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Analysis of Record-Low Ozone Values During the 1997 Winter over Lauder, New Zealand

E. J. Brinksma[1], Y. J. Meijer[2], B. J. Connor[3], G. L. Manney[4], J. B. Bergwerff[2], G. E. Bodeker[3], I. S. Boyd[3], J. B. Liley[3], W. Hogervorst[1], J. W. Hovenier[1], N. J. Livesey[4], D. P. J. Swart[2]

Abstract. Record-low ozone (O_3) column densities (with a minimum of 222 DU) were observed over the Lauder NDSC (Network for the Detection of Stratospheric Change) station (45°S, 170°E) in August 1997. Possible causes are examined using height-resolved O_3 measurements over Lauder, and high-resolution reverse trajectory maps of O_3 (initialised with Microwave Limb Sounder measurements) and of potential vorticity. The analysis shows that O_3 poor air originated from two regions: Below the 550 K isentrope (~22 km) subtropical air was observed, while between 600 and 1000 K (~25 – 33.5 km) the polar vortex tilted over Lauder for several days. A rapid recovery of the O_3 column density was observed later, due to an O_3 rich polar vortex filament moving over Lauder between 18 and 24 km, while simultaneously the O_3 poor higher vortex moved away.

Introduction

Measurements at Lauder and TOMS satellite data showed that the 1997 springtime and winter were characterised by low O_3 column densities throughout the Southern Hemisphere mid-latitude region, which could be largely accounted for by the phase of the Quasi Biennial Oscillation and a long-term decrease in the average ozone levels [*Connor et al.*, submitted to *Geoph. Res. Letters*]. The August '97 average over Lauder was 324 DU, which is 21 DU below the 1985–1996 August average. In this article, daily observations over Lauder in early August of 1997 are presented which are even lower, down to 222 DU. Similar cases in which the O_3 column density dropped abruptly and sharply were observed in September and October of 1997.

In the late winter of '97, TOMS observations showed an unusually distorted polar vortex edge, which was centred off the pole repeatedly. A perturbed polar vortex is associated with enhanced planetary wave activity, which may distribute vortex filaments over lower latitudes [e.g., *Schoeberl et al.,* 1992]. Similarly, filaments can be peeled off the subtropical barrier, and previous studies [e.g., *Waugh*, 1993] have linked subtropical stratospheric mixing and disturbances of the polar vortices in both hemispheres during the winter.

[1]Vrije Universiteit, Department of Physics and Astronomy, Amsterdam, The Netherlands.
[2]National Institute of Public Health and the Environment (RIVM) Air Research Laboratory, Bilthoven, The Netherlands.
[3]National Institute of Water and Atmospheric Research Ltd. (NIWA), Lauder, New Zealand.
[4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena

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Exchange between the vortex and mid-latitude air is important since it influences the amount of chemical processing of ozone [e.g., *Schoeberl et al.,* 1988]. Only a few observations of vortex filaments at Southern Hemisphere mid-latitudes have been previously reported [*Atkinson et al.*, 1989; *Atkinson and Plumb*, 1997; *Fairlie et al.*, 1997].

August '97 Observations

Ozone column density measurements were performed by a Dobson spectrophotometer and an ultraviolet scanning spectrometer (UVM) at Lauder, and by the Earth Probe TOMS satellite instrument within 0.25° lat. by 0.30° long. from Lauder. An offset of −12 DU was applied to the UVM data presented here to achieve good agreement with the Dobson data. This is consistent with a study based on long-term measurements over Lauder [*Bodeker et al.*, submitted to *J. Geoph. Res.*].

In Fig. 1, the O_3 column densities measured over Lauder in August 1997 and their 1985–1996 daily averages are compared. The presented UVM observations were performed at local noon (~0:45 UT), while Dobson spectrophotometer results are representative daily values. Apparently, from August 7 to 10 the measured values were over 2 standard deviations below the average. The record value of 222 DU was observed on August 9, 22 UT (not shown). A rapid recovery was observed on August 10, up to 340 DU at the start of August 11.

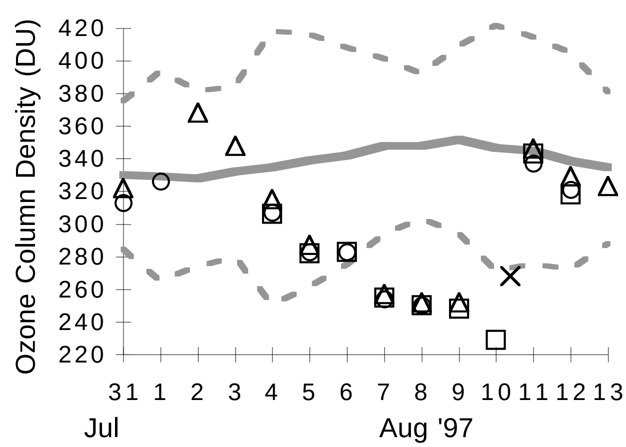

Figure 1. Results of O_3 column density measurements over Lauder in August of 1997 by UVM (squares), Dobson spectrophotometer (circles) and TOMS (triangles) are presented, compared to the daily ozone column densities averaged over 1985–1996 (grey line). The ×-mark denotes the August 10 lidar measurement at 10 UT.

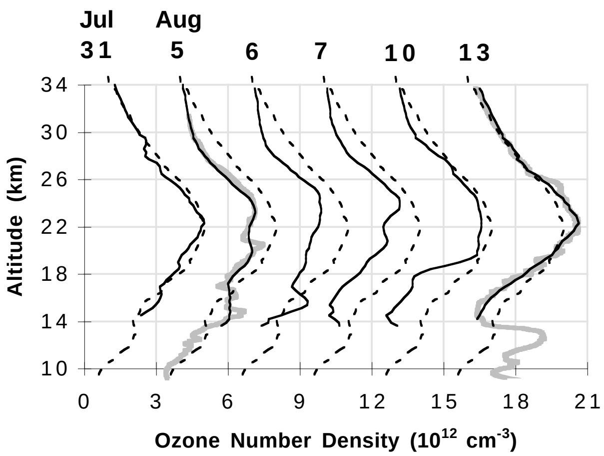

Figure 2. Height profiles of O_3 number density measured over Lauder from July 31 to August 13, 1997, by lidar (black lines) and sondes (thick grey lines). The mean profile for July 31 - August 10, derived from sonde measurements between 1986 and 1996, is superposed on all profiles as a reference (dashed lines). The profiles have been offset successively by $3 \times 10^{12} cm^{-3}$. On August 5 the lidar and sonde measurements were simultaneous, while on August 13 the lidar measurement was performed several hours before the sonde launch.

Height-resolved O_3 measurements over Lauder were measured by a stratospheric lidar [*Swart et al.*, 1994; 1995,], electrochemical concentration cell sondes, and a microwave radiometer [*Parrish et al.*, 1992]. The observations yield both O_3 number density as a function of height (Fig. 2) and O_3 mixing ratio as a function of potential temperature (Θ) (Fig. 3). Fig. 2 illustrates clearly the changes in the O_3 column density. On the other hand, the O_3 mixing ratio is conserved on constant Θ-surfaces (isentropes) in the absence of chemical and diabatic processes, and therefore, Fig. 3 is better suited to reveal O_3 variations caused by transport. Note that mixing ratio changes at low heights contribute strongly to the O_3 column density.

Ozone poor air (i.e., air with a low O_3 mixing ratio) was observed in two regions: A 'low region', from Θ=350–550 K (~13–22 km, the lower boundary is determined by the minimum height of the lidar measurements), and a 'high region', between Θ=600 K and 1000 K (~25–33.5 km). The microwave measurements, which are available above 20 km ($\Theta \simeq$500 K), confirm the lidar observations of reduced ozone, but are not included in these figures for clarity. Comparing the August 7 with the August 10 lidar observation shows that the O_3 number densities increased significantly between ~18.5 and 33.5 km ($\Theta \simeq$ 470–1000 K), causing the fast recovery observed on August 10 between 0 and 10 UT.

Using the lidar measurements, the evolution of the O_3 number density solely due to adiabatic ascent or descent of the air was computed. This was done by converting number density to mixing ratio, evaluating the evolution of the heights of the isentropes, and converting back to number density. These calculations showed that the observed changes could not be explained by adiabatic ascent or descent, except from August 10 to 13 between 18 and 23 km.

Analysis

Potential Vorticity (PV) on isentropic surfaces behaves as a dynamical tracer in the absence of diabatic effects, and can be a powerful tool for understanding transport processes that affect O_3 [*Hoskins et al.*, 1985]. The polar vortex is identified by high absolute PV values, and a region of strong isentropic PV gradients, associated with the polar night jet, demarks its boundary. High-resolution PV and O_3 maps on selected isentropic surfaces for August 4–10 were constructed using a reverse trajectory procedure [*Sutton et al.*, 1994; *Manney et al.*, 1998]. Maps were initialised with PV, or with O_3 reconstructed from Upper Atmosphere Research Satellite Microwave Limb Sounder (MLS) observations. The MLS O_3 data used here differ from those used by *Manney et al.* [1998] as the instrument obtained pressure information differently, and climatological temperature data and an unpublished retrieval algorithm (prototype MLS version 5) were used. The trajectory calculations [*Manney et al.*, 1998] were run with horizontal winds and estimates of diabatic descent rates computed from UKMO (United Kingdom Meteorological Office) data.

Maps at Θ=420 and 500 K (~16 and 20 km) indicate that in the lower stratosphere O_3 poor air with a low-latitude origin (i.e., with a low absolute value of the PV) mixed into mid-latitudes during the first week of August. In Fig. 4 regions where subtropical air is pulled up around the vortex are shown (right panel, mixing ratios of 0.5–0.6 ppmv, while the 1986–1996 average over Lauder at 420 K in early August was 0.7 ppmv). Evidently, these filaments are folded together with relatively O_3 rich filaments from the vortex edge region (mixing ratios above 0.8 ppmv). The filament which is seen on August 9, was present over Lauder between August 7 and 10, with the lowest mixing ratio (0.55 ppmv) observed at Θ=420 K on August 9.

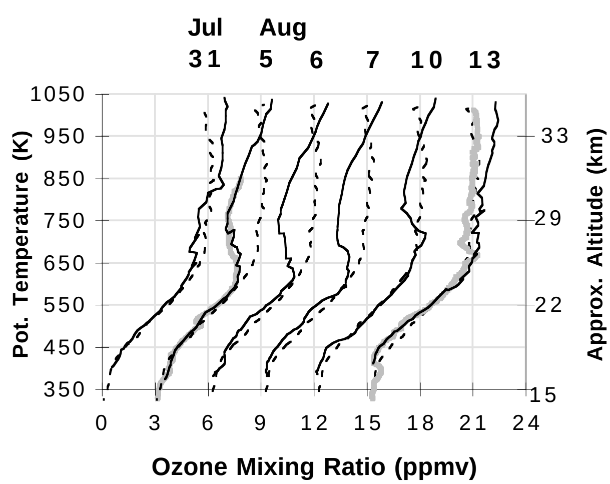

Figure 3. Potential temperature versus ozone mixing ratio between July 31 and August 13, 1997. The plotting conventions from Fig. 2 have been maintained. The approximate height scale on the right axis was derived from the lidar potential temperatures on August 5, and may vary considerably from day to day. Here, the profiles have been offset successively by 3 ppmv.

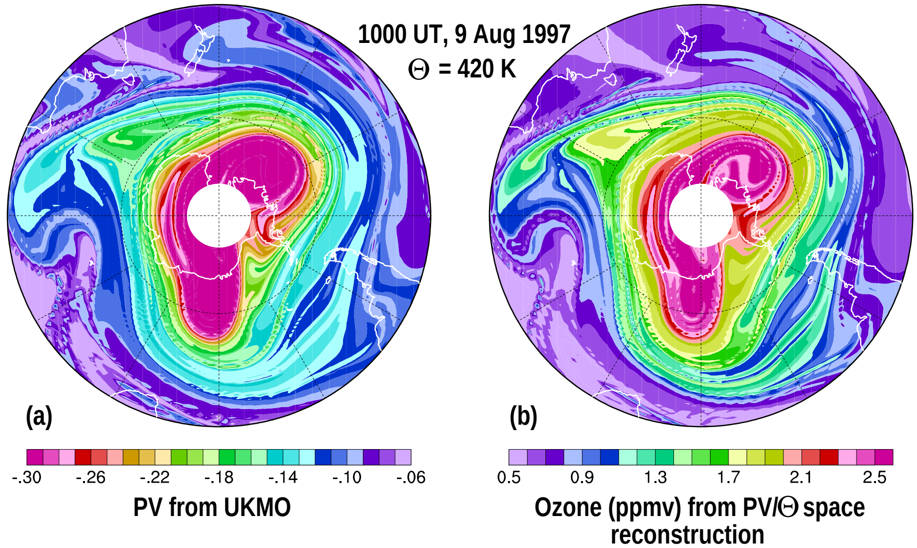

Figure 4. Maps of (a) the PV calculated by advection of UKMO PV from July 28, 1997, and (b) the O_3 mixing ratio calculated by advection of a PV/Θ-space reconstruction of MLS observations for July 28, 1997. Both maps are for Aug 9, 10 UT, Θ=420 K. The colourscale in (a) is in units of $10^{-4} K m^2 kg^{-1} s^{-1}$, in (b) the units are ppmv. The South Pole is situated in the centre of the maps, with New Zealand just left of the upward pointing dateline.

In the middle stratosphere the air had a distinctly different origin. Fig. 5 shows a map of the PV at Θ=850 K (∼31 km) on August 9, with the vortex clearly situated over Lauder. Further study shows that the polar vortex moved over Lauder between August 5 and 6, first above Θ=660 K (∼27.5 km), but on August 9 down to Θ=600 K (∼25 km). Above Θ ≃580 K, the polar vortex is O_3 poor as indicated by MLS O_3 data (not shown). On August 10 from Θ=600 K–1100 K (∼25–35 km) the vortex had been replaced by vortex edge air. Higher up the vortex moved away during the next days.

On August 10, the O_3 mixing ratios between 18 and 25 km (Θ ≃450–600 K) over Lauder increased abruptly (e.g., from 2.2 ppmv on Aug 9 to 2.8 ppmv on Aug 10 at Θ=500 K, while the 1986–1996 average was 2.4 ppmv). This was due to a passing filament of O_3 rich vortex edge air, which can be identified on the maps at 485 K and 500 K (cf. Fig. 6). At 520 K, the filament was visible to the north of New Zealand on August 10, and likely passed over Lauder earlier that day. At 420 K (∼16 km), the filament remained south of New Zealand.

The high-resolution PV maps were compared with daily UKMO PV data over Lauder for consistency. The daily data are spatial interpolations of the PV calculated from temperature and winds with 2.5° lat. by 3.75° long. resolution, at 12 UT, and are thus not expected to show the details of fila-

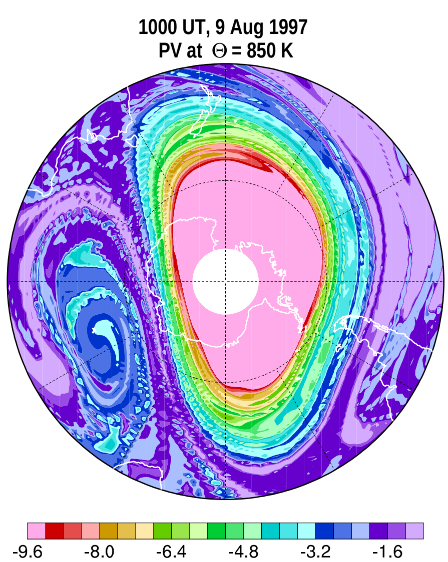

Figure 5. Map of the PV at Θ=850 K on August 9, 10 UT, calculated by advection of UKMO PV from July 28, 1997. Plotting conventions as in Fig. 4.

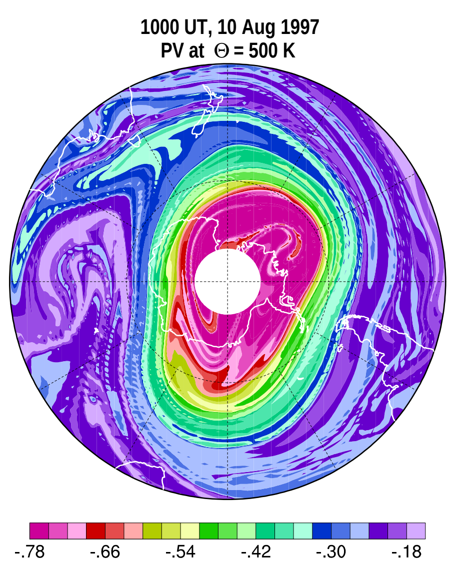

Figure 6. Map of the PV at Θ=500 K on August 10, 10 UT, calculated by advection of interpolated data of July 29, 1997. Plotting conventions as in Fig. 4.

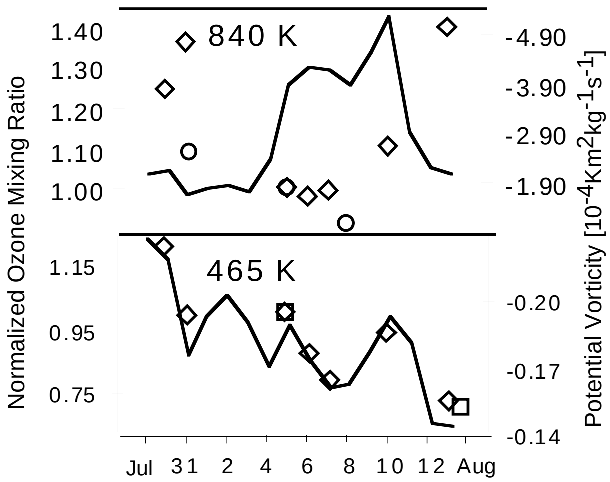

Figure 7. Time series of the daily UKMO PV (right vertical axis, solid line), and O_3 mixing ratio (left vertical axis) measured by lidar (diamonds), microwave (circles) and sondes (squares), at Θ=840 K (top panel) and 465 K (bottom panel). The mixing ratios plotted for each instrument have been normalised to the 5 August measurement by the same instrument. The sonde and lidar O_3 data have been smoothed to a potential temperature resolution of 100 K. The microwave O_3 data have been linearly interpolated to the shown values.

mentation seen on the high-resolution maps. In the bottom panel of Fig. 7 the daily data are shown at Θ=465 K ($\sim$18 km), along with the observed O_3 mixing ratios. Evidently they did not capture the filament of subtropical air well, but showed an overall decrease in the absolute value of the PV. This was also observed at 420 K and 520 K ($\sim$21 km), though not at 585 K ($\sim$24 km). Also, an increase around August 10 was revealed, when the O_3 rich vortex filament passed over Lauder. In the daily PV data, the filament extended down to 485 K, but not to 420 K, and extended up to 520 K, but not to 585 K, in agreement with the results of the high-resolution calculations. Note that absolute PV and O_3 mixing ratios are correlated.

The top panel of Fig. 7 shows daily UKMO PV data and O_3 at 840 K ($\sim$30.5 km), which represents the region between $\sim$585 K and 1000 K ($\sim$33.5 km). Evidently, air that originated from the polar vortex (high absolute PV) was O_3 poor. The only exception to this is August 10, when the PV at 840 K reaches a maximum while the O_3 mixing ratio has already started to increase. This likely reflects inaccuracies associated with the coarse resolution of the UKMO PV data.

Conclusions

A decrease of the O_3 column density over Lauder in excess of 100 DU can be attributed to a juxtaposition of O_3 poor air with a low-latitude origin in the lower stratosphere, and O_3 poor air from the polar vortex above about 25 km. Combined with the background conditions, which were 20 DU below average in August [*Connor et al.*, submitted to *Geoph. Res. Letters*] this resulted in the lowest O_3 values on record. The episode of low O_3 values ended when an O_3 rich lower vortex filament replaced the subtropical air over Lauder, while simultaneously the polar vortex moved away.

TOMS observations in the late winter show an unusually disturbed polar vortex, indicating enhanced planetary wave activity. This enhanced activity was the likely cause of the unusual dynamical situation over Lauder.

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E. J. Brinksma, Vrije Universiteit, Faculty of Physics & Astronomy, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands. email: ellen@nat.vu.nl

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