the Antarctic [Austin et al., 2003]. From this single model run, there is some indication from Figure 3 that over the latter 20 years of the model run, positive OMD' values are more likely; that is, Antarctic ozone depletion may recover slower than would be expected simply from projected changes in EESC.

4. Conclusions

[15] The analysis presented above shows that halogen loading in the stratosphere is the primary driver of the severity of Antarctic ozone depletion. Furthermore, year-to-year variability on top of this secular change is driven primarily by interannual variability in South Pole temperatures. These temperatures in turn are affected by midlatitude planetary wave activity, and addition of wave activity as an explanatory variable provides the most representative model of interannual variability in Antarctic ozone depletion. Our preliminary investigations of time lags indicate that planetary wave activity is likely to be preferable to temperatures if these dynamical variables are to be used to provide intraseasonal forecasts of the severity of Antarctic ozone depletion. Application of the regression model derived here to output from a single chemistry climate model run suggests that ozone over the Antarctic may recover slower than would be expected from changes in stratospheric halogen loading alone.

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