MAUSAM, **52**, 2 (April 2001), 397-412

551.510.534

# Twisting turning and pulsating of the Antarctic ozone hole, as revealed by TOMS data

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*(Received 3 December 1999, Modified 2 August 2000)*

**सार** - इस शोध-पत्र में टी.ओ.एम.एस./वर्षामेध 7 और उल्का 3 से प्राप्त आंकडों का प्रयोग करके 1992, 1993, 1994 के दौरान दक्षिणी गोलार्ध में वसंत ऋतु में एंटार्कटिक ओज़ोन छिद्रों के विकास का अध्ययन किया गया है। दक्षिणी ध्रुव में ओज़ोन छिद्रों का विकास अधिकतर सहज रहा, सितंबर माह के लगभग अंत तक इसमें निरंतर ह्रास और दिसंबर माह के लगभग अंत तक इनमें निरंतर वद्धि हुई है। 65$^{\circ}$ दक्षिणी अंक्षाश के निकट अवृत्ताकार (अंडाकार) आवर्त सीमा (दीर्घवृत्त के प्रमुख अक्ष के दोनों सिरो) को संगत रूप से पार करने के साथ-साथ विभिन्न अक्षांशों और देशांतारों पर ओज़ोन स्तरों ( ~220 डी.यू.) में उच्चावचन का पता चलता है। जिसमें 1992 में अंतर ~15 दिनों का (पूर्ण घूर्णन अवधि ~30 दिनों का ) और 1994 में 17 दिनों का अंतर (पूर्ण घूर्णन अवधि ~34 दिनों का) घूर्णन अवधि में पाया गया है, जोकि पूर्व के शोधकर्ताओं द्वारा बताई गई 2 से 3 सप्ताहों की अवधि से भिन्न है, यद्यपि इस परिभ्रमण में गति समान नहीं थी। पूर्ण परिभ्रमण के दौरान, अन्य अंतरालों में इस गति में कभी-कभी लगभग शून्य अंश (स्तंभी) से लेकर कुछ दिनों में अंतर 20$^{\circ}$ प्रतिदिन तक पाया गया है। अंडाकार सीमा से परे इस बीच निचले 30$^{\circ}$ दक्षिणी अक्षांशों तक के अंतर पर अक्सर कुछ दिनों (5-8) की अवधि के अवक्षय भी हुए हैं, जिनसे अंडाकार सीमा में वलीयन का पता चलता है जो संभवतः दक्षिणी गोलार्ध ध्रुवीय आवर्त के अंतर्गत प्रतिचक्रवातीय क्षोभमंडलीय प्रबलन के फलस्वरूप ओज़ोन के लघु छिद्रों अथवा/और क्षोभसीमा दाब में हुए परिवर्तनों के माध्यम से सकल ओज़ोन पर सिनाप्टिक विक्षोभों के प्रभाव के कारण हैं। ओज़ोन छिद्र के आकार कुछेक दिनों में ही दीर्घवृर्ताकार से लगभग पूर्णतः वृत्ताकार और विलोमतः उसी तरह परिवर्तित होते हैं और इसका क्षेत्र भी ~15-20 प्रतिशत परिवर्तित हो जाता है। इस प्रकार से ओज़ोन छिद्र उस स्थान पर विद्यमान पवन प्रणाली की तरंग संख्या 2 के घटकों में प्रबलता की भिन्नता के कारण वक्र, चक्करदार और स्पंदी था।

**ABSTRACT.** Using data from TOMS/Nimbus 7 and Meteor 3, the evolution of Antarctic ozone holes during the southern springs of 1992, 1993, 1994 was studied. At the South Pole, the evolution was mostly smooth, a steady decrease up to about September end and a steady recovery up to about December end. At latitudes near 65° S, the ozone levels (~220 DU) at different latitudes and longitudes showed fluctuations compatible with passing of a noncircular (oval) vortex boundary (two ends of a major axis of an ellipse), with a rotation period of ~15 days (full rotation period ~30 days) in 1992 and ~17 days (full rotation period ~34 days) in 1994, different from the 2-3 weeks reported by earlier workers. However, the rotation was not with uniform speeds. During a full rotation, the speeds varied sometimes from almost zero (stalling) for a few days to ~20° per day during other intervals. Outside the oval boundary, often there were depletions with spacings of a few (5-8) days, extending to lower latitudes up to ~30°S, indicating corrugations in the oval boundary, probably due to the effects of synoptic disturbances on total ozone through tropopause pressure changes and/or ozone mini- holes caused by anticyclonic tropospheric forcing under the southern polar vortex. The shape of the ozone hole changed from elliptic to almost circular and *vice versa* within a few days and the area also changed by ~15-20%. Thus, the ozone hole was twisting, turning and pulsating, probably due to a varying strength of the wave number 2 component of the wind system prevailing there.

**Key words** – Antartic ozone hole, TOMS data, Pulsations of ozone hole, Vertical structure.

## 1. Introduction

In the last two decades, the amount and distribution of total ozone has changed considerably all over the globe (Herman *et al.*, 1993; Stolarski *et al.*, 1992; and references therein), most dramatically in the Antarctic, where a springtime ozone hole was detected by ground-based Dobson spectrophotometers, *e.g.*, by Farman *et al.* (1985)

at Halley Bay and Argentine Islands, Chubachi and Kajiwara (1986) at Syowa, Komhyr *et al.* (1986), Bojkov (1986a,b) at South Pole. The hole was further investigated by Stolarski *et al.* (1986) and Stolarski (1988), using the measurements made by the polar orbiting Nimbus 7 satellite. Chandra and McPeters (1986) reported that the depletion was confined to 0-30°W longitudes. Solomon *et al.* (1986), Solomon (1988, 1990) offered an explanation in terms of chemical destruction by CFC compounds (see also Anderson *et al.* 1989). Explanations for the Antarctic ozone decrease range from chemical (Farman *et al.*, 1985; Solomon *et al.*, 1986; Callis and Natarajan, 1986; McElroy *et al.*, 1986; Crutzen and Arnold, 1986) to dynamical (Tung *et al.*, 1986; Mahlman and Fels, 1986). The Nimbus 7 total ozone mapping spectrometer (TOMS) indicated that from 1979 to 1988, there was a nearly linear decrease in the springtime Antarctic ozone minimum, from 200 to 118 Dobson units DU, (1 DU=1 miliatmosphere cm=$2.67 \times 10^{16}$ molecules $cm^{-2}$ ) (*e.g.*, Herman and Larko, 1994). After 1988, the minimum levelled out at ~118 DU; but the total area of the ozone hole region (220-DU contour) continued to increase, though still bounded by the south polar vortex wind system. Detailed structures of the Antarctic ozone holes since 1985 have been investigated and reported by several workers, more so for the 1991, 1992, 1993 and 1994 events (Herman and Larko, 1994; Herman *et al.*, 1995a,b; Hofmann *et al.*, 1994, 1995; Downey *et al.*, 1996). Whereas ozone is produced by solar UV radiation mainly in the low latitudes, atmospheric circulations transport it to higher latitudes until it encounters the polar vortex wind systems. In the northern hemisphere spring, where the polar vortex wind system frequently breaks down and allows equator-to-pole transport of ozone to penetrate the vortex wind system, high ozone amounts (350-550 DU) are observed throughout the north polar region. In the southern hemisphere spring, the equator-to-pole transport is not able to penetrate the strong south pole vortex wind system and ozone piles up near 65° S latitude, while the ozone in the southern polar vortex system (90° S to 65° S) gets isolated for 2-3 months. In recent years, the springtime ozone in the southern polar vortex region has been suffering chemical destruction due to elevated amounts of ClO at high latitudes (produced from increasing amounts of chlorofluorocarbons in the atmosphere), as observed by the Upper Atmospheric Research Satellite (UARS) and reported by Waters *et al.* (1993). In the northern hemisphere, the destruction is limited because of a coincident warming in the lower stratosphere to temperatures above the polar stratospheric cloud limit. But, in the southern hemisphere, the destruction starts in the Antarctic right from August-September, when the sun starts appearing over the horizon and the temperatures are very low, allowing polar stratospheric clouds to form and accelerate the chemical destruction. Since the southern vortex system remains strong for several months, the ozone destruction is almost complete atleast in some altitude belts (12-20 km, Hofmann *et al.*, 1994, 1995).

During the winter, the Antarctic circulation from 10 to 50 km and higher is dominated by a highly baroclinic cyclone centered close to the pole (Bojkov, 1986b). The stratospheric temperature decreases toward the pole. Whereas strong westerly winds at 100 hPa and above encircle the Antarctic like an intense jet, very light winds and extremely low temperatures dominate in the central core from April through October, causing the so-called 'winter stratospheric polar vortex' (see reviews by Labitzke and van Loon, 1972; McIntyre, 1982). Because of the strong influence of atmospheric dynamics on the formation of the ozone hole, its shape and orientation are constantly changing throughout the spring, from nearly circular over the south pole to strongly elliptical (oval) and off-center from the pole, congruent with the polar vortex wind system, with a rotation period of about 2 to 3 weeks (Herman *et al.*, 1995a). Since the Antarctic ozone hole had extended to larger areas in recent years, it would be interesting to investigate the fluctuations at various latitudes near and beyond the vortex boundaries. Earlier, polar orthographic projections showing contours of southern hemisphere TOMS ozone have been presented for selected days, several days apart, in various years (Newman *et al.*, 1991 and references therein, for 1986-1990; Herman *et al.*, 1995a, for 1993). In this communication, daily values of total ozone measured by TOMS are examined for the September, October, November of 1992, 1993 (partially) and 1994, with a view to identify events which could be possibly due to rotation of the vortex, and others probably caused by synoptic disturbances affecting the tropopause and the ozone levels (Schoeberl and Krueger, 1983; Schubert and Munteanu, 1988; Mote *et al.*, 1991; Vaughan and Price, 1991; Salby and Callaghan, 1993). Medium-scale (wave numbers 4-7) synoptic weather disturbances influence ozone in 5-20 km region, where dynamical effects dominate over chemical effects and ozone changes as large as 50 DU can be seen. Often, ozone mini-holes (transient depressions of several DU) are encountered, which are produced by the lifting of ozone-poor tropospheric air by a passing anticyclone (Newman *et al.*, 1988; McKenna *et al.*, 1989; Rood *et al.*, 1992; Orsolini *et àl.*, 1995). Total ozone fluctuations may also result from planetary or Rossby waves (wave numbers 1-3), which often accompany stratospheric warming events in polar winter and early spring (Allen and Reck, 1997, and references therein). Recently, Waugh (1997) made an elliptical diagnostics of stratospheric polar vortices and showed several differences between the Arctic and Antarctic vortices.

**Fig. 1.** The evolution of the Antarctic ozone hole during the spring of 1993 (selected from Plate 2 of Herman *et al.*, 1995a). The white line indicates the 220-DU contour. The top is longitude 90° W; right 0°, bottom 90°E, left 180°

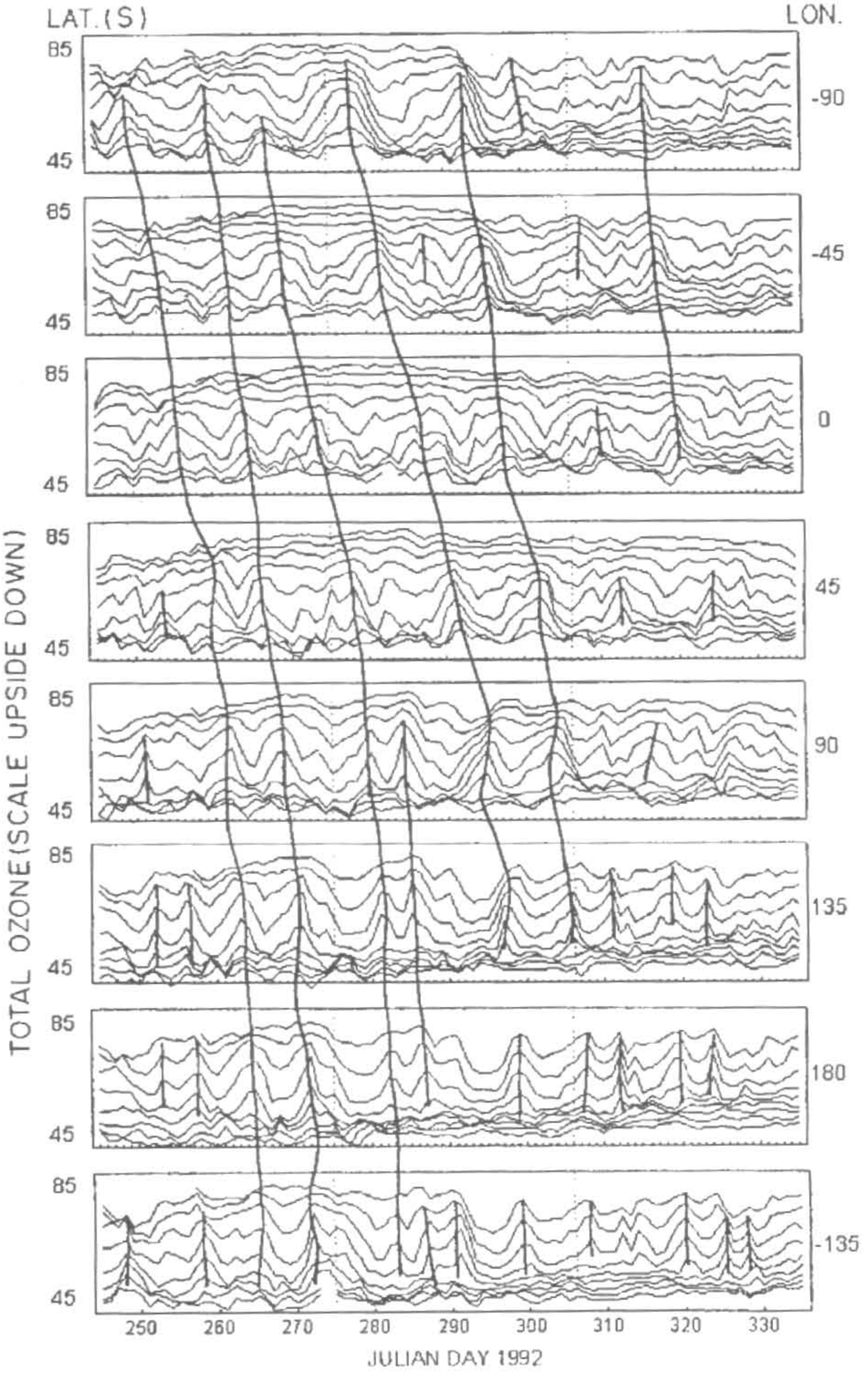

**Fig. 2.** Plots of ozone values during September-November 1992, in 8 frames at longitudes 45° apart. In each frame, the ozone values are plotted upside down so that the peaks indicate ozone holes. The top plots in each frame refer to 85°-80° S latitude belt, followed by those for lower latitude belts, 80°-75°S etc. up to 45°-40°S (zero level shifted downwards). Similar features (ozone minima) are connected with lines

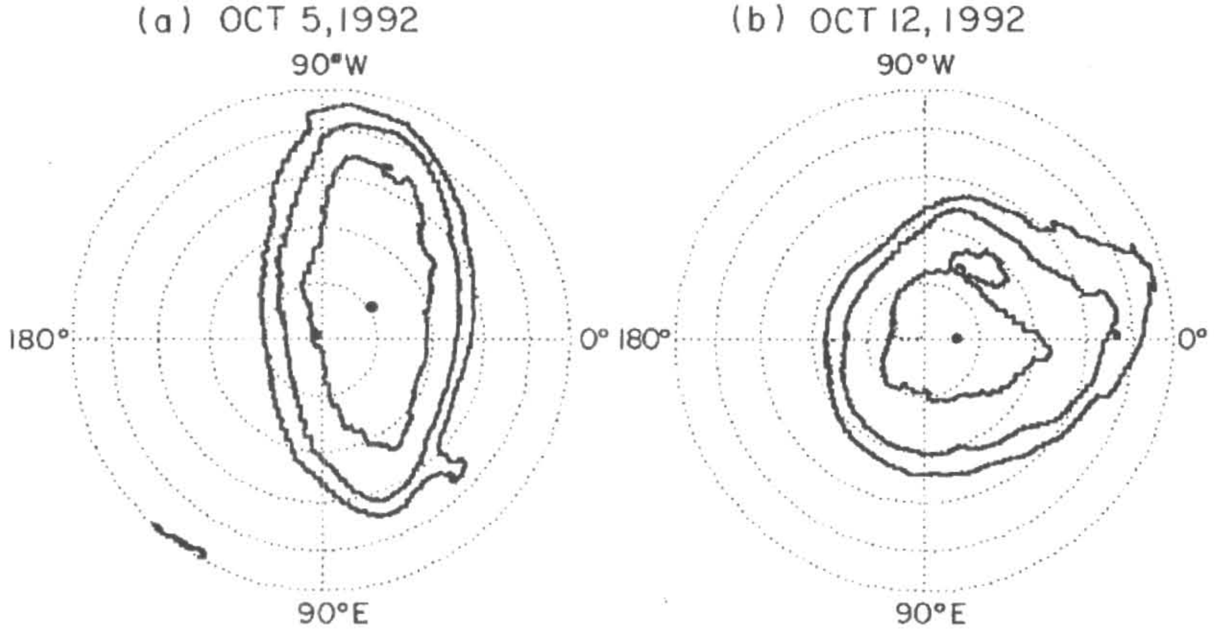

**Fig. 3.** South polar view of the ozone hole region, (a) 5 October 1992, (b) 12 October 1992. The top is longitude 90° W; right 0°, bottom 90° E, left 180°. The three contours are for 160 DU (innermost), 220 DU, 280 DU (outermost)

## 2. Data

The data used are the daily values from the total ozone mapping spectrometer (TOMS) on Nimbus 7 (Bowman and Krueger, 1985; Herman *et al.*, 1991, upgraded version 7.0), which operated upto May 6, 1993, and Meteor 3 which was launched on August 15, 1991. Fig. 1 shows the evolution of the Antarctic ozone hole during the spring of 1993 (September 2 - November 18, 1993, Meteor 3/TOMS data, from Plate 2 of Herman *et al.*, 1995a), the white line indicating the 220-DU contour. The top is longitude 90° W, right is 0°, bottom is 90° E and left is 180°. As can be seen, the contour often changes shape radically, from almost circular to elongated (elliptical) or *vice versa*. However, these plots are 7 days apart and rotation is not easily discernible. In what follows, day-to-day variations are examined.

## 3. Spring-time variations in various years

### (A) *Variations in 1992*

Fig. 2 is a plot of the ozone values for September-November 1992. In each frame for a particular longitude, the ordinate scale is upside down, *i.e.*, lower ozone values are above and higher values below. Hence, the peaks represent ozone minima (holes). In each frame, plots for nine latitude belts are shown in sequence, (stacked, zero shifted), from 85°-80° S at the top to 45°-40° S at the bottom. Thus, the ordinate represents ozone values as well as latitudes. Each frame refers to one longitude and the 8 frames refer to successive 8 longitudes, 45° apart, *viz.*, 90° W, 45° W, 0°, 45° E, 90° E, 135° E, 180°, 135° W. The following may be noted:

(*i*) In very high latitudes (uppermost traces in every frame), the fluctuations are small, as ozone values are all very low, indicating a uniformly deep hole. At lower latitudes, several fluctuations occur, most of these simultaneous at several latitudes, indicated by vertical connecting lines. These are probably due to elongated features of the vortex, sweeping over different latitudes simultaneously. However, in some cases, the peaks in the same frame can be connected only by slightly inclined lines, indicating that the regions swept at different latitudes with some lags or leads.

(*ii*) The spacings between these fluctuations are variable (5-15 days), indicating more than one feature sweeping around, oval ends and/or synoptic disturbances.

(*iii*) Some features are similar in successive frames and the connecting lines from one frame to the

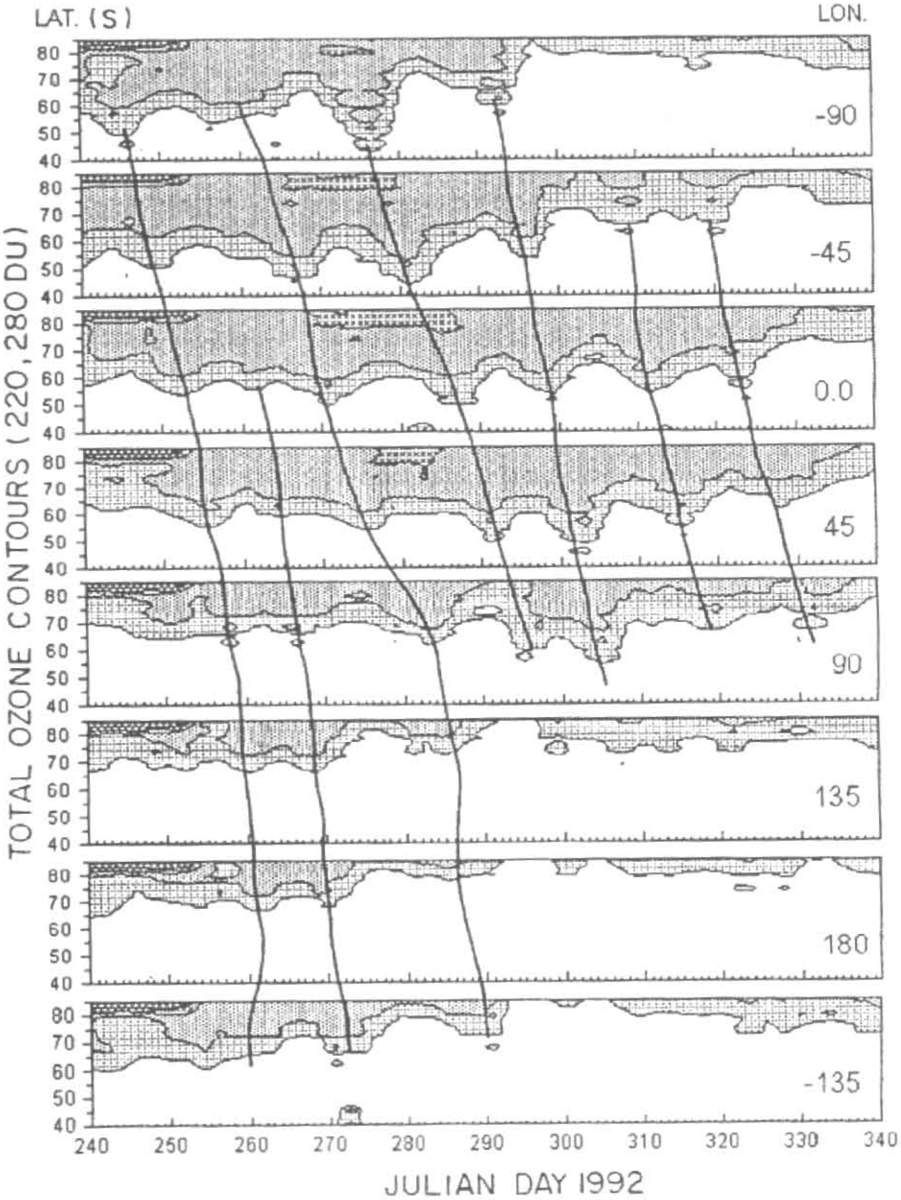

**Fig. 4.** Same as Fig. 2, with ozone values shown by contours, lowermost for 280 DU, the next above it for 220 DU

next seem to tilt in such a way that lower frames show the features later. This is consistent with a clockwise motion (say, decreasing western longitudes) as seen from above the South Pole.

(*iv*) In any frame, some features are restricted to one or two latitude belts only. These could be mini-holes, caused by tropospheric disturbances entering the lower stratosphere.

(*v*) The structures do not start at the same latitude belts in all longitudes. This indicates longitudinal asymmetry, which could be caused by an eccentricity of the vortex. Fig. 3(a) shows the contours (160, 220, 280 DU) for a specific day 5 October 1992. As can be seen, the oval was eccentric, its center shifted northwards, roughly along the 0° longitude. Thus, the structures seen in Fig. 2 could also be synoptic disturbances, occurring just outside the vortex walls, which were at different latitudes in different longitudes.

Fig. 4 depicts the same data in a different way. The major counters are for 280 DU and 220 DU. As can be seen, considerable fluctuations occurred during the 3 months September, October and November of 1992. Several ozone minima (features) can be identified and, in different frames, these seem to be shifted to later days, as seen from the connecting lines. We shall term these as major features. The contours extend to different low latitudes in different longitudes, indicating that the polar vortex may not be centered at the South Pole. In the longitudes 90° E, 135° E, 180°, 135° W (the four plots at the bottom), the extension to lower latitudes hardly reaches 65° S; but in other longitudes, it extends to 50° S latitudes. This is consistent with the eccentricity of the 220 DU contour shown in Fig. 3(a). In addition, features immediately outside the vortex wall are also involved. Following facts are noteworthy:

(a) The connecting lines indicate that major features occur at many longitudes, but later at more easterly longitudes. This is consistent with a clockwise rotation of the features, as seen from above the South Pole. At 90° W (top plot in Fig.4), the spacings in the major successive features were 16, 17, 15, 18 and 10 days. Thus, atleast during September-October, the features could be due to the rotation of a single elongated feature with a rotation period of ~16 days. However, since two elongated features are involved (the two arms of the elongated ellipse of Fig. 3a), the complete rotation period would be double, ~30 days.

(b) At longitude 45° W (second plot in Fig. 4), the same major features appear but a few days later, and the spacings of the features are 18, 15, 14, 14, 11 days, almost the same as at 90° W.

(c) At longitude 0° (third plot), the same major features have spacings 18, 16, 13, 13, 13 days, almost the same as at 90° W and 45° W longitudes. However, an additional feature appeared in between the first and second feature, so that the 18 days spacing was split into 11 and 7 days.

(d) At longitude 45° E (fourth plot), the features persisted as at 0° longitude.

(e) At longitude 90° E (fifth plot), an additional feature appeared ~9 days before the first major feature. Thus, the features had spacings 9, 7, 17, 15, 7, 15, 12 days.

(f) At longitude 135° E (sixth plot), the last feature disappeared.

(g) At longitudes 180° and 135° W (two plots at the bottom of Fig. 4), some features became obscure and others receded to higher latitudes, due to the eccentricity shown in Fig. 3a, with the polar vortex center shifted considerably northwards in the 0° longitudes.

(h) The connecting lines reveal another important feature. The phase lag at successive longitudes was not constant. From 90° W to 90° E longitudes (through 0° longitude), the rotation speed was much larger (equivalent to 30 or more days for a full rotation) as compared to that for 90° E to 90° W longitudes (through 180° longitude) (~15 days). Part of this might be related to the eccentricity.

Thus, the polar vortex was not only eccentric (much more northwards towards 0° longitude), but seemed to be twisting and turning irregularly. This is illustrated further.

Fig. 5 shows the evolution of the polar vortex on successive days from 15 September to 29 October of 1992. For the plot of each day, the top is longitude 90° W, right is 0°, bottom is 90° E and left is 180°. The contour is for 220 DU. It is fairly smooth most of the time and indicates that it is within the vortex. When clearly oblong (elliptical), the axis of the ellipse can be roughly demarked by a straight line as shown. The following may be noted:

(*i*) From 15 September to 17 September, the axis of the ellipse rotated clockwise by about ~45° (almost 20° per day); but, in the next 4 days, the ellipse deformed to almost circular and regained almost elliptical shape only on 22 September. Let us assume that on 22 September, the axis pointed almost vertically up. From 22 September to 29 September (7 days), the axis seems to have turned clockwise by ~80° (~12° per day), pointing to the right, from 29 September to 5 October (7 days) by another 90° (~13° per day), pointing downwards, and from 5 October to 11 October (6 days) by another 50° (~8° per day). In 19 days (22 September – 11 October), it turned by ~220°, *i.e.*, ~12° per day, equivalent to a full rotation (360°) period of ~30 days. However, it became almost circular on 12 October and

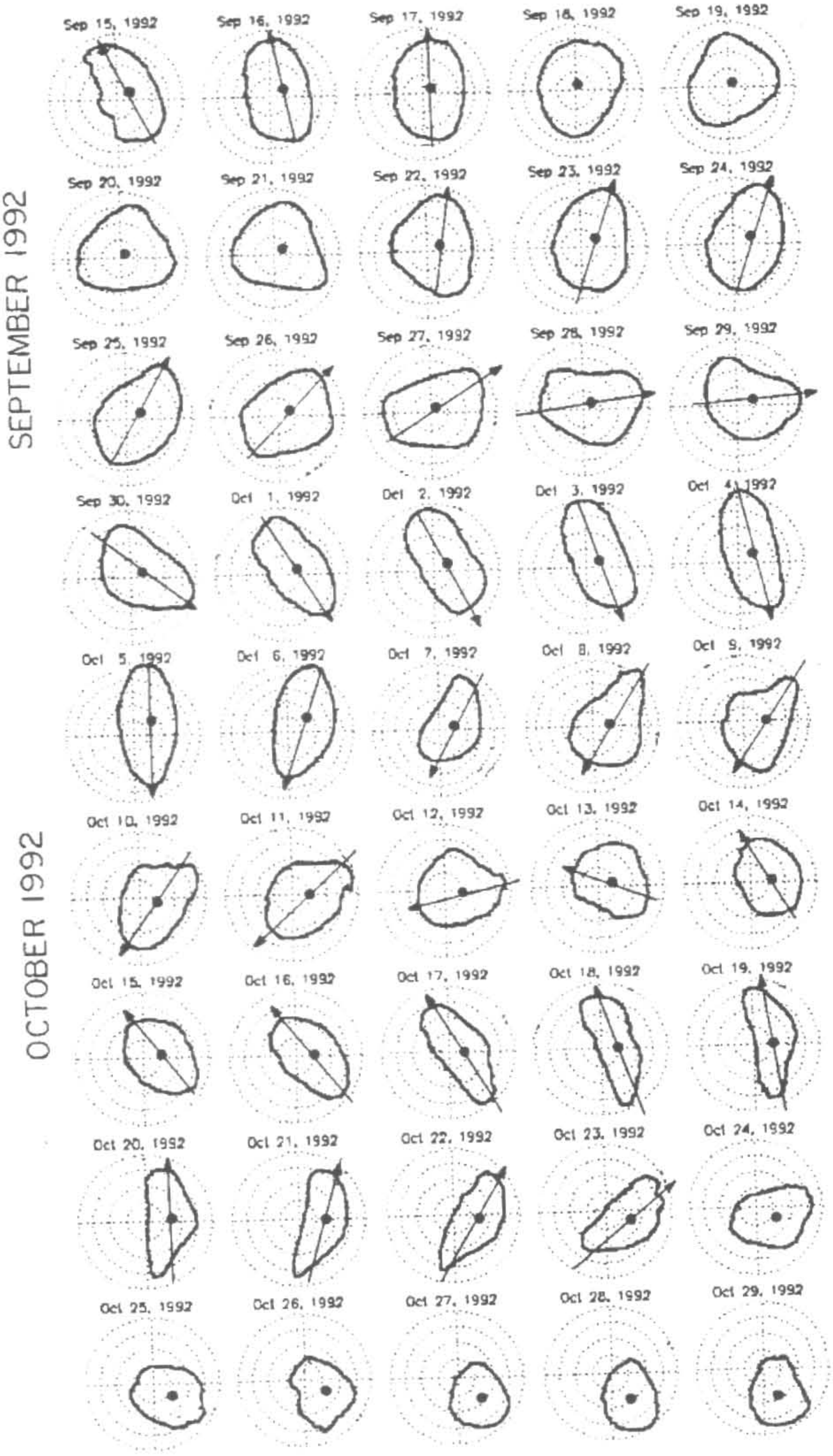

**Fig. 5.** Polar view of the ozone hole region, on successive days from 15 September to 29 October (spring), 1992. Whenever an elliptic shape is discernible, the axis is marked by a line and successive dates reveal its clockwise rotation, with irregular speeds. The top is longitude 90° W; right 0°, bottom 90° E, left 180°. The dot marks approximately the center of the hole region

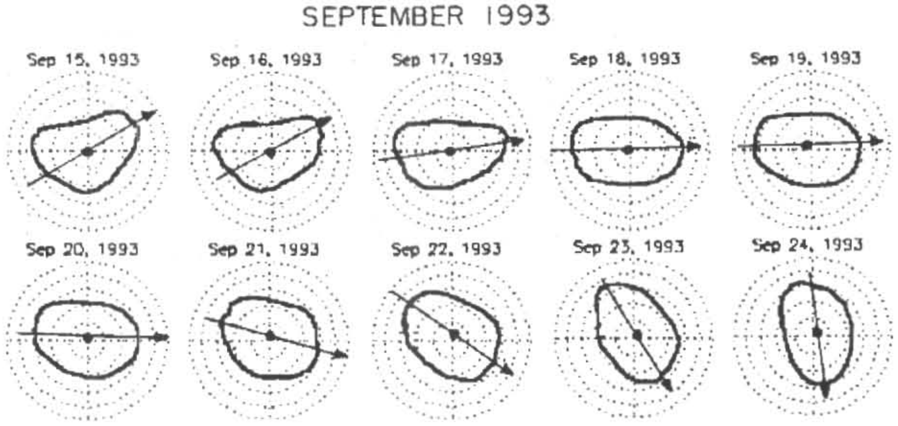

**Fig. 6.** Same as Fig. 5, for a few days in the spring of 1993

continued circular on 13 October. On 14 October, elliptical shape was partly regained; but the axis turned clockwise by only about 45° in the next 6 days (~8° per day), pointing vertically up on 20 October. In the next 3 days, it turned rapidly by almost 60° (~20° per day) and then became circular and remained so up to 29 October. (Later, it continued to become elliptic again and continued its clockwise rotation, not shown here). Thus, during this whole period, the rotation was not discernible when the shape was circular; but in other intervals when the contour was elliptic, the rotation speed did not seem to be constant. It varied widely (0° to 20° per day). Overall, the orientation of the axis on 15 September was seen again on 14 October, indicating a full rotation period of ~30 days. Similarly, the orientation of the axis on 22 September was seen again on 21 October, indicating again a full rotation period of 29-30 days. Thus, during 1992, the full rotation period was ~30 days.

(*ii*) An interesting feature is the centering of the contour (shown by a dot). Most of the time, the center of the ellipse or circle was slightly northward (to ~80° S) along the 0° longitude. However, after 23 October, it seems to have shifted eastward, to ~30° - 60° E, and to lower latitudes. Thus, the center itself rotated around the geographic South Pole, clockwise by ~60°, and moved away to lower latitudes, mostly in the end part of October 1992.

(*iii*) The actual areas of the various ovals and circular shapes in Fig. 5 were measured. It was found that these varied considerably. Thus, an ellipse, when deformed into a circular shape, had an area 15-20% different. Of course, the areas were, in general, smaller by the end of October, as expected (hole dissipation).

(*iv*) In Fig. 3(a), contours of different ozone levels (160, 220, 280 DU) were shown for a selected day 5 October 1992 when the contours were elliptic. For comparison, Fig. 3(b) shows similar contours on another selected day 12 October 1992, when the contours were almost circular. On both of these days, the 160 DU and the 220 DU contours are mostly smooth and parallel to each other, indicating that both were within the vortex and changed shape simultaneously. The 280 DU contour is almost parallel to the 210 DU contour but not quite and is, in general more corrugated, indicating effects of synoptic disturbances. The changing shapes and the irregular rotation rates of the 220 DU contours would give fluctuating total ozone levels at any given location (specific latitude and longitude), with minima spaced at different but large time intervals (~15 days). On the other hand, corrugations in the 280 DU contour due to high-latitude atmospheric wave activity (including synoptic disturbances), would cause longitudinal fluctuations and differences of ozone levels spaced at smaller intervals (~5 days), as seen in Figs. 2 and 4.

In conclusion, the ozone hole rotates with irregular speeds (turning and twisting) and pulsates (oval to circular, with variable areas) during the course of its evolution and decay.

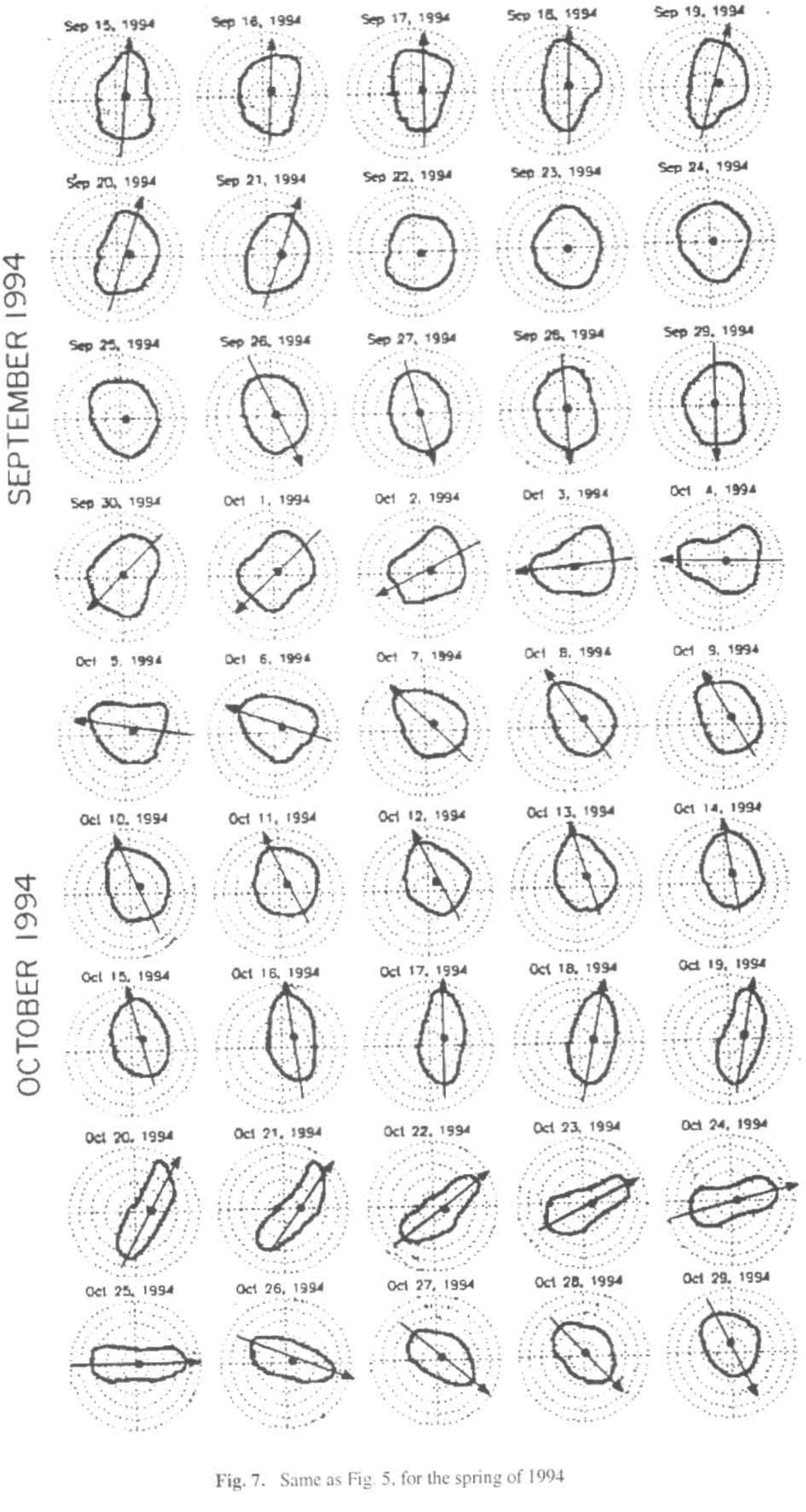

**Fig. 7.** Same as Fig. 5, for the spring of 1994

(B) *Variations in 1993 and 1994*

For 1993, we had very short data. Fig. 6 shows the evolution of the ozone hole during 15-24 September 1993. The shape was ill defined in the first two days but became elliptic by 24 September. However, in the 6 days from 15 September to 20 September, the rotation was only ~40°, ~7° per day. But during the next 4 days from 20 September to 24 September, the rotation was ~80°, ~20° per day. Thus, rotation rates varied widely.

Fig. 7 shows the counters during 15 September – 29 October, 1994. Here, the contours are almost circular in many more days than in 1992 (Fig. 5). The axes could be traced only approximately up to the first week of October, after which the elliptical shape was seen better and the axes more certain. However, the irregular rotation rates are clearly seen. From 15 September (axis up) to 21 September (6 days), the rotation was only ~30°, ~5° per day. Thereafter, the shape changed to almost circular and the axis was lost. But, from 21 September up to 26 September (axis almost down) (5 days), the rotation was most probably ~120°, ~24° per day. From 26 September onwards, the rotations for every successive 4 days were, 26-30 September, ~70°, 30 September – 4 October, ~40°, 4-8 October, ~60°; 8-12 October, ~20°, 12-16 October, ~15°, 16-20 October, ~50°, 20-24,October, ~30°, 24-28 October, ~50°, a widely varying range of rotation rates, 4°-18° per day. Overall, the position of the axis on 15 September (almost vertically up) is seen again only on 18 October, yielding a full rotation period of ~34 days. Similarly, the position of the axis on 26 September is seen again on 29 October, again yielding a full rotation period of ~34 days. Thus, in 1994, the full rotation period was ~34 days, larger than the 30 days in 1992.

## 4. Vertical structure, evolution and dissipiation

The total ozone data do not give any indication of the changes in the vertical structure of ozone. However, considerable information is available through ozonesonde programs. NOAA Climate Monitoring and Diagnostics Laboratory has been conducting year-round ozonesonde programs at Amundsen-Scott Station at the South Pole since 1986. For 1992, Hofmann and Oltmans (1993) reported that the rate of ozone decrease during formation of the springtime ozone hole and the severity of ozone loss in the lower stratosphere were greater in 1992 as compared to previous years. On 11 October 1992, total ozone reached an all-time low of ~105 DU at South Pole Station and there was an apparent ozone void between 14-18 km. (Satellite measurements had shown a 25% larger extent of the ozone hole in 1992 as compared to earlier years). The increase of ozone hole intensity in 1992 was probably due to the sulphuric acid droplets which formed in the stratosphere following the Pinatubo volcano eruption in the Philippine Islands in 1991 and were trapped in the south polar vortex.

For 1993, Hofmann *et al.* (1994) reported ozonesonde results wherein the South Pole value of ozone dropped to ~90 DU (lesser than 105 DU of 11 October 1992) on 12 October 1993 and a 5 km thick region (14-19 km) was devoid of ozone. The increased hole level in 1993 was attributed to prolonged presence of PSC (polar stratospheric clouds) at 18-23 km, combined with the continued presence of sulphate aerosols from the Pinatubo eruption and, increased chlorine levels.

For 1994, Hofmann *et al.* (1995) reported ozonesonde values of 102 DU on 5 October 1994. There was complete destruction between 15-20 km.; but destruction in the 10-14 km region was lesser, probably due to diminished stratospheric aerosol from the Pinatubo eruption. However, as in 1993, ozone was again observed to be reduced in the 22-24 km region, indicating that the ozone hole was now extending to a region unaffected prior to 1992.

For 1995, Hofmann *et al.* (1997) reported ozonesonde values of 98 DU in the first week of October 1995, with loss of ozone extending up to 23 km. This extension upward in recent years is attributed to human-produced halogens. The depletion prolonged much longer in 1995, well in November and December, because of the longer than normal lifetime of the 1995 winter polar vortex. The 14-18 km region was almost void for a longer time, with record low values throughout December.

Another group has been conducting measurements with balloon-borne instruments at McMurdo Station (78° S, 167° E) since 1986. In 1993, record low ozone values (130 DU) were measured (Johnson *et al.,* 1995) in the middle of October. In 1994 and 1995, minimum values were 138 DU and 139 DU and occurred in the first week of October (Nardi *et al.,* 1997). This was followed by a continued short-term decrease in the 12-20 km column (almost complete depletion over 14.5-19.5 km); but, at the same time, ozone replenishment above 20 km, caused by transport of ozone-rich lower latitude air across the vortex wall, or shrinking of the vortex at the upper levels, was occurring. Since more than thirty profiles were measured in each hole season (22 August – 1 November), it was possible to monitor the day-to-day evolution. In general, McMurdo ozone variations were similar to those of a location well within the south pole vortex, far from the vortex edge. However, there have been earlier occasions when vortex edges oscillated over McMurdo. For example, in August and September of 1990, the vortex edge had two excursions over McMurdo, which could be identified from the simultaneous measurements of wind speeds, which increased from nominal values of 20-30 ms$^{-1}$ (inside the vortex) to 40-70 m s$^{-1}$ (outside the vortex) at 20-30 km altitude (Deshler and Hofmann, 1991).

Near Punta Arenas (53° S, 71° W), Chile, vertical distributions were investigated by ozonesondes launched on balloons on selected days from the Brazilian Antarctic Station Comandante Ferraz (62° S, 58° W). Details are given in Kirchhoff *et al.* (1997a,b). During the ozone hole of 25 September 1992, ozone destruction was almost complete at 15-17 km. A similar pattern was seen on 3 and 20 October, 1992. Later in 1995 also, 12, 13, 14 October 1995 showed substantial decreases in the 15-18 km height range, though not as severe as in 1992. In these balloon flights, upper air temperatures and winds were also monitored. The winds in the stratosphere near 55° S were found to be blowing in a clockwise direction when the observer is looking down at the South Pole. Total ozone charts from TOMS showed a succession of low and high ozone "clouds" passing over Punta Arenas in a sequence of just a few days. Backward trajectories showed a polar outward motion from the South Pole, mainly from west to east, but with a component to the north, and the wind direction over Punta Arenas seemed to be in agreement with this stratospheric air motion in the polar region.

A particularly interesting feature of the verticle profiles over Punta Arenas on 12, 13, 14 October 1995 was the presence of vertical layers or laminae. Similar laminated structures in ozone verticle profiles were reported by Mlch and Lastovicka (1996) but in central Europe. As mentioned by Kirchhoff *et al.* (1997b), such laminations were not observed at McMurdo. These were not observed by Hofmann *et al.* (1994) at the South Pole either, where almost complete depletion was observed at 14-19 km. It seems that sometimes, the ozone-poor air leaks out from the ozone hole and spreads in the form of filaments, which result in laminations at lower latitudes.

At Santa Maria (30° S, 54° W), RS, Brazil, Kirchhoff *et al.* (1996) conducted balloon flights on 26 and 28 October 1993 and found that the 28 October profiles were very different. Near 16 km, 75% ozone had disappeared on 28 October, as compared to 26 October. NASA/TOMS ozone data plotted on a projection showed a clear tongue of low ozone stretching from the Antarctic ozone hole to the South American continent on 18 and 28 October but not on 26 October. Air mass trajectories at 20 and 25 km heights showed that on 28 October, the air mass at Santa Maria had an Antarctic connection.

Apart from ozone, other long-lived tracers can also be used for studying the structure and evolution of stratospheric polar vortices. Waugh (1997) used nitrous oxide ($N_2O$) data from the Geophysical Fluid Dynamics Laboratory 'SKYHI' general-circulation model (GCM), fitted 'equivalent ellipses' to data on isentropic surfaces at different altitudes and showed that (a) when the Antarctic vortex moved off the pole, it did so throughout the lower and middle stratosphere and, (b) in late winter (September- October), the vortex was more elongated at higher altitudes. Many other details, including comparison of Antarctic and Arctic vortices, have been reported by Waugh.

## 5. Conclusions and discussion

The TOMS/ Nimbus 7 and Meteor 3 data were used to examine the extension to lower latitudes of Antarctic ozone holes during the springs of 1992, 1993, 1994. The following was noted:

(*i*) In the vicinity of the South Pole, the ozone hole evolution was mostly smooth, a monotonic decrease upto almost the end of September, followed by a monotonic recovery by November end or a little later. Occasionally, some fluctuations were seen at the South Pole also, indicating that the vortex center was oscillating near the South Pole. The shape of the vortex was almost circular for a few days, oval for the next few days, and back to circular. Thus, the vortex was pulsating most of the time, with 15-20% changes in area also.

(*ii*) In latitudes near 65°S, considerable fluctuations were seen, often compatible with the notion of an eccentric and/or noncircular (oval) vortex, with the two tips of the major axis of the ellipse reaching these latitudes and rotating (turning) and sweeping over these areas. The overall speed was ~15 days (full rotation ~30 days) in 1992 in ~17 days (full rotation ~34 days) in 1994, different from the 2-3 weeks mentioned in literature (Herman *et al.*, 1995a). However, during one rotation, the speed was by no means uniform. Often, the vortex seemed stalled (zero speed of rotation) for a few days, while during some other days, it rotated fast. The rotation speeds varied in a wide range (0 to 20° per day).

(*iii*) There were instances when at these latitudes (65° S), narrow (5-10 day spacings) structures appeared, extending towards lower latitudes beyond the edge of the vortex, even up to ~30° S. These structures could spread non-uniformly in different longitudes, probably because of the eccentricity of the vortex. However, these structures were often outside the vortex walls and should be due to effects of synoptic disturbances. Some structures were confined to small regions. These should be transient mini-holes, caused by changes in the upper-tropospheric circulation.

(*iv*) Thus, the ozone hole seems to be twisting, turning and pulsating, probably due to the varying strength of the wave number 2 component of the wind system there.

Planetary scale waves (wave numbers 1-3) comprise most of the zonally asymmetric component of the stratospheric circulation (Manney *et al.*, 1991). During winter and spring, wave 1 is quasi-stationary in both hemispheres. But wave 2 is quasi-stationary only in the Northern Hemisphere, and propagates regularly eastward in the Southern Hemisphere (*e.g.*, Leovy and Webster, 1976; Mechoso *et al.*, 1988). The mechanism involved in the generation and behaviour of wave 2 in the Southern Hemisphere winter and spring is not quite clear. A vertical propagation of waves 1 and 2 generated in the troposphere is suggested as the dominant mechanism for generation of their counterparts in the stratosphere (Randel *et al.*, 1987), but the eastward propagation of wave 2 in the stratosphere only is still a mystery, though many mechanisms have been suggested (references in Manney *et al.*, 1991). Observational evidence for wave 2 characteristics is provided by Shiotani *et al.* (1990), who reported a wave 2 of a period 9.2 days in the Southern Hemisphere stratosphere in the spring of 1983, and by Manney *et al.* (1991) who reported that the wave 2 peaked between 55°-65°S and had a regular eastward propagation with periods ranging from 5 to 40 days. Also, there can occur a vacillation between wave 1 and 2 amplitudes (Mechoso *et al.*, 1988; Manney *et al.*, 1991), suggesting *in situ* nonlinear wave-wave interaction. In some years, wave 1 and wave 2 amplitudes are strongly anticorrelated in time during September and October, while in some other years, the two are positively correlated during August and September. While wave 1 is usually quasi-stationary, there were instances when wave 1 moved eastward with wave 2 for 4-10 days. The complicated interaction between waves 1 and 2 results in the complicated rotation of the southern stratospheric vortex, as described in the present communication.

Springtime stratospheric ozone destruction in the Antarctic is mainly chemical, due to anthropogenic emissions of chlorine and bromine compounds (Solomon *et al.*, 1986; Stolarski *et al.*, 1986) like chlorofluorocarbons, carbon tetrachloride, methyl chloroform, and the halons. The CFCs and halons released at the earth's surface mostly in the northern hemisphere, spread over the globe and drift slowly to the tropical stratosphere, where sunlight breaks them into stable reservoir species. These species spread to other latitudes in the stratosphere. During austral winter, extremely low stratospheric temperatures (below ~80°C) develop in the intense circulation of the polar vortex over Antarctica and assist the development of PSCs (polar stratospheric clouds), which act as sites for transforming chlorine and bromine species into more active forms, When sunlight appears in the Antarctic in September, rapid chemical reactions start destroying ozone in the vortex. By early October, ozone at 13-20 km is almost completely destroyed. However, by that time, temperatures rise, PSCs evaporate, chemical destruction ceases and ozone-rich air from other latitudes invades the polar upper stratosphere, starting the recovery of Antarctic ozone level, which is complete by December.

In contrast to the northern-hemisphere where the polar vortex breaks down frequently and mid-latitude air is able to push towards the north pole, the south polar vortex is very strong and is considered to isolate air mass very well for 2-3 months. Nevertheless, some transport in and out of the vortex wall is envisaged. Prather and Jaffe (1990) and Prather *et al.* (1990) used a three-dimensional chemical transport model and showed that the transport of ozone-poor air from the Antarctic vortex resulted in measurable decreases of column ozone extending to 30°S during austral summer. The central question is whether the air within the vortex is relatively isolated, horizontally by an impermeable potential vorticity "barrier" at the position of the jet stream and vertically by weak radiatively cooled descending motions ("containment vessel" hypothesis), or whether the air is rapidly flushed through the vortex ("flowing processor" hypothesis, Randel, 1993). For a high degree of isolation of the vortex in the horizontal direction. McIntyre (1989) states that since potential vorticity of an air parcel is a conserved quantity in the absence of diabatic heating or friction, quasi-horizontal (isentropic) gradients in potential vorticity tend to obstruct horizontal cross-vortex mass exchange. There is weak mixing at the edge and stronger stirring on both sides of the vortex boundary (Schoeberl *et al.* 1989; Hartmann *et al.*, 1989a). Many numerical studies support the containment vessel hypothesis and some of these recognize a transition altitude near the 400-K isentropic surface (60-79 hPa), above which the vortex is completely isolated and below, small amounts of vortex air mix into the midlatitudes in the form of elongated filaments (Bowman, 1993a,b; Chen, 1994; McIntyre, 1995). These filaments are eroded when planetary waves propagate upward and break in the lower and middle stratosphere (McIntyre and Palmer, 1983), folding and stretching vortex air in a narrow band around the vortex. When out of the main body of the vortex, air mixes rapidly into the midlatitudes.

For the flowing processor hypothesis, Tuck *et al.* (1993) noticed the occurrence of large amounts of dehydrated air in the southern midlatitudes, which they attributed to a continuous outflow of cold and dry vortex air, by as much as one vortex mass per month. Such an outflow would need a rapid inflow from the mesosphere implying large radiative cooling rates, contrary to those observed (Hartmann *et al.*, 1989b). Recently, the degree of isolation of the Antarctic stratospheric vortex in late winter and spring was investigated quantitatively by using a three-dimensional global tracer transport model (Wauben *et al.*, 1997). When tracer mass was injected at ~73 hPa well inside the vortex on 1 August, about 65% of this mass left the vortex within 3 months, 78% of this outflow by air descending into the troposphere, and 22% through quasi-horizontal mixing into the midlatitude stratosphere due to planetary wave-breaking events. These results disagree (quantitatively) with the "flowing processor" hypothesis, with the vortex mass flushed out each month only 1/5th of that envisaged by Tuck *et al.* (1993), and quasi-horizontal (cross-vortex) outflow and the estimated inflow from the mesosphere also much smaller than that envisaged by Tuck *et al.* (1993). These results support the "containment vessel" hypothesis, implying that the Antarctic vortex is fairly well isolated from its surroundings during late winter and spring. The polar vortex is probably a kind of wobbling, cylindrically shaped mass of air in which radiative cooling causes overall steady descending flow from the stratopause to the tropopause, with very little leakage to the sides; and warm, ozone-rich midlatitude air is obstructed from entering the vortex area. However, the cylindrical shape is not perfect. Even in a gross way, it seems to be oval shaped and rotates with a period of about 4 weeks (not 2-3 weeks, as reported by earlier workers, Herman *et al.*, 1995a) due to the wave number 1 component of the wind system; but, the wave number 2 component of the wind system often creates complications. The oval shape changes to nearly circular (or *vice versa*), the rotation speeds vary in a wide range, and the center shifts away from the South Pole in a meandering motion, probably due to different time-variations of the magnitudes of the contributions of the different wave numbers (1 and 2) during the evolution and decay of the ozone hole.

## *Acknowledgements*

Thanks are due to Dr. Herman and others of the Nimbus 7 and Meteor 3 TOMS Ozone Processing team for providing the TOMS data. This work was partially supported by FNDCT, Brazil under Contract FINEP-537/CT.

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