

# Low ozone concentrations over Macquarie Island during 1997

## Part I: trajectory analysis

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(Manuscript received September 2000; revised April 2001)

**Observations from both ground-based and satellite instruments show record low ozone column densities between 20°S and 60°S throughout 1997. The monthly averaged record from the Total Ozone Mapping Spectrometer (TOMS) indicates that measurements from 1997 are lower than both the TOMS climatological mean (1979-1996) and measurements from 1998 and 1999 by up to 20 Dobson units. Macquarie Island ozonesonde data from 1997 are used to investigate the vertical structure of ozone variations during particular low ozone events observed in the southern middle latitudes. Analysis of three low ozone events over Macquarie Island during winter, spring and early summer are conducted using trajectory methods. Results suggest that low ozone events during 1997 are due to either vertical movements of the tropopause, tilting of the polar vortex, or in the case of early summer, remnants of the ozone hole.**

### Introduction

Ozone concentrations have been decreasing globally for the last 20 years in part due to increasing chlorine concentrations in the stratosphere (WMO 1999). The most dramatic example of these reductions has been identified in the high latitude southern hemisphere, where ozone levels are nearly entirely depleted in the lower stratosphere during September and October each year. This phenomenon, which is commonly referred to as the Antarctic ozone hole, has become a regular feature of the springtime high southern latitudes. While the severity of the Antarctic ozone hole has remained nearly constant during the last decade, significant year to year variability has been observed (WMO 1999).

The amount of total ozone over a particular location has natural variations due to both chemical and dynamical processes. In the southern hemisphere, the maximum observed total column ozone occurs during the spring between 45°S and 60°S. This is primarily due to the large-scale transport of ozone rich air from the tropical stratosphere to the southern middle latitudes. This region of higher ozone air in the middle latitudes normally surrounds relatively lower ozone air present in the polar region. Thus there are large meridional gradients in ozone concentrations between the polar and middle latitudes. Indeed, these meridional ozone gradients have recently increased due to anthropogenic ozone loss occurring over Antarctica in spring.

In winter, the strong winds of the polar vortex largely inhibit meridional exchange between the middle and high latitudes, and thus prevent the large-scale transport of middle latitude ozone rich air into the high latitudes. During spring, the normally circum-

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polar vortex often becomes elongated and disturbed, allowing a potential exchange between polar and middle latitude air. Once the polar vortex is pushed off the pole, ozone depleted air may be transported into the ozone rich middle latitudes. For example, it is not uncommon for the edge of the polar vortex to pass over the southern tip of Chile and Argentina during the spring months of September and October (Perez et al. 2000).

The influence of the ozone hole over the southern latitudes near Australia and New Zealand, however, is not as obvious. Prevailing meteorological conditions produce a ridge of high ozone air near the longitudes of Australia and New Zealand that are rarely penetrated by large-scale intrusions of ozone depleted air from high latitudes (Randel and Newman 1998; Atkinson 1997). However, this does not necessarily mean that the ozone hole has no effect on ozone concentrations over Australia and New Zealand. For example, the analysis of Atkinson et al. (1989) suggests that low ozone values observed over Australia during December 1987 were directly related to the Antarctic ozone hole via the so called 'ozone dilution' effect. High resolution trajectory analysis indicates that small-scale filaments from the ozone hole can be transported to the middle latitudes regardless of longitude (Randel and Newman 1998). In addition, there is some evidence that a component of the declining ozone trends observed in the mid-latitude southern hemisphere are due to the presence of the Antarctic ozone hole (Atkinson and Plumb 1997).

During 1997, low ozone columns were observed throughout the southern hemisphere middle latitudes. Although the cause of these low ozone anomalies has not yet been confirmed, analysis from Connor et al. (1999) suggests that large-scale circulation variability is responsible. In addition, extremely low ozone columns were observed in a number of locations, including record low values over Lauder, New Zealand during August 1997 (Brinksma et al. 1997; Connor et al. 1999).

Ozone monitoring at Macquarie Island (159°E, 55°S) includes a Dobson spectrophotometer that has been measuring total ozone since 1978 (Lehmann et al. 1992a) and weekly ozonesonde flights that have been observing ozone profiles during the last four years. Comparisons of the Macquarie Island ozonesonde data with satellite observations are discussed in further papers in this issue including Grainger and Cordero (2002). The analysis of balloon observations from Macquarie Island provide an excellent opportunity to study vortex-mid-latitude exchange in the data-sparse latitudes of the southern hemisphere.

Low ozone events over Macquarie Island are examined using a variety of measurements and model techniques, and will be presented in two companion papers. In this paper, a number of low ozone events over Macquarie Island will be examined using trajectory model calculations. In the companion paper, a three-dimensional ozone analysis system is used to further analyse the large-scale structure and evolution of ozone variations during 1997 (Grainger and Cordero 2002).

## Analysis techniques

Variations in ozone concentration can be a result of both dynamical and chemical processes, and various analysis techniques are commonly used to better understand the origin of tracer variations. In this study, trajectory techniques are used to identify horizontal variations in transport and the relationship to observed low ozone concentrations. In addition, vertical motions due to synoptic-scale variations in the tropopause can also influence ozone concentrations and will also be examined.

Trajectory methods, which have been widely used for transport studies, are especially useful in data-sparse regions of the atmosphere (e.g. Morris et al. 1995). In this study, our trajectory calculations are performed using wind and temperature fields from the Australian Bureau of Meteorology Global Assimilation and Prediction system (GASP) analyses (e.g. Seaman et al. 1995). Wind fields are initially interpolated onto isentropic surfaces, allowing the parcel location to be advected either forward or backwards in time. Trajectory calculations are initialised using nine parcels surrounding Macquarie Island to identify the sensitivity of the trajectory path to the initial parcel location. All trajectory model calculations assume that diabatic processes are small and thus parcels are constrained to a single isentropic surface. This assumption is normally valid in the middle latitude lower stratosphere for up to ten days (Pierce et al. 1994) since the corresponding diabatic heating rates are relatively small.

Reverse domain filling (RDF) is also used to examine the influence of horizontal advection on ozone concentrations. RDF uses a large number of backward trajectories on isentropic surfaces to produce a single high-resolution map of ozone concentrations (Sutton et al. 1994). The final grid is chosen with a horizontal resolution of 1°x1°, using eight day backward trajectories. The initial ozone distribution, as used in the RDF calculations, is obtained from the Ozone Analysis System, and is thoroughly discussed in the companion paper (Grainger and Cordero 2002).

Vertical motions are inferred by examining variations in tropopause height, which has been found to be well correlated with total ozone (Hoinka et al. 1996). For example, an increase in tropopause height produces a reduction in the ozone column as ozone poor air from the troposphere replaces ozone rich air of the lower stratosphere. In contrast, decreases in tropopause height bring higher ozone air to lower levels and thus increases the ozone column. Weekly variations in tropopause height are estimated from the MI ozonesonde temperature profiles, while daily tropopause height variations are estimated from fields of 300 hPa geopotential height using the National Center for Environmental Prediction re-analyses. In this study we assume that over Macquarie Island in non-summer months, chemical processes are relatively slow compared to transport processes (Perliski et al. 1989) although this cannot be strictly confirmed and represents a source of some uncertainty.

## Southern hemisphere ozone in 1997

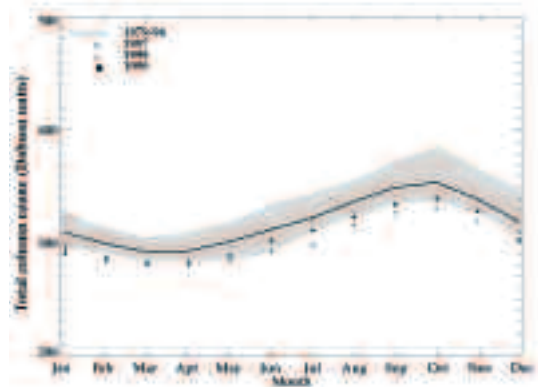
### Global observations

Satellite measurements of total ozone from the Total Ozone Mapping Spectrometer (TOMS) are available from 1979 through to the present, with only a few data gaps. This long-term record is an excellent dataset for studying ozone variability over various spatial and temporal scales. In Fig. 1 the monthly mean TOMS observations from 1979 through 1996 averaged between 30°S and 60°S are compared to observations from 1997, 1998 and 1999. Also indicated are the minimum and maximum range of values observed between 1979 and 1996. From Fig. 1 we note that during the later half of 1997, total ozone was lower than any other year on record and between 10–25 DU below the 1979–1996 average. In the lower latitudes (20°S–40°S), even larger negative ozone anomalies were found during 1997, while at high latitudes (poleward of 60°S) and north of 20°S (including the northern hemisphere), ozone columns were within the range of values previously recorded.

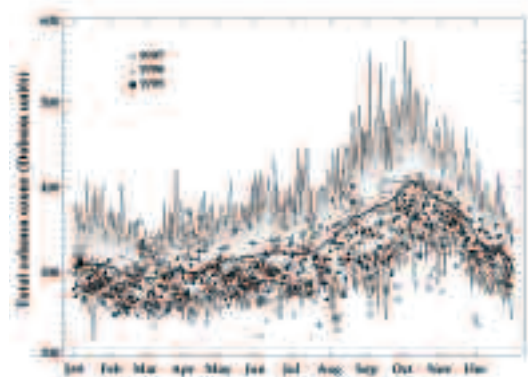
### Dobson measurements at Macquarie Island

Figure 2 shows observations from the Dobson spectrophotometer at Macquarie Island during 1997, 1998 and 1999 compared with the long-term mean calculated between 1979–1996. Although significant day to day variations are observed, it is evident that total ozone columns during 1997 were well below the long term mean. In addition, during 1997 several low ozone events were observed during the later half of the year. For example, daily column ozone densities of more than 70 DU below the long-term mean are

**Fig. 1** Time series of TOMS monthly averaged total column ozone between 30°S–60°S averaged from 1979 through 1996. The black heavy line represents the time mean between 1979–1996, while the grey shading represents the range of values obtained between these same years. The diamonds, plus signs and solid circles represent measurements during 1997, 1998 and 1999 respectively.



**Fig. 2** Time series of daily total column ozone measurements from the Dobson spectrophotometer at Macquarie Island. The solid black line represents the total ozone averaged between 1979–1996, while the shaded values denote the range of minimum and maximum values obtained during those years. Daily total ozone values from 1997, 1998 and 1999 are shown with the diamonds and plus signs and solid circles, respectively.



observed in June, August, September, October and December. While low ozone events are also observed during 1998 and 1999, they were generally not as low or as frequent as those observed in 1997.

## Low ozone events over Macquarie Island

Three low ozone events that occurred during the winter, spring and early summer of 1997 will be examined in detail. The goal will first be to characterise these low ozone events, and then to investigate the mechanisms responsible for the low ozone columns. The specific dates of study were chosen by matching a particularly low ozone event identified from the Dobson instrument with a coinciding Macquarie Island ozonesonde flight. Table 1 shows the Dobson measurements during three time periods when low ozone events were observed over Macquarie Island. It is clear that for each of these time periods, total ozone values for at least one day were well below the long-term mean.

### Winter event

The winter circulation at high southern latitudes is often described by a strong polar vortex which is nearly zonal around Antarctica. At this time of year, large-scale planetary wave activity is relatively low, and thus the vortex is somewhat isolated from the middle latitudes.

Towards the middle of July, total ozone values above Macquarie Island reached as low as 277 DU, over 45 DU below the long-term average, and 24 DU below the 1997 30-day mean (calculated around 15 July). In Fig. 3, the profile of the 15 July ozonesonde observation is compared to a monthly averaged profile. The monthly averaged profile, hereafter referred to as the monthly mean, is calculated by averaging all the ozonesonde flights (normally one per week) within fifteen days before or after 15 July. Total ozone

calculations using the MI ozonesonde data from 15 July are over 40 DU below the ozonesonde observations for the monthly mean, where the partial ozone column was calculated from the surface to 30 km in altitude. The 15 July ozonesonde reached over 30 km and generally showed lower ozone concentrations compared with the monthly mean between 12 and 25 km. With the exception of a notch at 16 km in altitude, the 15 July profile appears to be smooth and consistently lower than the average profile. However, at the peak of the ozone profile, near 25 km in altitude, the profile from July 15th is nearly 0.5 ppmv larger than the average profile.

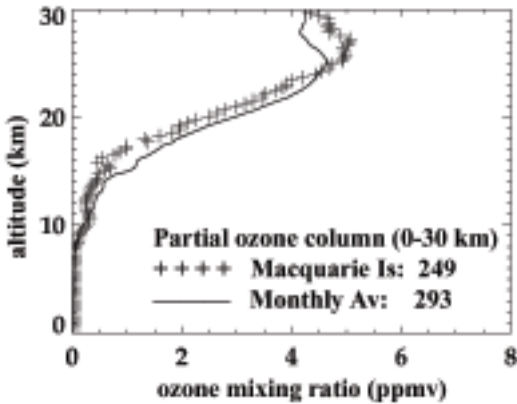
Analysis of the trajectory calculations during middle July shows little indication of large-scale intrusions between the vortex and the mid-latitudes. Back trajectory calculations initialised at Macquarie Island, as seen in Fig. 4, indicate that the vortex circulation was nearly zonal during this time period. Thus, it does not appear that horizontal transport played a major role in the low ozone columns observed in mid-July.

Tropopause height variations during middle July over Macquarie Island do correspond well with observed ozone variations. For example, on 12 July, the height of the 300 hPa pressure level was approximately 200 m higher than the monthly mean. Corresponding variations in tropopause height of this magnitude can explain a 20-30 DU decrease in the ozone column (Hoinka et al. 1996; Lehmann et al. 1992b). These results agree well with temperature profiles from the MI ozonesonde, which also show a significant shift in the approximate tropopause height between 15 July and other flights in July. Although vertical motions do not appear to explain all of the observed variability, they seem to represent a major

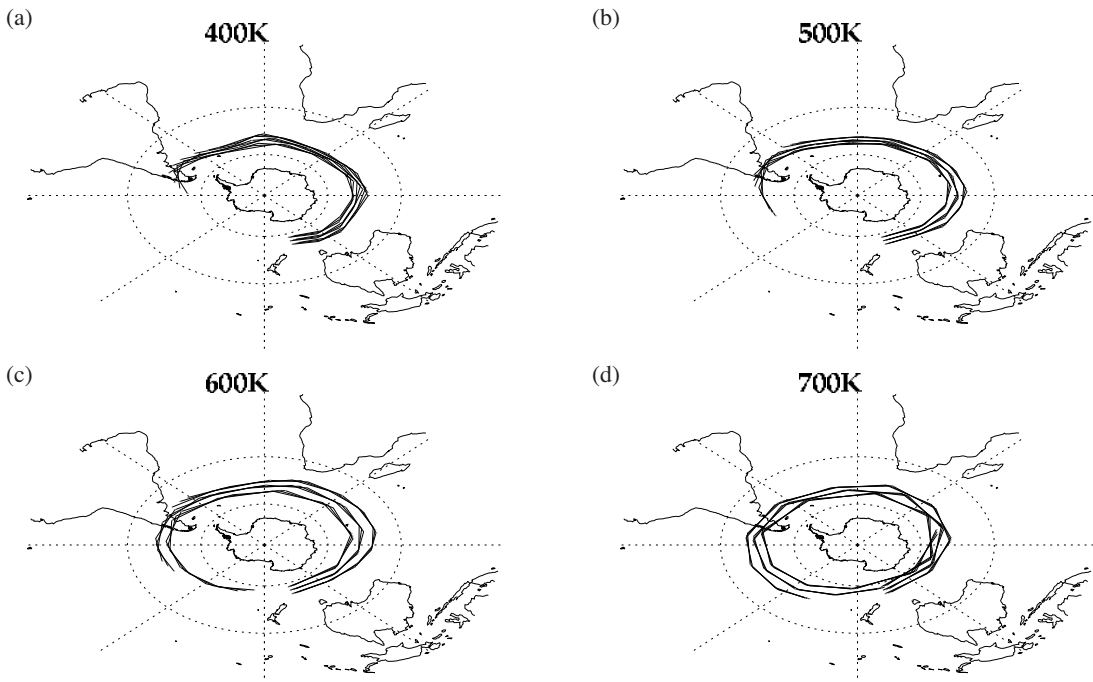
**Table 1. Total ozone measurements from the Macquarie Island Dobson spectrophotometer for three time periods during winter, spring and early summer. The asterisks denote the corresponding date when MI ozonesonde measurements were taken. Also shown is the average total ozone as calculated from 30 day means centred around the corresponding MI ozonesonde launch date. These averages are calculated for 1997 and the years between 1979-1996. All units are given in DU.**

<i>Winter</i>		<i>Spring</i>		<i>Early Summer</i>	
<i>Average Total Ozone</i>		<i>Average Total Ozone:</i>		<i>Average Total Ozone:</i>	
301 (1997)		336 (1997)		311 (1997)	
325 (1979-1996)		375 (1979-1996)		345 (1979-1996)	
Day	Total Ozone	Day	Total Ozone	Day	Total Ozone
Jul 11	323	Aug 30	344	Nov 29	295
Jul 12	285	Aug 31	319	Nov 30	246
Jul 13	277	Sep 1	291	Dec 1	238
Jul 14	331	Sep 2	295*	Dec 2	289
Jul 15	289*	Sep 3	250	Dec 3	311*
Jul 16	340	Sep 4	262	Dec 4	307
		Sep 5	No Data		
		Sep 6	285		

**Fig. 3** Macquarie Island ozonesonde profiles during July. Plus signs indicate 15 July ozonesonde profile, while solid line indicates an average of the four nearest (in date) profiles to 15 July. Also indicated is the partial ozone column (calculated between 0 and 30 km in altitude) from both the 15 July profile and the average profile.



**Fig. 4** Nine parcel grid of five day back trajectories initialised at Macquarie Island on 15 July 1997. Trajectories are calculated at (a) 400K, (b) 500K, (c) 600K and (d) 700K.



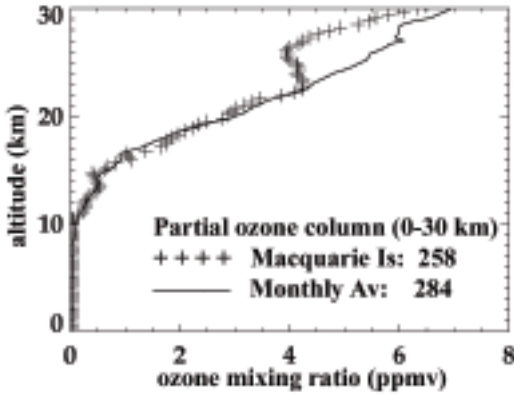
component of the low ozone values found in mid-July.

### Spring event

The return of sunlight to the high latitude southern hemisphere triggers the catalytic processes that rapidly destroy ozone via reactions with active chlorine. The area and depth of the ozone hole typically reaches its maximum in October, depending on meteorological conditions. During spring and early summer, large scale wave events often disturb the polar vortex thereby allowing the possible exchange of polar and middle latitude air.

In early September, total ozone measurements over Macquarie Island were up to 120 DU below the long term average and over 85 DU below the 1997 average (see Table 1). During this time, TOMS observations show that the vortex was shifted off the pole slightly towards the latitudes of Oceania. Comparisons of the 2 September MI ozonesonde profile with the monthly mean, as shown in Fig. 5, indicate large differences between 23 and 30 km in altitude. For example, the 2 September profile at 26 km is nearly 1.5 ppmv lower than the monthly average.

Fig. 5 As in Fig. 3 except for 2 September.



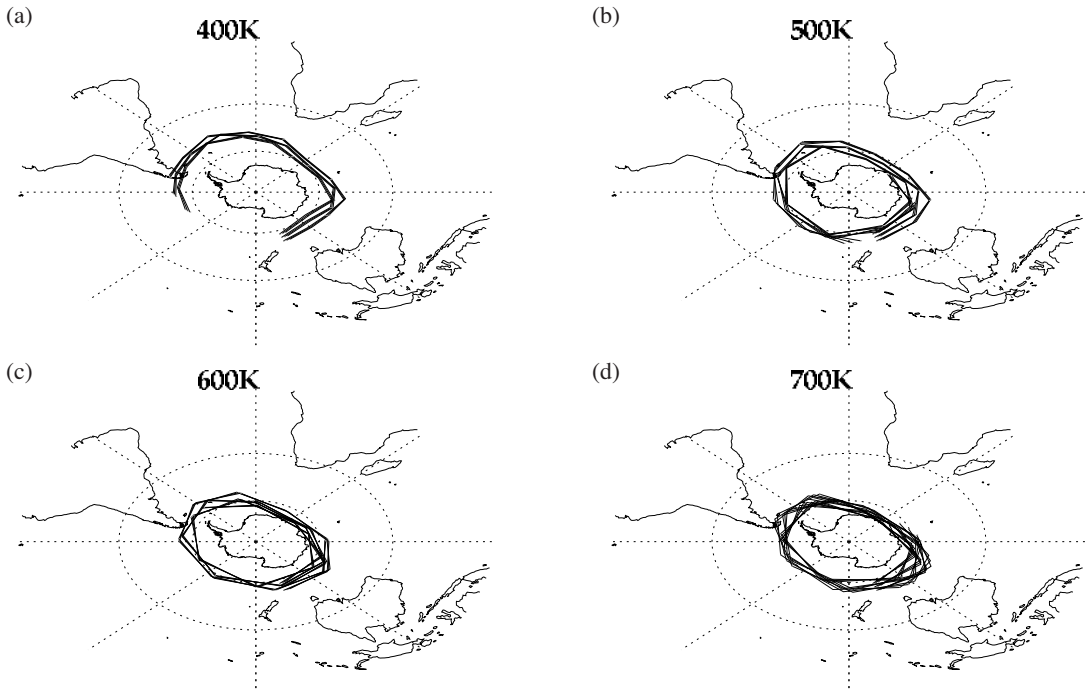
The ozone partial column (0-30 km) on 2 September is 26 DU below the mean profile, compared to the Dobson data which indicates that 2 September was 45 DU below the 1997 mean. This difference implies

that lower than average ozone mixing ratios on 2 September extended above 30 km.

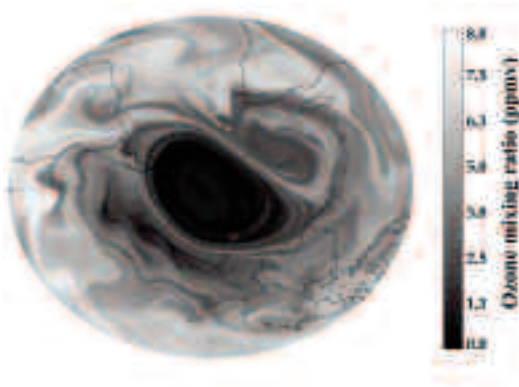
The analysis of the meteorological conditions during early September, including observations from TOMS, suggest that the polar vortex was tilted over the longitudes near Macquarie Island. In Fig. 6, five-day back trajectories from Macquarie Island show that prior to 2 September in the middle stratosphere (600-700K), air parcels experienced higher latitudes than in the lowest levels of the stratosphere (400-500K). For example, at the 700K level, the back trajectories clearly show how air parcels crossed over latitudes poleward of 65°S just two days before the low ozone event was observed, while at 400K, the air parcels remained equatorward of 60°S during the previous five days. The change in the trajectories between 400 and 700K indicates that the upper levels of the polar vortex were tilted off the pole.

The tilting of the polar vortex over Macquarie Island is more clearly illustrated in the ozone RDF calculations as shown in Fig. 7. The low ozone densities, as indicated by the dark shading, are primarily

Fig. 6 As in Fig. 4 except for 2 September.



**Fig. 7** Southern hemisphere distribution of ozone mixing ratio at the 700K level on 3 September computed using an eight day reverse domain fill calculation. The 'X' symbol indicates the location of Macquarie Island.



contained in the polar vortex, although thin filaments of vortex air can be observed in the middle latitudes. On 3 September, the edge of the polar vortex is clearly over Macquarie Island at the 700K level (near 25 km in altitude). At lower altitudes, however, RDF calculations show that Macquarie Island is outside of the main vortex. These calculations correspond well with the Macquarie Island ozonesonde observations showing lower than average ozone concentrations above 23 km in altitude.

During October, additional low ozone events were also observed over Macquarie Island. Analysis of these events indicates similar processes as were observed in early September. At times the edge of the polar vortex, especially in the middle stratosphere, may pass over Macquarie Island thus reducing ozone concentrations. During these events, vertical transport, as indicated by tropopause height variations, is found to play a relatively minor role compared to horizontal transport.

### Early summer

In late spring/early summer, as the polar stratosphere continues to warm, the magnitude of the westerly winds that define the polar vortex begin to weaken. During this time, the shape of the vortex often becomes distorted or even split apart. This transition continues until about middle summer, when easterly winds are normally present throughout the southern hemisphere middle atmosphere.

In early December, ozone values over Macquarie Island dropped rapidly from 295 DU on 29 November to 238 DU on 1 December, a reduction of almost 90 DU

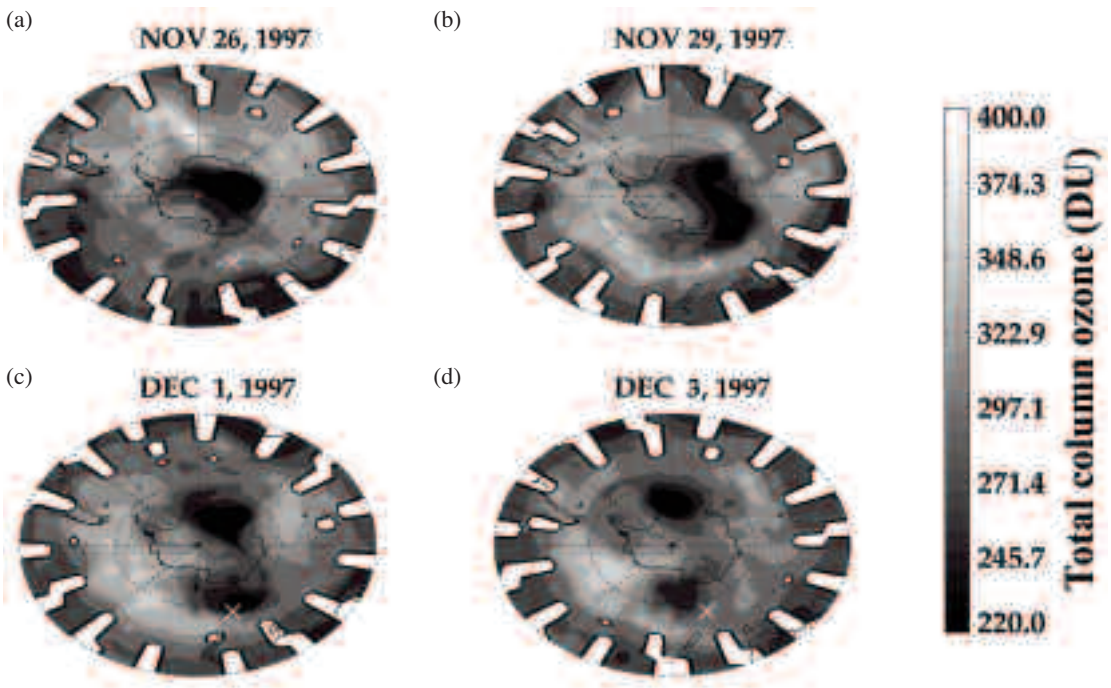
below the long-term mean and over 70 DU below the 1997 30 day mean. Observations from TOMS in late November (see Fig. 8) illustrate how low ozone air associated with the polar vortex is broken apart into two distinct air masses, one of which later passes over Macquarie Island. On 26 November, the region of ozone depleted air is somewhat distorted in shape but remains centrally located over the Antarctica continent. By 29 November, this air mass has been drawn into the middle latitudes near 60°S, apparently by the development of an anticyclone over Antarctica near the longitude of 90°W. On 1 December, the low ozone air mass has been split into two distinct regions located at nearly opposite ends of the Antarctic continent. During this time extremely low ozone measurements were recorded over Macquarie Island, as indicated in Fig. 8(c). By 3 December, these two low ozone air masses are separated by roughly 180° of longitude, while they remain near the same latitude.

The TOMS instrument, which measures total ozone, cannot indisputably resolve this event as due to vortex breakup. We therefore use an analysis of modified potential vorticity (MPV) derived from GASP analyses to examine the dynamical properties of the polar vortex during this period. In the lower stratosphere MPV serves as an excellent diagnostic of the vortex distribution, where the 40 potential vorticity unit can serve as an indicator of the edge of the polar vortex. A time series of MPV distributions at the 500K level from late November through to early December confirms the splitting apart of the polar vortex near 1 December. In Fig. 9, the MPV distribution at 500K shows how the polar vortex is split into two distinct parts, in excellent agreement with the TOMS observations for the same date (See Fig. 8(c)).

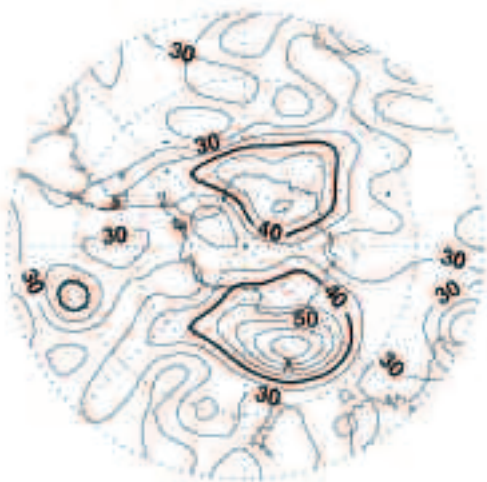
Macquarie Island ozonesonde observations on 3 December indicate low ozone anomalies near 15 km in altitude. In Fig. 10, the 3 December Macquarie Island ozonesonde profile is compared with the monthly mean. The largest differences are found near 15 km in altitude, where ozone concentrations on 3 December are nearly zero. These low ozone values, concentrated between 15-17 km in altitude, contribute to a 15 DU decrease in total ozone compared to average conditions. The ozone partial column (0-26 km) on 3 December is 34 DU below the mean profile, while the Dobson data on 3 December was essentially the same as the 30-day mean. The discrepancy between the Dobson and ozonesonde data implies that higher than average ozone concentrations were present above 26 km on 3 December.

While the largest decrease in the ozone column occurs two days prior to the ozonesonde observation, the low ozone mixing ratios observed in the lower stratosphere on 3 December and both the MPV analy-

**Fig. 8** Daily maps of total column ozone from TOMS in 1997 for (a) 26 November, (b) 29 November, (c) 1 December and (d) 3 December. Missing data in the lower latitudes, as indicated by the white shading, are due to the satellite observing pattern. The 'X' symbol indicates the location of Macquarie Island.



**Fig. 9** MPV at the 500K isentropic level for 1 December, where the contour interval is 5 PV units ( $10^{-6}\text{K m}^2\text{kg}^{-1}\text{s}^{-1}$ ), and the 40 PV unit is denoted by the thick black contour. The 'X' symbol indicates the location of Macquarie Island.



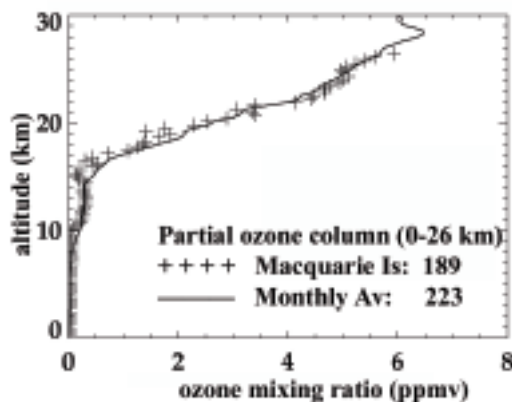
sis and TOMS observations all suggest that the measured air mass over Macquarie Island was a remnant of the ozone hole. The chemical destruction of ozone, which typically occurs during late winter and early spring, is primarily located between 12 and 20 km in altitude (Hoffman et al. 1994). This example during early summer illustrates how low ozone air densities from the high latitudes can move into the middle latitudes after the break-up of the polar vortex.

## Summary

Monthly mean total ozone observations between 20°S and 60°S in 1997 were lower than previously recorded, and lower than observations in 1998 and 1999. In addition, numerous observations of lower than average total ozone were recorded in various southern hemisphere locations, including Macquarie Island. The continual ozone observations at Macquarie Island, including the ozonesonde program, are important tools for monitoring and understanding ozone processes in the middle to high latitudes.

Observations from the ground-based Dobson spec-

Fig. 10 As in Fig. 3 except for 3 December.



trophotometer at Macquarie Island in 1997 document instances where total ozone dipped well below the range of values previously recorded. In particular, occurrences of record low total ozone occurred in five out of six months during the later half of 1997. Low ozone events occurring in winter, spring and early summer were studied and characterised using the Macquarie Island ozonesonde observations and various analysis techniques.

During winter, little variation in the vortex structure suggests that horizontal motions did not play a large role in the development of low ozone events over Macquarie Island. In addition, ozonesonde observations show that ozone profiles appear to be shifted in altitude, characteristic of vertical movements of the tropopause rather than horizontal motions. Analysis of tropopause height variations suggests that vertical motions are largely responsible for the low ozone variations observed in mid July.

An analysis of a low ozone event during early September (spring) suggests a tilting of the polar vortex with altitude over the longitudes near Macquarie Island. Trajectory analysis indicates that low ozone air at the 700 K level (25 km) had a high latitude origin, while air masses at lower altitudes had remained in the middle latitudes. These results corresponded well with the ozonesonde observations, which showed lower than normal ozone concentrations restricted between 23-30 km in altitude.

The final case study event occurred in late November/early December. Analysis of the polar vortex, in conjunction with observations from TOMS both suggest that this low ozone event was a result of the breakdown of the polar vortex. Low ozone mixing ratios observed in the lower stratosphere on the 3 December ozonesonde flight are consistent with air of Antarctic origin. This example illustrates how air

from the ozone hole may eventually mix into middle latitudes after the vortex breaks up.

Finally, it should be noted that low ozone variations can be expected to continue for years to come. The natural variability in stratospheric dynamics coupled with a decreasing ozone trend would produce lower ozone anomalies with increasing frequency. For example, if the  $-4\%$ /decade trend is removed (WMO 1999) from the Macquarie Island ozone observations, the 1997 observations do not appear quite as low as indicated in Fig. 2. This suggests that while decreasing ozone trends may explain some of the variability observed in 1997, dynamical variations likely played a dominant role. A more detailed examination of the general variability of 1997 ozone concentrations, and their relationship to Macquarie Island observations is presented in the companion paper.

## Acknowledgments

The authors would like to thank the observing and processing teams responsible for both the Macquarie Island Ozonesonde data and the Macquarie Island Dobson data. In addition, we would also like to acknowledge NASA for their TOMS observations, Dan Cohen for his assistance with the trajectory calculations and Dr. Shuhua Li for his helpful comments.

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