USING A SIMPLE STATISTICAL MODEL TO ASSESS THE IMPACTS OF GREENHOUSE CLIMATE CHANGE ON RECOVERY OF THE ANTARCTIC OZONE HOLE

Julia Carpenter and David Karoly*
School of Earth Sciences, University of Melbourne, VIC 3010, Australia.

1. INTRODUCTION

In recent years, the magnitude of the Antarctic ozone hole has remained relatively stable. It is currently predicted that springtime Antarctic ozone will return to pre-ozone hole levels by the mid 21st century as ozone depleting substances (ODSs) in the stratosphere return to pre-1980 levels (WMO, 2007).

Recently, increasing concentrations of greenhouse gases in the atmosphere and associated global warming have emerged as a major factor in future atmospheric conditions. It is expected that global temperatures will rise at an unprecedented rate throughout the next century. A predicted and observed consequence of increasing greenhouse gases is a trend of decreasing stratospheric temperatures (Solomon et al., 2007). As ozone depletion is closely related to stratospheric temperatures, the rate and magnitude of this stratospheric cooling may affect Antarctic ozone concentrations.

Previous studies have shown stratospheric temperature and effective equivalent stratospheric chlorine (EESC) to be accurate predictors of Antarctic ozone levels (Huck et al., 2005, Newman et al., 2006). EESC is a measure that quantifies the ozone-depleting potential of ODSs in terms of the equivalent ozone-depleting effect that would occur if all ODSs in the stratosphere were chlorine. The EESC values used in this analysis are adjusted to include a 5.5 year time lag which accounts for the time taken for ODSs to be transported from the surface, where they are emited, to the lower polar stratosphere and the chemical transitions that take place during this time (Newman et al., 2007).

Previous studies have also investigated the addition of planetary wave activity as a predictor of variations of Antarctic ozone (Huck et al., 2005). The vertical propagation of planetary scale Rossby waves from the troposphere into the stratosphere transports heat into the polar vortex, hence warming the stratosphere (Schoeberl and Hartmann, 1991). While the inclusion of wave activity and the associated eddy heat fluxes slightly improved the model's ability to replicate year to year variability, spring stratospheric temperature over Antarctica was the dominant factor in determining interannual ozone variability (Huck et al., 2005). This is because wave activity and stratospheric temperature are strongly correlated, hence very little additional information is included in the model by adding wave activity. For this reason, and because the primary focus of this work is to investigate the Antarctic ozone response to longer term greenhouse gas emission trends rather than interannual variability, planetary wave activity has not been included as a predictor of stratospheric ozone in this study. This exclusion has the added benefit of simplifying the statistical model and allowing it to be used with a wider range of climate model simulations including those that do not provide planetary wave information.

This study has used a multiple linear regression model with EESC and stratospheric temperature as predictors to estimate future total column ozone concentrations in Antarctica. The regression model is developed using observations from 1979-2006. Predictions are made with this model for stratospheric temperatures simulated for three different IPCC greenhouse gas emission scenarios, in order to investigate the effects of climate change on Antarctic ozone recovery.

2. DEVELOPMENT OF THE REGRESSION MODEL

Stratospheric chlorine concentrations are the primary driver of long term ozone variations and interannual variation of Antarctic ozone is dominated by variability in stratospheric temperatures (Solomon et al., 1986; Solomon, 1999; Fahey, 2007). This is demonstrated in Figure 1. A regression model has been developed which forecasts variations of monthly mean ozone from 60-80°S in October using EESC as the sole predictor. As shown in Fig. 1a, the long term trend is well represented but very little of the interannual variability is accounted for. This is reflected in the R^2 value of 0.48 between the observed and predicted ozone. Fig. 1b shows the results from a regression model with 100hPa temperature as the sole predictor. In this case the year-to-year fluctuations in total column ozone in October are well replicated but the overall trend is missing, particularly in the years prior to 1985. The R^2 value for this case is 0.43. By creating a regression model using both EESC and 100hPa temperature as predictors, as in Fig. 1c, both the long and short term trends are accounted for. This is reflected in the very high R^2 value of 0.90.

The regression model was developed using the observed monthly mean total column ozone values derived from the National Aeronautics and Space Administration (NASA) merged ozone data sets (NASA, 2007). Stratospheric temperature data are from the National Centers for Environmental Protection/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al., 1996). Data are expressed as single values representing the monthly mean area-weighted average for 60-90°S for temperature and 60-80°S for ozone due to incomplete ozone data poleward of 80°S.

---

* *Corresponding author address:* David Karoly, School of Earth Sciences, University of Melbourne, VIC 3010, Australia; email: dkaroly@unimelb.edu.au

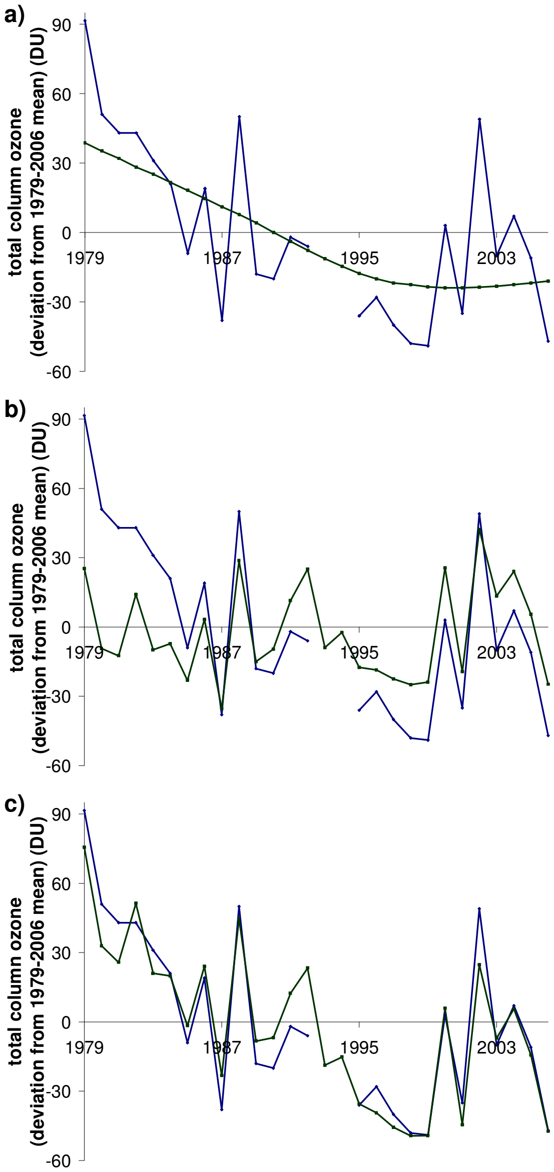

Figure 1. Observed and modeled October mean total column ozone for a regression generated using a) regression generated using EESC as sole predictor of Antarctic ozone; b) 60-90S average 100hPa temperature as sole predictor of Antarctic ozone; and c) both EESC and 100hPa temperature as predictors. In each case the blue line represents observed ozone (60-80°S) and the green indicates ozone predicted using the regression model.

Initially, regression models were produced for each of the southern hemisphere spring months using either 100hPa or 50hPa temperatures. 100hPa temperatures resulted in linear regression models with slightly higher R and R^2 values between observed and predicted ozone compared to 50hPa temperatures. The difference in the results was small and is most likely not indicative of a statistically significant difference between the models. However, as this result is consistent across all three months, 100hPa temperatures are used for the final model.

There are a large number of years, particularly between 1993 and 2006, which was when ozone is declining and at a minimum, where complete ozone data is not available for the entire month of September. Therefore September data are not used in the analysis.

The latitude bands for stratospheric temperature used in previous studies are different to those used in this model. Newman et al. (2006) found that the best correlations occur when using the average temperature from 60-75°S for 11-30 September at 50hPa. Conversely, Huck et al. (2005) achieved their best results using South Pole temperatures at 100hPa rather than a zonal mean temperature for 55-75°S. These differing results are possibly related to the different measures used for ozone loss. Newman et al. (2006) quantify ozone loss in terms of the size of the ozone hole, the maximum area with total ozone below 220 DU. Huck et al. (2005) used ozone mass deficit in order to eliminate saturation effects, which are known to be present when the ozone hole is measured in terms of maximum area (Bodeker et al., 2005). The measure of total column ozone that is used in this study is different again. As the majority of ozone in the atmosphere resides in the lower stratosphere, total column ozone, measured in Dobson Units (DU), is an accurate measure of the severity of the ozone hole. Each of these methods of ozone hole quantification is valid but variations in results may be due to using different methods for determining ozone levels.

The final regression models that will be used in this analysis are:

October ozone anomaly (in DU) = 21.79 – 1.342 x EESC (in ppm) + 5.225 x 100hPa temperature (in K)

November ozone anomaly (in DU) = 24.15 – 1.240 x EESC (in ppm) + 5.870 x 100hPa temperature (in K)

The three variables; EESC, temperature and ozone; have all been expressed in terms of deviations from their 1979-2006 averages. This means that when temperatures predicted by different climate models are used with this regression model, any consistent temperature bias in the climate model will not influence the accuracy of the ozone values predicted by the regression model. It is important to make this change as a number of climate models are used and it is not uncommon for an individual climate model to consistently have biases in its simulated temperature in the Antarctic lower stratosphere.

3. TESTING THE REGRESSION MODEL USING COUPLED CHEMISTRY-CLIMATE MODELS

Coupled Chemistry-Climate Models (CCMs) are an excellent tool for assessing the accuracy of the regression models beyond the time frame of observations. As many of the photochemical processes related to ozone depletion occur in the middle atmosphere, the CCMs' explicit representation of chemical reactions important for ozone, as well as better vertical resolution in the stratosphere and upper troposphere compared to Global Climate Models (GCMs) make these models very useful for testing the regression models.

It is important to note that while globally-averaged ozone is well represented by the CCMs, the modeled ozone hole is not exactly the same as the observed ozone hole. For the Atmospheric Model with Transport and Chemistry (AMTRAC), the October averaged ozone hole is deeper and more prominent than the observed ozone hole. There is a low bias of 30-45DU in the absolute values of Antarctic ozone, but the overall trend of ozone depletion since 1980 agrees with observations (Austin and Wilson, 2006). Conversely, the Canadian middle atmosphere model (CMAM) significantly underestimates the annual column ozone variation in the high latitudes of the southern hemisphere (de Grandpre et al., 2000). The temperature trends seen in each of the models are in agreement, and each shows a statistically significant globally averaged mean cooling in the stratosphere, which is consistent with the cooling trend reported in the most recent IPCC report (Eyring et al., 2007; Trenberth et al., 2007).

EESC (Newman et al., 2007), 100hPa temperatures and total column ozone values from 1980-2006 from the seven CCMs were used to develop multiple regression models to predict Antarctic ozone concentrations. A separate regression model was created using the data from each of the chemistry climate models: AMTRAC, CCSRNIES, CMAM, GEOSCCM, MRI, SOCOL and WACCM. Further details of these models are provided in Eyring et al. (2007). The regression relations were then used to forecast past (1960-2006) and future (2007-2100) ozone variations for each model. The forecasts can then be compared to the ozone values explicitly calculated in the models. Each of these models used greenhouse gas forcings based on the IPCC A1B scenario (Nakicenovic et al., 2000). CFC and halon concentrations were the same as those presented in WMO/UNEP 2003 (Austin and Wilson, 2006).

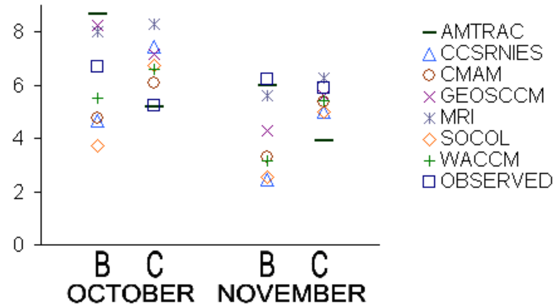

Figure 2. Regression coefficients for CCMs (B=EESC coefficient multiplied by 5, C=temperature coefficient)

A comparrison of regression coefficients for the different CCMs is given in Fig. 2. The regression coefficients are slightly smaller in magnitude when November values are used, as the comparatively higher average November temperature means that changes in EESC and temperature have slightly less effect on ozone concentrations than is seen in October.

Ozone predicted using the multiple regression model correlates very well with the ozone predicted by the CCMs (see Fig. 3). This tells us that given accurate temperature forecasts, the statistical model has a high level of skill in predicting Antarctic ozone variability into the 21st century. The similarity of the regression coefficients between models and observations suggests that, on the whole, the regression model accurately represents the relative influences of EESC and temperature on ozone depletion. It is important to note that there are small negative biases in the predicted ozone from the regression model compared with most of the CCMs for periods further into the future or past. This suggests that non-linearities in the processes determining ozone concentrations, as included in the CCMs, may be important for the prediction of long-term ozone trends and may limit the long-term accuracy of the regression model.

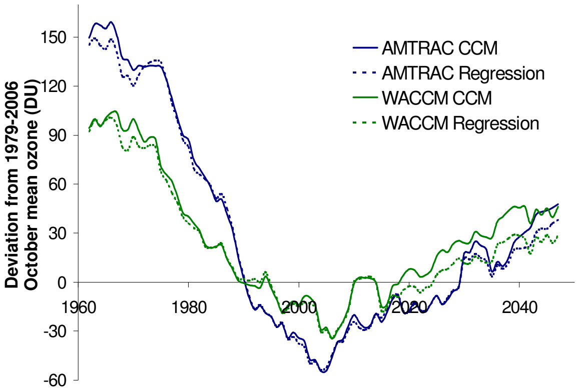

Figure 3. Five-year average CCM ozone and regression ozone from 1960 to 2049 for two CCMs; AMTRAC and WACCM.

4. CLIMATE MODEL TEMPERATURES AND RECOVERY OF THE OZONE HOLE

In order to investigate the influence of anthropogenic greenhouse gas (GHG) emissions on future Antarctic ozone recovery, the multiple regression model is applied to temperatures from ensembles of simulations with five different global climate models available from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007). Each of these models was run multiple times with slight variations in initial conditions using emissions from three GHG scenarios (A2- high emission, A1B-medium emission, B1- low emission). The results are then combined to create a 22 member ensemble for the A1B scenario and 21 member ensembles for A2 and B1 scenarios.

The regression model and coefficients, developed using observed relationships between EESC, monthly mean 100hPa temperature anomalies at 60-90°S for and monthly mean total column ozone anomalies at 60-80°S for October and November, were then applied using monthly mean 100hPa temperature anomalies from the models for the different GHG emission scenarios. As there are variations in the concentration of hydrofluorocarbons (HFCs) in the different IPCC scenarios, but no variation in the CFC concentrations, the same EESC values were used for each scenario. This allows the effect of future temperature changes resulting from each of the GHG scenarios on future Antarctic ozone levels to be investigated. For each of the three GHG emission scenarios, the minimum, maximum and mean ozone (area-weighted average for 60-80°S) was calculated across the multi-model ensemble as a five year moving average in order to eliminate some of the noise due to large interannual variability.

A return to 1980 values is a common definition for ozone recovery and is used by Austin and Wilson (2006), Shindell and Grewe (2002) and Eyring et al. (2007). There is evidence that some Antarctic ozone depletion occurred before this date nevertheless, the exact magnitude of this depletion is difficult to determine due to the lack of satellite data in the region prior to 1979.

The following conditions have been set to define Antarctic ozone recovery from the regression model results: a) The five year anomaly with respect to mean 60-80°S ozone for the given month in 1978-82 is greater than zero; and b) remains greater than zero for the next five consecutive years. The year of recovery is then the last year of the first five year period with a positive ozone anomaly with respect to 1978-82. The best estimate of ozone hole recovery time is given by the mean values. Results are given in Table 1.

October

	Earliest	Average	Latest
B1	2067	2076	2086
A1B	2066	2080	
A2	2065	2086	

November

	Earliest	Average	Latest
B1	2064	2092	
A1B	2066		
A2	2059		

Table 1. Best estimate of the year of Antarctic ozone recovery according to conditions a and b. A blank indicates no recovery prior to 2097. Also included are the years of earliest and latest recovery given by individual model realisations for each of the GHG emissions scenarios.

When compared to Antarctic ozone recovery years cited in recent literature, the results for October are quite similar but there are some important discrepancies. Newman et al. (2006) predict for September a return to 1980 ozone levels in 2068, with a 95% uncertainty range of 2053-2084 for GHG emissions equivalent to the IPCC mid-range scenario.

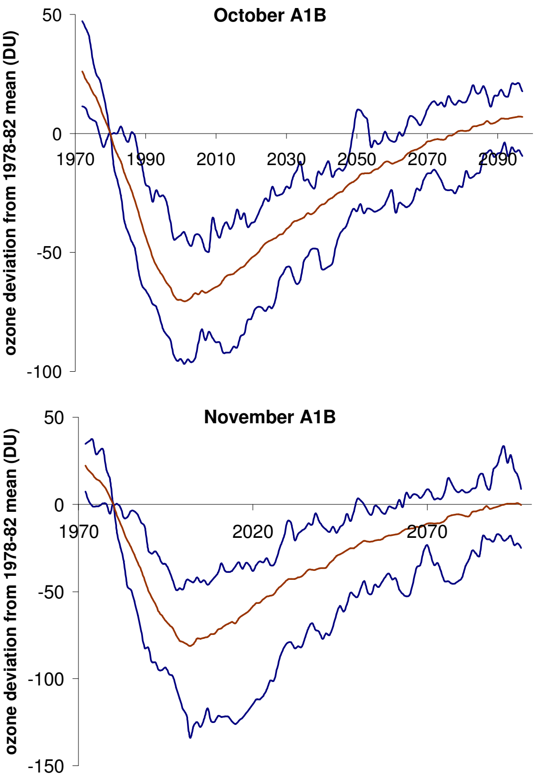

Figure 4. Top: October A1B; Bottom: November A1B. The mean value (red) represents the best estimate of 5-year average ozone for a given year, the average over all 22 ensemble members. The blue lines are the maximum and minimum 5-year moving average ozone concentrations predicted by the multi-model ensemble. Each run has been normalised by setting the 1978-82 mean total column ozone at 60-80°S to zero.

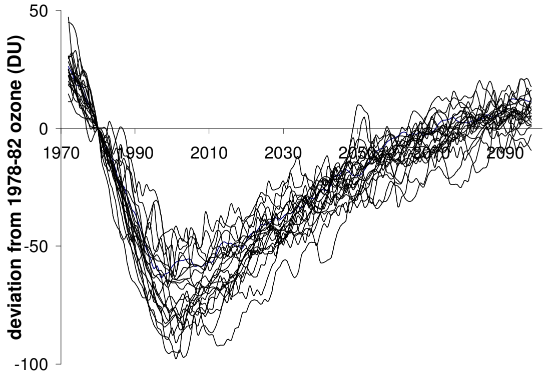

Figure 5. Normalised results of individual model runs for the October A1B scenario.

Stratospheric cooling due to increased GHG emissions was estimated to extend this recovery time by approximately four years (Newman et al. 2006), implying that increased GHG emissions cause only a small delay in ozone recovery. His best estimate is about 15 years earlier and error range is slightly smaller but relatively consistent with those predicted using this statistical model for October ozone hole recovery. Recovery for November is approximately 12 years later than for October, which suggests that the 15 year difference between September and October recovery predictions is not unreasonable. These results are also consistent with those published in the most recent UNEP/WMO ozone assessment (Bodeker et al., 2007). The stratospheric cooling resulting from the high emission (A2) scenario delayed by 6 years the best estimate of October recovery predicted by the statistical model, which is similar to the 4 years estimated by Newman et al. (2006) for September. However, the uncertainty range for this estimate is significantly greater and it is uncertain in some individual model realisations whether full recovery is ever achieved. This suggests it is possible that due to a cooler stratosphere full recovery of Antarctic ozone to 1980 levels may not occur for this high emission scenario.

November results predict even later recovery, and for the A1B and A2 scenarios, the best estimate is that recovery will not occur prior to 2097. The future evolution of November ozone in the Antarctic region has not been investigated in any depth in previous work as Antarctic ozone depletion is most severe in September and October. Thus it is not possible to compare these results to published work. Despite this, the delayed November ozone recovery is consistent with the colder and longer lived polar vortex in November found in recent observations and the CCM model simulations, which provides additional confidence that this delayed recovery is a real phenomenon that merits further investigation.

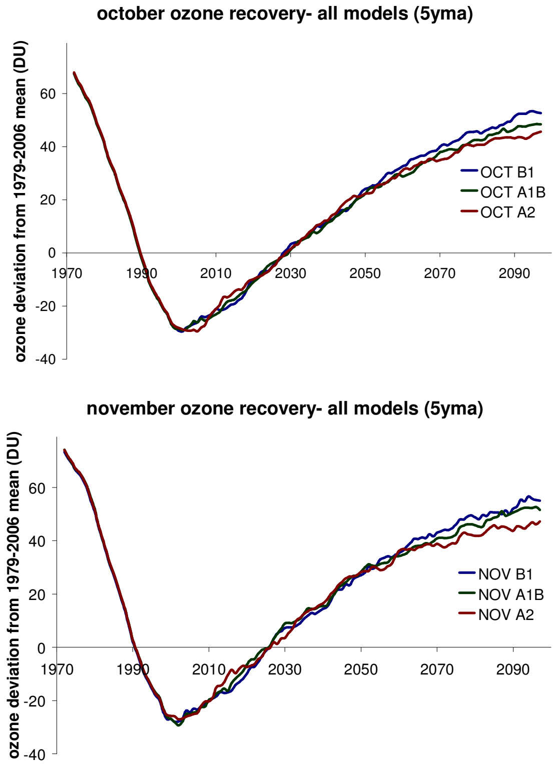

Figure 6. Comparison of predicted Antarctic ozone recovery in October and November for the three GHG emission scenarios.

A question that needs to be asked is why is this statistical model so good at predicting ozone, particularly over such a large timescale. One reason is that the mechanisms of Antarctic ozone depletion are quite well understood and we can be confident that the predictors chosen for this analysis are those which have the greatest influence on stratospheric ozone concentrations. Another reason is that ozone and temperature are not strictly independent, as ozone has an influence on temperature just as temperature influences ozone concentration. This means that by knowing the temperature in the stratosphere, we already have a great deal of information regarding the ozone concentrations, which is why the ozone predicted by the regression model compared so well to the ozone predicted by the chemistry climate models. The net effect of this relationship is that the accuracy of the ozone predictions is only as good as the accuracy of the temperature predictions.

5. CONCLUSIONS

EESC and Antarctic lower stratospheric temperatures are accurate and reliable predictors of Antarctic total column ozone concentrations. Testing against 21st century CCM ozone predictions provides confidence in the regression model’s ability to simulate future ozone concentrations in the Antarctic region provided that the temperatures used are accurate.

For a mid range GHG emission scenario the model predicts a return to pre-1980 ozone levels around 2080 for October and no recovery prior to 2097 for November. For both months the earliest predicted recovery is 2066. A date for latest recovery is not available as temperature data is unavailable past 2100. In each case recovery is expected earlier for the low GHG emission scenario and later for the high GHG scenario but there is not a large difference in the confidence intervals with the exception of the October B1 case.

6. REFERENCES

Austin, J. and Wilson, R.J. (2006) Ensemble simulations of the decline and recovery of stratospheric ozone *Journal of Geophysical Research* **111** doi:10.1029/2005JD006907.

Bodeker, G.E., Shiona, H. and Eskes, H. (2005) Indicators of Antarctic Ozone Depletion *Atmospheric Chemistry and Physics,* **5,** 3811-3845.

Bodeker, G.E. et al. (2007) Chapter 6: The Ozone Layer in the 21st Century. In WMO (World Meteorological Organization) *Scientific Assessment of Ozone Depletion: 2006*, Global Ozone Research and Monitoring Project - Report No. 50, Geneva, pp572.

de Grandpre, J., Beagly, S.R., Fomichev, V.I., Griffioen, E., McConnell, J.C. and Medvedev, A.S. (2000) Ozone climatology using interactive chemistry: Results from the Canadian Middle Atmosphere Model *Journal of Geophysical Research* **105** 26475-91.

Eyring et al. (2007) Multimodel projections of stratospheric ozone in the 21st century *Journal of Geophysical Research* **112** doi:10.1029/2006JD008332.

Fahey, D.W. (Lead Author) (2007), *Twenty Questions and Answers about the Ozone Layer: 2006 Update*, 50 pp., World Meteorological Organization, Geneva, 2007. [Reprinted from *Scientific Assessment of Ozone Depletion: 2006*, Global Ozone Research and Monitoring Project - Report No. 50, 572pp., World Meteorological Organization, Geneva, 2007.]

Huck, P.E. McDonald, A. J. Bodeker, G.E. and Struthers, H. (2005) Interannual variability in Antarctic ozone depletion controlled by planetary waves and polar temperature *Geophysical Research Letters,* **32.** doi:10.1029/2005GL022943.

Kalnay, E. and Coauthors (1996) The NCEP/NCAR Reanalysis 40-year Project. Bull. Amer. Meteor. Soc., **77**, 437-471.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor, 2007: The WCRP CMIP3 multi-model dataset: A new era in climate change research,Bulletin of the American Meteorological Society, 88, 1383-1394.

Nakicenovic, N. et al (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K., 599 pp.

NASA (2007) TOMS/SBUV merged total and profile ozone data sets. http://code613-3.gsfc.nasa.gov/Data_services/merged/index.html

Newman, P.A., Nash, E.R., Randolph Kawa, S., Montzka, S.A. and Schauffler, S.M. (2006) When will the Antarctic ozone hole recover? *Geophysical Research Letters,* **33.**

Newman, P.A., Daniel, J.S., Waugh, D.W. and Nash, E.R. (2007) A new formulation of equivalent effective stratospheric chlorine (EESC) *Atmos. Chem. Phys. Discuss.* **7** 4537-52.

Shindell, D.T. and Grewe, V. (2002) Separating the influence of halogen and climate changes on ozone recovery in the upper atmosphere *Journal of Geophysical Research* **107,** 4144. doi: 10.1029/2001JD000420.

Schoeberl, M.R. and Hartmann, D.L. (1991) The dynamics of the stratospheric polar vortex and its relation to springtime ozone depletions *Science* 251.n4989 pp46-7.

Solomon, S., Rolando, R., Garcia, F., Rowland, S. and Wuebbles, D.J. (1986) On the depletion of Antarctic ozone *Nature,* **321,** 755-758.

Solomon, S. (1999) Stratospheric Ozone Depletion: A Review of Concepts and History. *Reviews of Geophysics,* **37,** 275-316.

Solomon, S. et al. (2007) Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Forth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Trenberth, K.E. et al. (2007) Chapter 3. Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Forth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

WMO (2007) *Executive Summary: Scientific Assessment of Ozone Depletion: 2006*, 39 pp., World Meteorological Organization, Geneva, 2006. [Reprinted from *Scientific Assessment of Ozone Depletion: 2006*, Global Ozone Research and Monitoring Project - Report No. 50, 572pp., World Meteorological Organization, Geneva, 2007.