# Unusual stratospheric transport and mixing during the 2002 Antarctic winter

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Received 12 February 2003; revised 7 April 2003; accepted 10 April 2003; published 17 June 2003.

[1] Unusually large planetary wave activity in the 2002 Antarctic winter stratosphere weakened and warmed the polar vortex. Three minor warmings during August and early September preceded a late-September major warming when the middle stratospheric zonal winds reversed to easterly and the polar temperature increased by an additional 25 K. Polar Ozone and Aerosol Measurement (POAM III) ozone data at high southern latitudes show unusually large variability in 2002 compared to previous POAM III years (1998–2001). Analyses of air parcel transport indicate this variability is caused by large-scale isentropic transport. Diagnostics of transport and mixing show that during the major warming the lower stratospheric vortex remained intact, while the middle stratospheric vortex split into two pieces; one piece rapidly mixed with extravortex air, while the other returned to the pole as a much weaker and smaller vortex. *INDEX TERMS:* 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Allen, D. R., R. M. Bevilacqua, G. E. Nedoluha, C. E. Randall, and G. L. Manney, Unusual stratospheric transport and mixing during the 2002 Antarctic winter, *Geophys. Res. Lett.*, *30*(12), 1599, doi:10.1029/2003GL017117, 2003.

## 1. Introduction

[2] Stratospheric major warmings cause some of the most dramatic changes observed in the earth's atmosphere. Planetary waves propagating up from the troposphere trigger rapid zonal wind deceleration, polar temperature increase, and distortion and/or splitting of the winter vortex. They are accompanied by enhanced isentropic transport and diabatic descent [e.g., *Manney et al.*, 1994]. Warmings are classified as major if at 10 hPa the zonal mean temperature gradient reverses and the zonal mean wind turns easterly poleward of 60°, and minor if the temperature gradient reverses but winds remain westerly. Minor warmings occur in both hemispheres, but until 2002 major warmings were observed only in the northern hemisphere (NH). The first known major warming in the southern hemisphere (SH) occurred in September 2002 [*Varotsos*, 2002; *Baldwin et al.*, 2003; *Hoppel et al.*, 2003; *Sinnhuber et al.*, 2003; *Weber et al.*, 2003]. This letter documents how the major warming, and the unusual stratospheric meteorology that preceded the warming, affected polar ozone transport.

[3] We first examine SH stratospheric meteorological conditions from 1979–2002 using the National Centers for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCAR) Reanalysis [*Kistler et al.*, 2001], to highlight the unusual behavior in 2002. Next, to document the effects of this unusual meteorology on ozone, we examine data from the Polar Ozone and Aerosol Measurement instrument (POAM III). POAM III (hereinafter POAM) has been measuring ozone in the polar regions of the NH and SH at high vertical resolution on a continuous basis since April 1998 [*Lucke et al.*, 1999]. POAM ozone has been validated against coincident sonde, satellite, and aircraft measurements [*Prados et al.*, 2003; *Lumpe et al.*, 2003; *Randall et al.*, 2003].

[4] To diagnose isentropic transport we use tracer equivalent latitude (TrEL, defined as the latitude that encloses the same area as the contour of a long-lived tracer) generated from global isentropic advection-diffusion calculations of an artificial tracer driven by Met Office assimilated winds [*Swinbank and O'Neill*, 1994]. Derivation and applications of TrEL are presented in *Allen and Nakamura* [2003]. TrEL is calculated daily on 16 potential temperature (θ) levels from 320 to 1900 K (∼10 to 50 km). To diagnose isentropic mixing, we use equivalent length ($L_e$) calculated from the tracer advection analysis [*Allen and Nakamura*, 2001]. Large $L_e$ indicates rapid mixing, while local minima indicate mixing barriers.

## 2. Results

[5] Figure 1 shows the NCEP-NCAR total eddy heat flux, zonal mean zonal wind, and zonal mean temperature for 1979–2002. Eddy heat flux provides a measure of vertically propagating wave activity. Normally, the 10 hPa (∼32 km) heat flux is weak through early July. Beginning in mid-May 2002, however, every 1–3 weeks there is a large heat flux

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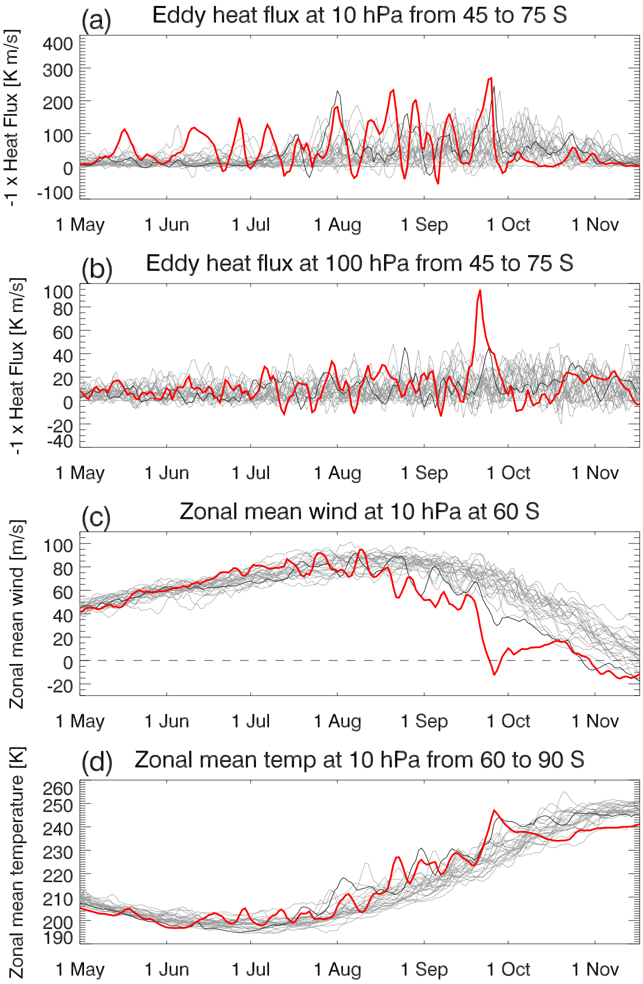


**Figure 1.** NCEP/NCAR Reanalyses for 1 May–17 November 1979–2001 (grey), 1988 (black), and 2002 (red) (a and b) 10 and 100 hPa total eddy heat flux averaged from 45–75°S and multiplied by −1 to make poleward flux positive. (c) 10 hPa zonal mean wind at 60°S. (d) 10 hPa zonal mean temperature averaged from 60–90°S. Latitudinal averages are area-weighted.

anomaly. During August and September 2002 the frequency and intensity of these anomalies increase. Until July, the 100 hPa (∼15 km) heat flux (an indicator of tropospheric forcing) does not seem unusually large. However, in July and August, the 100 hPa heat flux anomalies strengthen significantly. *Weber et al.* [2003] show that the 100 hPa transient (departure from monthly mean) heat fluxes in July and August 2002 are slightly larger than the 1992–2001 range. In late September 2002, the 100 hPa heat flux rises dramatically to twice the largest value observed from 1979–2001, in agreement with *Sinnhuber et al.* [2003] and *Weber et al.* [2003]. Thus, unusually large tropospheric forcing accompanied the late September major warming.

[6] The 10 hPa zonal wind is normal until late July, when it becomes highly variable, with minima roughly lining up with peaks in the 10 hPa heat flux as expected. In 1979–2001 the zonal wind generally increases until early September, and then begins a seasonal decline. In 2002, wind fluctuations are superposed on a deceleration beginning in early August; by early September, the 2002 wind is ∼20–30 m/s weaker than normal. The most dramatic change occurs from 17–27 September 2002, when the wind reverses from ∼60 m/s westerly to ∼15 m/s easterly [also noted by *Varotsos*, 2002 and *Sinnhuber et al.*, 2003]. The zonal wind remains easterly until 30 September, when it reverses to westerly. The final warming at 10 hPa occurred very early, on 31 October 2002.

[7] The 2002 10 hPa polar temperature also shows unusual fluctuations, coinciding with the 10 hPa heat flux anomalies. In late August and September, four sudden warmings occur. The first three (on 22 August, 1 September, and 10 September) are minor warmings, since winds remained westerly. In late September, polar temperatures increased by ∼25 K during the major warming. After the warming, temperatures decreased to lower than normal for late October/November. The wind and temperature patterns observed in 2002 somewhat resemble those for 1988, when enhanced wave activity resulted in a weakened vortex and an anomalously small ozone hole [*Schoeberl et al.*, 1989; *Kanzawa and Kawaguchi*, 1990]. In 1988 the zonal winds remained westerly during these warmings, but turned easterly in late October, indicating a very early final warming.

[8] Figure 2 shows POAM ozone and TrEL, at the POAM locations for August and September 1998–2002 throughout the stratosphere. In August 2002, POAM samples TrEL values well outside the 1998–2001 range above ∼700 K, while in September 2002, TrEL extends farther equatorward, reaching nearly 10°S at 960 K. This indicates that in 2002 POAM sampled air that originated from much lower latitudes than in previous years. Consequently, in both August and September 2002, much higher ozone was

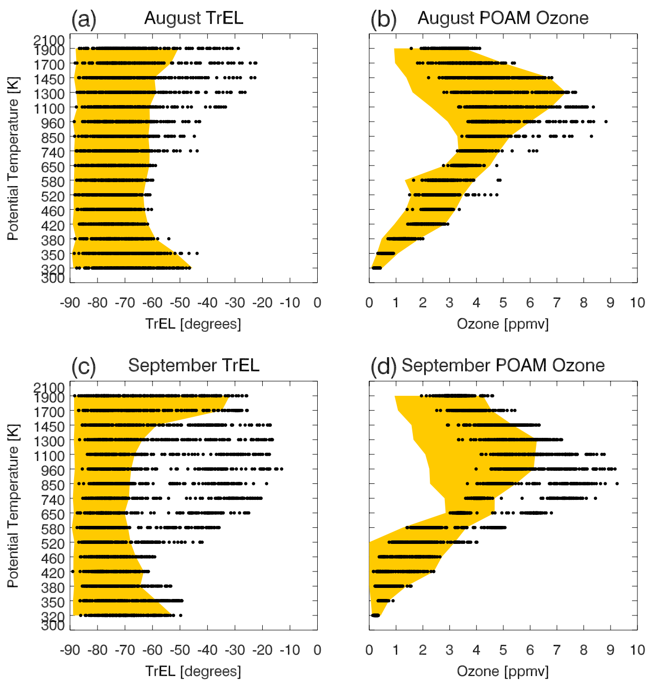


**Figure 2.** (a and c) TrEL and (b and d) ozone mixing ratio at the POAM SH measurements for August (a and b) and September (c and d). Shaded regions indicate the range of values observed during 1998–2001, dots pertain to individual POAM measurements in 2002.

observed from 520–1300 K. Mixing ratios in September 2002 reached over 9 ppmv, clearly indicating sampling of low latitude air. The lowest values observed by POAM above ~650 K were higher than the minimum in the 1998–2001 range. This is partly due to the lower latitude sampling, but may also be influenced by enhanced isentropic mixing and diabatic descent in 2002.

[9] Figure 3 shows SH TrEL and the streamfunction at 460 and 850 K (~20 and 32 km) during the major warming along with vertical profiles of TrEL at the POAM locations. At 460 K, the streamfunction is roughly pole-centered on 15 September, but is pushed off the pole and distorted into a dumbbell shape by 25 September. The 460 K TrEL 60°S contour (roughly indicating the vortex edge) remains intact during this period; although on 5 October a tongue of high (magnitude) TrEL air is being stripped off the vortex. By 15 October the 460 K vortex is still intact, but is slightly smaller and weaker than it was on 15 September.

[10] At 850 K, a large Australian anticyclone (black streamlines) forms in late September. As it intensifies, the polar vortex breaks in two by 25 September. The piece that is west of South America on 25 September stretches southward around the anticyclone by 30 September and then mixes with ambient air. The larger piece near southern Africa on 25 September moves back near the pole, as tongues of high (magnitude) TrEL air are stripped away. Significant entrainment of low latitude air into the vortex is not apparent at either level, suggesting the vortex core remains isolated. Global Ozone Monitoring Experiment (GOME) total ozone maps show a similar morphology [*Sinnhuber et al.*, 2003]; around 25 September the ozone hole split into two; one piece quickly disappeared, while the other returned to the pole.

[11] The vertical tilt of the vortex changes rapidly during the warming. On 15 September, the TrEL values at POAM locations tilt slightly equatorward with height above 350 K. From 25 September to 5 October, the TrEL profiles change rapidly with height, with values ranging from 10 to 90°S. This strong vortex tilting is a common characteristic of NH major warmings [*e.g.*, *Manney et al.*, 1994]. Since part of the column contains extra-vortex air with elevated ozone levels, the total column ozone increases. *Hoppel et al.* [2003] showed that the 21–60 km ozone partial column, derived from POAM profile measurements, increased by ~150 DU during the major warming. Similarly, GOME total ozone (averaged from 50–90°S) during late September 2002 was ~40–50 DU larger than the 1995–2001 [*Weber et al.*, 2003]. By 15 October, as the wave activity dies down, the TrEL values are nearly vertically aligned up to 1100 K.

[12] Figure 4 shows 460 and 850 K POAM ozone and $L_e$ as a function of TrEL and time. At 460 K, ozone decreases during August and September by an amount similar to previous years [*Hoppel et al.*, 2003]. During the warming, the TrEL values sampled by POAM at 460 K temporarily shift from poleward of ~70°S to equatorward of ~70°S (Figure 4a). When POAM samples polar TrEL values again in early October, the ozone is slightly lower, perhaps indicating a small amount of additional loss in late September. This is in contrast to the previous four POAM measurement years, in which large chemical loss occurred during this time period [*Hoppel et al.*, 2003]. The 460 K $L_e$ shows a broad minimum from 50–70°S during June-early September demarking the vortex edge. Until the major warming, the position and width of the barrier remains fairly constant, suggesting the enhanced mid-stratospheric wave activity did not strongly affect the lower stratospheric vortex. During the major warming, $L_e$ at the barrier increases, followed by an ~10° poleward shift of the minimum, consistent with the reduction of vortex size observed in Figure 3.

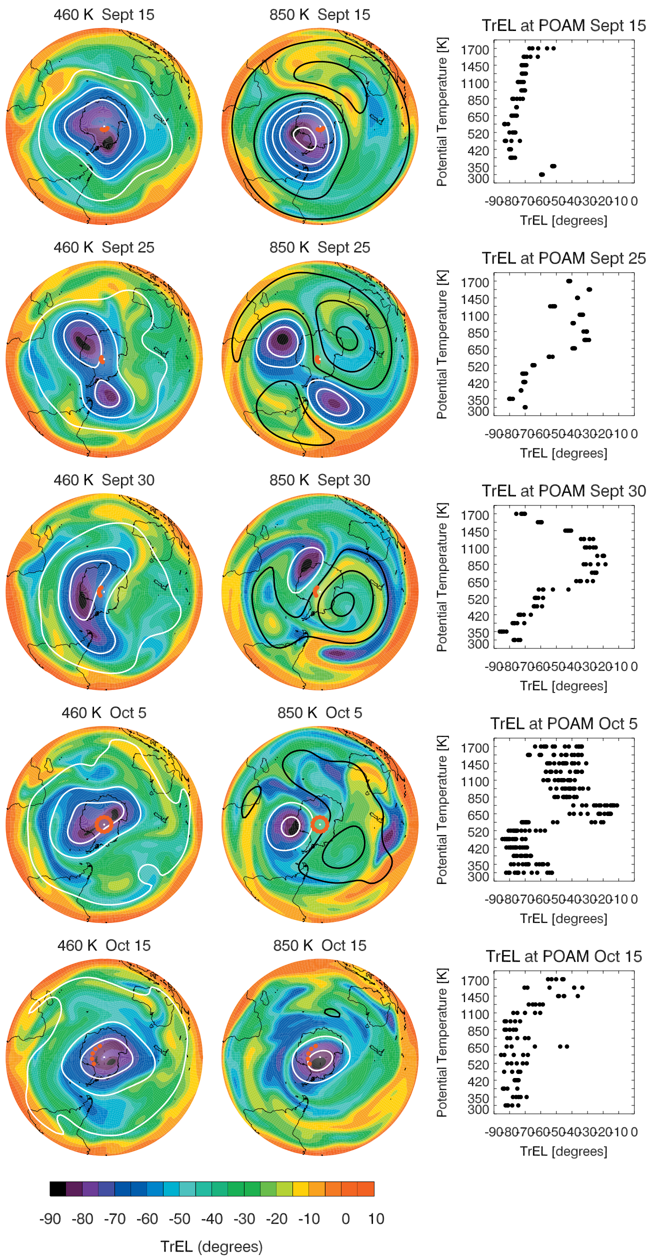


**Figure 3.** SH (0–90°S) Lambert equal area maps of TrEL at 460 K (left column) and 850 K (middle column) for 15, 25, 30 September, and 5, 15 October 2002. White contours are streamfunction for 0, 5, 10, 15 $\times$ $10^7$ $s^{-1}$, and black contours are streamfunction for $-5$, $-10$, $-15$ $\times$ $10^7$ $s^{-1}$. Right column: TrEL at the individual POAM measurement locations (red dots in synoptic maps) for each day.

[13] At 850 K (Figure 4c), the TrEL range for the POAM observations widens episodically during July–September,

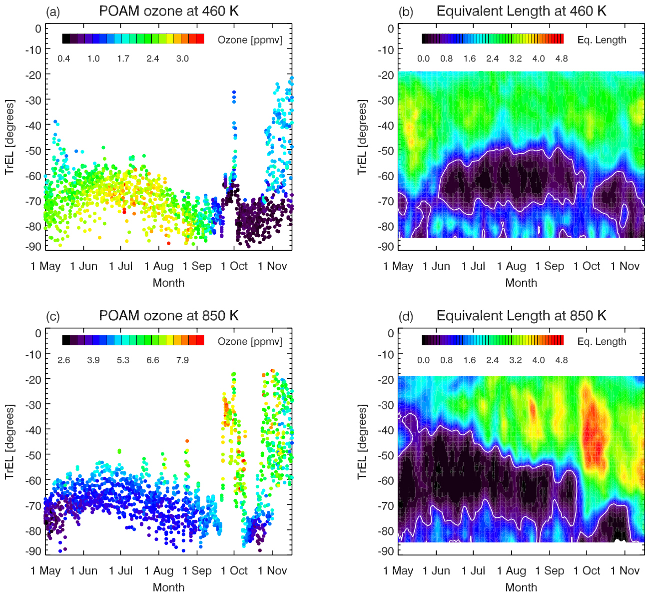


**Figure 4.** (a and c) POAM ozone at 460 and 850 K as a function of TrEL and time for 1 May–17 November 2002. Each dot represents one POAM measurement with the color indicating the ozone mixing ratio. (b and d) Equivalent length ($L_e$) at 460 and 850 K from 1 May–17 November 2002. Units are normalized by $\ln(L_e^2/L_o^2)$, where $L_o = 2\pi a \cos(\mathrm{TrEL})$ and $a$ is the earth's radius. The value of 1.0 is highlighted with a white contour.

coincident with the 10 hPa heat flux enhancements (Figure 1). During the major warming, TrEL changes rapidly as low latitude/ozone-rich air is advected over POAM locations. Following the warming, POAM again measures polar TrEL values and ozone characteristic of vortex air. The 850 K $L_e$ (Figure 4d) shows that the vortex mixing barrier was quite broad in early June, but steadily decreased in size and strength over the next several months. During the major warming, a region of very large $L_e$ (rapid mixing) occurs from 20–60°S and vortex size drops rapidly. The barrier then gradually increases in size and strength until the final warming in late October.

## 3. Discussion

[14] The observations presented in this letter raise many important questions. Why was there such large wave activity in the stratosphere in the 2002 winter? Did the early wave activity set up conditions that favored the major warming? What forced the extremely large 100 hPa heat flux that immediately preceded the major warming? Does the similarity between 1988 and 2002 yield any clues? What is the likelihood of such waves occurring in the future, either in the SH or NH? Could the dynamical activity of the Antarctic increase with time, and is there a connection to climate change?

[15] Another interesting aspect is that the ozone hole can be strongly affected by transport processes occurring above the region of large photochemical loss. In 2002, at the time of the major warming, the column anomaly caused by this transport (∼150 DU) is far larger than that caused by reduced ozone depletion (∼30 DU) [*Hoppel et al.*, 2003]. Such large deviations are due to strong vertical wind shear with large horizontal ozone gradients. The wind shear causes vortex tilting, so that the column integration in the polar region includes ozone-rich extravortex air. More detailed analyses will help quantify these effects.

[16] **Acknowledgments.** The POAM III instrument is sponsored by the Office of Naval Research. Support for scientific analysis comes from the Naval Research Lab and NASA. Work at the Jet Propulsion Laboratory, California Institute of Technology was done under contract with the National Aeronautics and Space Administration.

## References


Allen, D. R., and N. Nakamura, A seasonal climatology of effective diffusivity in the stratosphere, *J. Geophys. Res.*, *106*(D8), 7917–7935, 2001.

Allen, D. R., and N. Nakamura, Tracer equivalent latitude: A diagnostic tool for isentropic transport studies, *J. Atmos. Sci.*, *60*(2), 287–304, 2003.

Baldwin, M. P., T. Hirooka, A. O'Neill, and S. Yoden, Major stratospheric warming in the southern hemisphere in 2002: Dynamical aspects of the ozone hole split, *SPARC Newsletters*, No. 20, 24–26, 2003.

Hoppel, K. H., et al., POAM III observations of the anomalous 2002 Antarctic ozone hole, *Geophys. Res. Lett.*, *30*(7), 1394, doi:10.1029/2003GL016899, 2003.

Kanzawa, H., and S. Kawaguchi, Large stratospheric sudden warming in Antarctic late winter and shallow ozone hole in 1988, *Geophys. Res. Lett.*, *17*(1), 77–80, 1990.

Kistler, et al., The NCEP-NCER 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*(2), 247–267, 2001.

Lucke, R. L., et al., The Polar Ozone and Aerosol Measurement (POAM) III instrument and early validation results, *J. Geophys. Res.*, *104*(D15), 18,785–18,799, 1999.

Lumpe, J. D., et al., Comparison of POAM III ozone measurements with correlative aircraft and balloon data during SOLVE, *J. Geophys. Res.*, *108*(D5), 8316, 10.1029/2001JD000472, 2003.

Manney, G. L., J. D. Farrara, and C. R. Mechoso, Simulations of the February 1979 stratospheric sudden warning: Model comparisons and three-dimensional evolution, *Mon. Weather Rev.*, *122*(6), 1115–1140, 1994.

Manney, G. L., et al., Simulation of the December 1998 stratospheric major warming, *Geophys. Res. Lett.*, *26*(17), 2733–2736, 1999.

Prados, A. I., et al., POAM III ozone in the upper troposphere and lowermost stratosphere: Seasonal variability and comparisons to aircraft observations, *J. Geophys. Res.*, *108*(D7), 4218, 10.1029/2002JD002819, 2003.

Randall, C. E., et al., Validation of POAM III ozone: Comparisons with ozonesonde and satellite data, *J. Geophys. Res.*, in press, 2003.

Schoeberl, M. R., R. S. Stolarski, and A. J. Krueger, The 1988 Antarctic ozone depletion: Comparison with previous year depletions, *Geophys. Res. Lett.*, *16*(5), 377–380, 1989.

Sinnhuber, B. M., M. Weber, A. Amankwah, and J. P. Burrows, Total ozone during the unusual Antarctic winter of 2002, *Geophys. Res. Lett.*, in press, 2003.

Swinbank, R., and A. O'Neill, A stratosphere-troposphere data assimilation system, *Mon. Weather Rev.*, *122*(4), 686–702, 1994.

Varotsos, C., The southern hemisphere ozone hole split in 2002, *Environ. Sci. and Pollut. Res.*, *9*(6), 375–376, 2002.

Weber, M., et al., Dynamical control of NH and SH winter/spring total ozone from GOME observations in 1995–2002, *Geophys. Res. Lett.*, in press, 2003.



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