A transport model study of the breakup of the Antarctic ozone hole in November 2000

Simon Grainger[1] and David J. Karoly[2]

School of Mathematical Sciences, Monash University, Clayton, Australia

Received 22 October 2002; revised 9 December 2002; accepted 29 December 2002; published 4 April 2003.

[1] A 3-D off-line transport model is used to examine the breakup of the Antarctic ozone hole in late November and early December 2000. The use of a transport model enables an analysis of the vortex breakup that is not possible from the use of ozonesonde observations alone. By initializing ozone mixing ratio on 1 September 2000, and using parameterized ozone production and loss rates, the evolution of the Antarctic ozone hole is simulated. The model simulation shows that during late November and early December 2000, the Antarctic ozone hole splits into two sections, with low-ozone air subsequently transported over New Zealand and south-eastern Australia. Modeled ozone values agree well with ozonesonde profiles, confirming the role of horizontal transport in the dilution of mid-latitude ozone. *INDEX TERMS:* 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342). **Citation:** Grainger, S., and D. J. Karoly, A transport model study of the breakup of the Antarctic ozone hole in November 2000, *Geophys. Res. Lett.*, *30*(7), 1368, doi:10.1029/2002GL016494, 2003.

1. Introduction

[2] Since the discovery of the Antarctic ozone hole in the mid-1980s by *Farman et al.* [1985], there has been extensive study of stratospheric ozone loss. The processes involved in the Antarctic ozone hole are now well understood, see *Solomon* [1999] for a review. However, meridional transport out of the polar regions has not been fully quantified, and it is therefore difficult to obtain a quantitative understanding of Southern Hemisphere (SH) mid-latitude ozone loss [*World Meteorological Organisation* (*WMO*), 1999]. One mechanism for mid-latitude ozone loss is dilution caused by the final breakup of the Antarctic ozone hole, proposed by *Atkinson et al.* [1989]. They described a case in December 1987, when low ozone values over Melbourne, Australia appeared to be associated with advection of low-ozone air following the breakup of the Antarctic ozone hole. Subsequently, *Atkinson and Plumb* [1997] examined this case in more detail using contour advection of reconstructed ozone. They found a large contribution to the change in reconstructed ozone during the vortex breakup from quasi-horizontal advection in mid-latitudes. The 1987 polar vortex breakup caused a small but significant mid-latitude dilution effect, but it was unclear whether this extended as far as Melbourne.

[3] Other studies have looked at ozone dilution in the Northern Hemisphere [e.g., *Knudsen et al.*, 1998] and at low ozone events in SH mid-latitudes using observations and trajectory analysis [e.g., *Brinksma et al.*, 1998; *Perez et al.*, 2000; *Cordero and Grainger*, 2002]. Here, ozone is modeled using a 3-D off-line transport model incorporating parameterized ozone production and loss rates. This makes possible an analysis of the vortex breakup and advection to mid-latitude regions that cannot be done by using ozonesonde observations alone. The use of parameterized chemistry means that the evolution of the Antarctic ozone hole can be simulated. The model and data used are briefly described in the next section. A case study, the breakup of the Antarctic ozone hole in late November and early December 2000, is examined in section 3. This case is of particular interest because the transport model simulation and ozonesonde data indicate that reduced ozone values in the lower stratosphere in mid-latitudes were associated with transport of air out of the ozone hole. A discussion of the results is presented in section 4.

2. Model and Data

[4] The transport model has been adapted from the NCAR Middle Atmosphere Community Climate Model version 2 (CCM2). Advection is done using the Semi-Lagrangian Transport (SLT) scheme of *Williamson and Rasch* [1989] with conservation of tracer mass applied after each transport time step [*Rasch et al.*, 1995]. Arbitrary input meteorological data can be used, with tracer output on the same grid as the input data. Variants of CCM2 have been used in a number of stratospheric transport studies [e.g., *Rasch et al.*, 1995; *Li et al.*, 2002, and references therein].

[5] In the transport model, ozone is a passive tracer. Here, ozone chemistry is modeled by applying parameterized production and loss rates at the end of each time step. Rates were taken from the NASA GSFC 2-D chemical transport model [*Rosenfield et al.*, 1997], which uses parameterized polar stratospheric clouds from *Considine et al.* [1994] to simulate development of the Antarctic ozone hole. Although these are climatological rates, they have been successfully used to model the total ozone annual cycle [*Douglass et al.*, 1996].

[6] Wind data is taken from daily UK Met Office UARS analyses [*Swinbank and O'Neill*, 1994]. These have a horizontal resolution of 3.75° longitude by 2.5° latitude at 22 pressure levels from 1000 to 0.31 hPa. One-hour time steps are used, with linear interpolation of winds to each

[1]Now at Bureau of Meteorology Research Centre, Melbourne, Australia.

[2]Now at School of Meteorology, University of Oklahoma, Norman, OK, USA.

0094-8276/03/2002GL016494

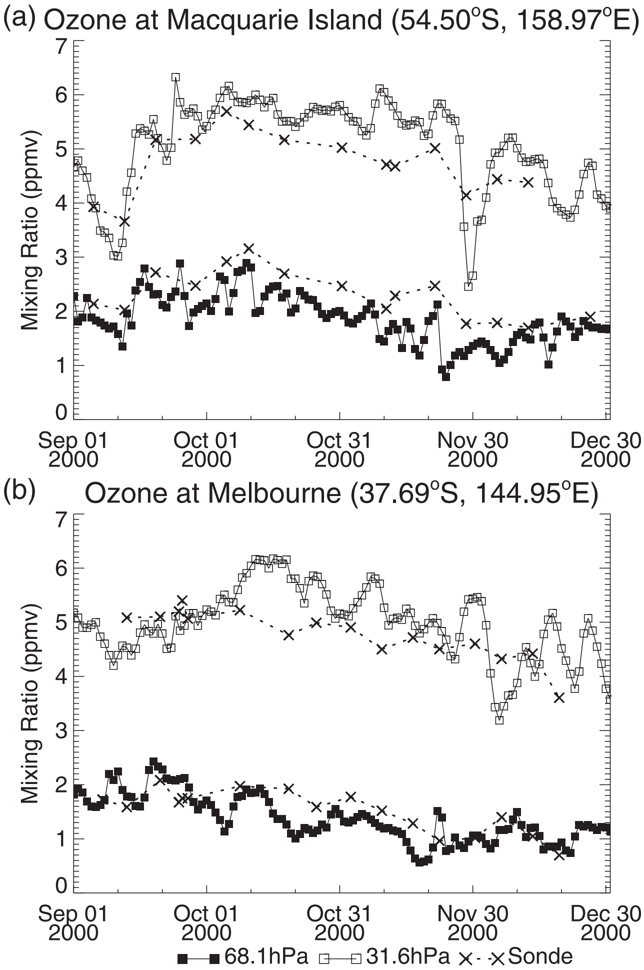

Figure 1. Modeled ozone mixing ratio from 1 September 2000 to 31 December 2000 for 68.1 hPa (■) and 31.6 hPa (□) interpolated to the location of (a) Macquarie Island and (b) Melbourne. Also shown are ozonesonde data at 68.1 and 31.6 hPa (×).

time step. The analyses have been used previously in stratospheric transport studies [e.g., *Manney et al.*, 1998].

[7] The ozone mixing ratio initial conditions are derived from blending the stratospheric climatology used by *Randel et al.* [1999] with the tropospheric climatology of *Logan and McPeters* [1999]. Zonal mean monthly mean values are linearly interpolated to the initial time, then scaled so that the integrated ozone column at each grid point matches TOMS total ozone for that day. Spin-up effects are not significant in the model output.

3. Breakup of the 2000 Antarctic Ozone Hole

[8] In order to simulate the evolution of the Antarctic ozone hole, the model was initialized at 12UTC 1 September 2000 and run until 12UTC 31 December 2000. Daily model output is examined at four SH ozonesonde stations: Syowa (69°S, 40°E), Macquarie Island (55°S, 159°E), Melbourne (38°S, 145°E) and Lauder (45°S, 170°E). Ozonesonde data can be used to evaluate the vertical ozone distribution, although they are typically only available at seven-day intervals.

[9] Modeled ozone mixing ratio at 68.1 and 31.6 hPa interpolated to Macquarie Island and Melbourne is shown in Figure 1. At Macquarie Island (Figure 1a) there is low ozone in early September as the result of the passage of the edge of the Antarctic ozone hole. Ozone reaches a maximum in early October with a steady decline afterwards. The ozone maximum occurs slightly later in October at Melbourne (Figure 1b), where there is also a steady decline during October–December. At both stations, there is variability on weekly time scales caused by synoptic scale weather events.

[10] Also shown in Figure 1 is ozonesonde data interpolated to 68.1 and 31 hPa. Modeled ozone is slightly lower than the ozonesonde data at 68.1 hPa, and slightly higher at 31.6 hPa. However, trends over the four-month period are the same, and the model better represents the variablility on weekly time scales. At Syowa (not shown), the model reproduces the observed ozone hole, although the loss during September is not fully reproduced.

[11] The most significant change in modeled ozone on a weekly time scale in the model run occurs at Macquarie Island (Figure 1a) and Lauder (not shown) in late November, when there is a rapid decrease followed by an equally rapid rise several days later. At Melbourne (Figure 1b), there is a smaller decrease at 31.6 hPa in early December. During this period, there is also a large increase in ozone at Syowa (not shown). Figure 2 shows the modeled ozone mixing ratio at 31.6 hPa at three-day intervals starting from 12UTC 26 November 2000. The ozone hole, which had been displaced from over the South Pole earlier in November, is over Antarctica on 26 November (Figure 2a) and has been stretched. By 29 November (Figure 2b), the ozone hole has been split into two parts, with one part directly over

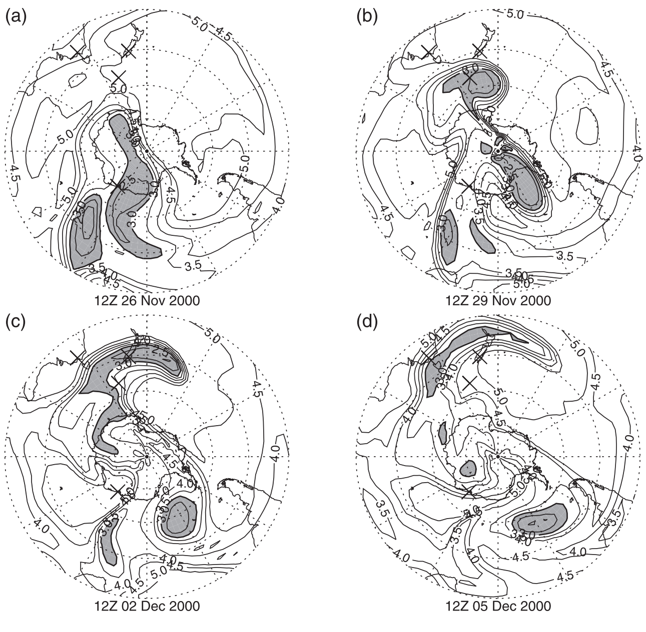

Figure 2. Modeled ozone mixing ratio for 31.6 hPa from the South Pole to 30°S at 12UTC on (a) 26 November 2000, (b) 29 November 2000, (c) 2 December 2000 and (d) 5 December 2000. The contour interval is 0.5 ppmv and regions less than 3 ppmv are shaded. Crosses indicate the location of the ozonesonde stations. The International Dateline is towards the top of each plot.

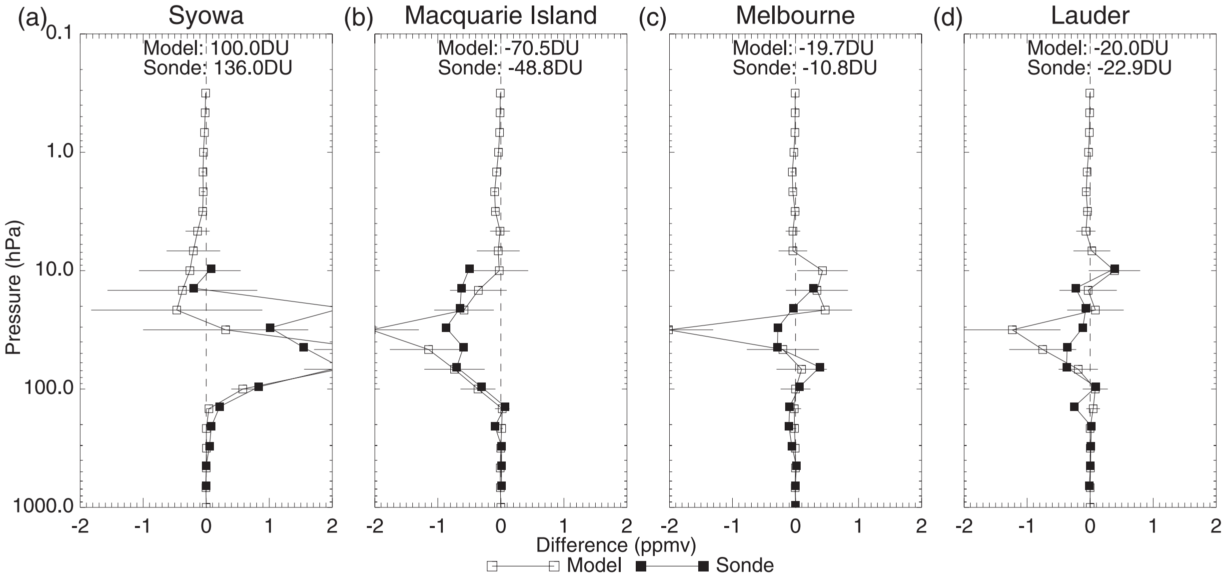

Figure 3. Change in ozone (ppmv) from model (□) and ozonesonde (■) profiles at the following stations and dates: (a) Syowa, 22 to 29 Nov, (b) Macquarie Island, 21 to 28 Nov, (c) Melbourne 1 to 7 Dec, and (d) Lauder, 29 Nov to 4 Dec 2000. Differences are positive when the later profile is greater than the earlier profile. Vertically integrated differences are given in each plot. Horizontal bars indicate the standard deviation estimated for each station (see text for details).

Macquarie Island in the Southern Ocean. High-ozone air has been wrapped around the other part of the ozone hole and is over Syowa. On 2 December (Figure 2c), the ozone hole remnant from Macquarie Island is now over New Zealand and is starting to be stretched zonally. Both ozone hole remnants are stretched further on 5 December (Figure 2d), when there is now decreased ozone over Melbourne. The stretching of the ozone hole remnant suggests that the low-ozone air is mixed into the mid-latitude region, which implies a dilution effect.

[12] Model transport during this period is dominated by horizontal advection. Examination of the 600K Isentropic Potential Vorticity from the UK Met Office analyses (not shown) indicates that the ozone hole remnants coincide with polar vortex remnants. In addition, the estimated tropopause height during this period (not shown) is decreasing, indicating more stratospheric air in each column. Hence, vertical transport from above in this case would lead to increased ozone, and not the modeled decrease.

[13] Changes in modeled ozone over this period are shown in Figure 3. The profiles used at each station coincide with ozonesonde flights closest to the passage of the ozone hole remnant. At Syowa (Figure 3a), there are large increases in ozone between 100 and 46.4 hPa. At the mid-latitude stations (Figures 3b–3d), the largest decreases in modeled ozone occur at 31.6 hPa. The magnitude and vertical extent of the ozone loss in mid-latitudes decreases as the ozone hole remnant moves equatorward. However, this could be because the ozonesonde flights are not coincident with the passage of the low-ozone air. To indicate if these changes are unusual, an estimate of the variability of the seven-day change in ozone profile for each station is obtained by taking the standard deviation of all pairs of seven-day modeled ozone differences over November and December from runs for 1997–2000. The error bars in Figure 3 indicate that the changes between 100 and 31.6 hPa at the stations are unlikely to have been caused by typical seven-day variability.

[14] Also shown in Figure 3 are the differences in the ozonesonde flights. At all stations, the profiles of the modeled ozone changes are similar to those seen in the ozonesonde data. In general, the modeled ozone tends to overestimate the magnitude of the SH mid-latitude loss.

4. Discussion

[15] The 3-D off-line transport model is able to reproduce both the week-to-week variability and seasonal trends seen by ozonesonde data. In addition, it is able to represent the large-scale horizontal flow, which cannot be done using ozonesonde data alone. In late November and early December 2000, the modeled Antarctic ozone hole split into two parts and was transported to mid-latitudes. At the same time, high-ozone air was transported over Antarctica. Similar to the case in December 1987 considered by *Atkinson and Plumb* [1997], one remnant of the ozone hole resulted in several days of low ozone over New Zealand and south-eastern Australia, before being apparently mixed into SH mid-latitudes, with a potential dilution of ozone.

[16] Comparisons with mid-latitude ozonesonde profiles during the passage of the ozone hole remnant indicate that the modeled ozone shows too much loss. This is a result of the recovery of the modeled Antarctic ozone hole in November being too slow. The most likely cause of this is too weak vertical motion inferred in the model from the input analyzed vertical wind field. In situ ozone production rates are low, so recovery of the ozone hole is driven by dynamic processes, particularly large-scale descent from the upper stratosphere [*WMO*, 1999]. If insufficient ozone is transported from above into the polar vortex, then the recovery of the modeled ozone hole will not occur, meaning the magnitude of later possible dilution will be overesti-

mated. If the stratosphere is unusually cold, then climatological ozone production and loss rates will be inaccurate. However, NCEP analyses (not shown) indicate that in October–December 2000 lower stratospheric temperatures did not differ greatly from the long-term mean.

[17] The results presented in this paper indicate that applying parameterized production and loss rates to ozone in a transport model can be a useful tool for studying the impact of the ozone hole on SH mid-latitudes. Further work is intended to quantify this impact, and to assess the interannual variability of the dilution effect.

[18] **Acknowledgments.** Adaptation of CCM2 was carried out by the Cooperative Research Centre for SH Meteorology, Australia. UK Met Office analyses were made available by the British Atmospheric Data Centre. Ozonesonde data were obtained from the World Ozone and Ultraviolet Data Center archive. The authors would like to thank Greg Bodeker, NIWA, New Zealand for making the Lauder ozonesonde data available. Comments from R. Atkinson, E. Cordero, A. Downey, S. Li and anonymous reviewers improved the paper. This work was support by an ARC Research Grant.

References

Atkinson, R. J., and R. A. Plumb, Three-dimensional ozone transport during the ozone hole breakup in December 1987, *J. Geophys. Res.*, *102*, 1451–1466, 1997.

Atkinson, R. J., W. A. Matthews, P. A. Newman, and R. A. Plumb, Evidence for the mid-latitude impact of Antarctic ozone depletion, *Nature*, *340*, 290–293, 1989.

Brinksma, E. J., et al., Analysis of record-low ozone values during the 1997 winter over Lauder, New Zealand, *Geophys. Res. Lett.*, *25*, 2785–2788, 1998.

Considine, D. B., A. R. Douglass, and C. H. Jackman, Effects of a polar stratospheric cloud parameterization on ozone depletion due to stratospheric aircraft in a two-dimensional model, *J. Geophys. Res.*, *99*, 18,879–18,894, 1994.

Cordero, E. C., and S. Grainger, Low ozone concentrations over Macquarie Island during 1997, part I, trajectory analysis, *Aust. Meteorol. Mag.*, *51*, 85–94, 2002.

Douglass, A. R., C. J. Weaver, R. B. Rood, and L. Coy, A three-dimensional simulation of the ozone annual cycle using winds from a data assimilation system, *J. Geophys. Res.*, *101*, 1463–1474, 1996.

Farman, J. G., B. G. Gardner, and J. D. Shanklin, Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction, *Nature*, *315*, 207–210, 1985.

Knudsen, B. M., W. A. Lahoz, A. O'Neill, and J.-J. Morcrette, Evidence for a substantial role for dilution in northern mid-latitude ozone depletion, *Geophys. Res. Lett.*, *25*, 4501–4504, 1998.

Li, S., E. C. Cordero, and D. J. Karoly, Transport out of the Antarctic polar vortex from a three-dimensional transport model, *J. Geophys. Res.*, *107*(D11), 4675, doi:10.1029/2001JD000508, 2002.

Logan, J. A., and R. D. McPeters, Ozone climatology, in *Models and Measurements II*, chap. 4, edited by J. H. Park et al., *NASA Ref. Publ.*, *NASA/TM-1999-209554*, 502 pp., 1999.

Manney, G. L., J. C. Bird, D. P. Donovan, T. J. Duck, J. A. Whiteway, S. R. Pal, and A. I. Carswell, Modeling ozone laminae in ground-based Arctic wintertime observations using trajectory calculations and satellite data, *J. Geophys. Res.*, *103*, 5797–5814, 1998.

Perez, A., E. Crino, I. Aguirre de Carcer, and F. Jaque, Low ozone events and three-dimensional transport at midlatitudes of South America during springs of 1996 and 1997, *J. Geophys. Res.*, *105*, 4553–4561, 2000.

Randel, W. J., F. Wu, J. M. Russell III, and J. Waters, Space-time patterns of trends in stratospheric constituents derived from UARS measurements, *J. Geophys. Res.*, *104*, 3711–3727, 1999.

Rasch, P. J., B. A. Boville, and G. P. Brasseur, A three-dimensional general circulation model with coupled chemistry for the middle atmosphere, *J. Geophys. Res.*, *100*, 9041–9071, 1995.

Rosenfield, J. E., D. B. Considine, P. E. Meade, J. T. Bacmeister, C. H. Jackman, and M. R. Schoeberl, Stratospheric effects of Mount Pinatubo aerosol studied with a coupled two-dimensional model, *J. Geophys. Res.*, *102*, 3649–3670, 1997.

Solomon, S., Stratospheric ozone depletion: A review of concepts and history, *Rev. Geophys.*, *37*, 275–316, 1999.

Swinbank, R., and A. O'Neill, A stratosphere-troposphere data assimilation system, *Mon. Weather Rev.*, *122*, 686–702, 1994.

Williamson, D. L., and P. J. Rasch, Two-dimensional semi-Lagrangian transport with shape preserving interpolation, *Mon. Weather Rev.*, *117*, 102–129, 1989.

World Meteorological Organisation (WMO), Scientific Assessment of Ozone Depletion: 1998, *Global Ozone Research and Monitoring Project-Rep. 44*, Geneva, Switzerland, 1999.

S. Grainger, Bureau of Meteorology Research Centre, 150 Lonsdale St., Melbourne, Victoria 3001, Australia.

D. J. Karoly, School of Meteorology, University of Oklahoma, 100 E. Boyd St., Norman, Oklahoma 73019, USA.