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Rotating tongues (Protrudences) of ozone-poor air in the Antarctic ozone hole, sweeping over lower latitudes: signatures in ground-based Dobson data

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सार — धरातल आधारित डॉब्सन स्पैक्ट्रोफोटोमीटर से प्राप्त आँकड़ों का प्रयोग करके 1992, 1993, 1994 और 1995 के दौरान दक्षिणी गोलार्ध में बसंत ऋतु में एंटार्कटिक ओज़ोन छिद्रों के विकास का अध्ययन किया गया। दक्षिणी ध्रुव में ओज़ोन छिद्रों का विकास अधिकतर सहज रहा, लगभग सितम्बर माह के अंत तक इसमें निरंतर ह्रास हुआ है और लगभग दिसम्बर माह के अंत तक इनमें निरंतर अभिवृद्धि हुई है। 65 डिग्री दक्षिणी अक्षांश के निकट, 15 से 20 दिनों की घूर्णन अवधि में अवृत्ताकार [अंडाकार] भ्रमिल सीमा [कि नारा, रोटेटिंग टंग] को पार करने के कारण विभिन्न अक्षांशों और देशांतरों पर ओज़ोन स्तरों में उच्चावचन का पता चलता है। तथापि, इस बीच ~30 डिग्री तक के निम्न दक्षिणी अक्षांशों में अक्सर अवक्षय भी हुए हैं जिनसे अंडाकार सीमा में वलीयन का पता चलता है जिसका प्रभाव एक रोटेटिंग टंग से भी अधिक के समपरिमाण में रहा है। कुछ अन्य अवक्षय अल्प अवधि (5-8 दिन) के भी रहे हैं, जिनका समान देशांतरों में विभिन्न अक्षांशों पर एक साथ होना आवश्यक नहीं है। ये निम्न अक्षांशों पर बहुत अधिक हुए जिससे सम्भवतः दक्षिणी गोलार्ध ध्रुवीय भ्रमिलता के अंतर्गत प्रतिचक्रवातीय क्षोभमंलीय प्रबलन के फलस्वरूप ओजोन के लघु छिद्रों अथवा/और क्षोभसीमा दाब में हुए परिवर्तनों के माध्यम से सकल ओज़ोन पर सिनॉप्टिक विक्षोभों के प्रभाव का पता चलता है।

ABSTRACT. Using data from ground-based Dobson spectrophotometers, the evolution of Antarctic ozone holes during the southern springs of 1992, 1993, 1994 and 1995 was studied. At the South Pole, the evolution was mostly smooth, steady decrease up to about September end and a steady recovery up to about December end. At latitudes near 65°S, the ozone levels at different latitudes and longitudes showed fluctuations compatible with passing of a noncircular (oval) vortex boundary (edge, rotating tongue), with a rotation period of 15-20 days. However, often there were depletions in-between, extending to lower latitudes up to ~30°S, indicating corrugations in the oval boundary with effects equivalent to those of more than one rotating tongue. There were other short- spaced (5-8 days) depletions, not necessarily simultaneous at different latitudes in the same longitude, and more copious at lower latitudes, probably indicating 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.

Key words— Antarctic ozone hole, Oval vortex, Rotating tongue, Ozone mini holes.

1. Introduction

Since 1979, the amount and distribution of total ozone has changed considerably all over the globe (Herman *et al.*, 1993; Stolarski *et al.*, 1992). The most dramatic change has been the development of the (southern) springtime Antarctic ozone hole, reported by Chubachi (1984), Chubachi and Kajiwara (1986) for Syowa, Farman *et al.* (1985) for Halley Bay and Argentine Islands, Komhyr *et al.* (1986), Bojkov (1986a,b) for South Pole, and further investigated by Stolar-

ski *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 (Anderson *et al.*, 1989). 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

TABLE 1

List of stations

Station	Symbol	Latitude (°S)	Longitude(°)
South Pole	SP	90	0
Belgrano II	BE	78	35W
Halley Bay	HA	74	27W
Syowa	SY	69	40E
Faraday	FA	65	64W
Marambio	MA	64	57W
Ushuaia	US	55	68W
Punta Arenas	PA	53	71W
Buenos Aires	BA	35	59 W
Santa Maria	SM	30	54W
Cachoeira Paulista	CP	23	45W
Cuiaba	CU	16	56W
Huancayo	HU	12	75W
Natal	NA	6	35W
Macquaire Island	MI	55	159E
Lauder	LA	45	170E
Melbourne	ME	38	145E
Perth	PE	32	116E
Brisbane	BR	27	153E
Darwin	DA	12	131E
Irene	IR	25	28E
Maputo	MA	26	33E

minimum, from 200 to 118 Dobson units DU, (1 DU=1 miliatmosphere cm = 2.67×10^{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; Downery *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 CIO at high latitudes (produced from increasing amounts of chloroflourocarbons 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 lower stratospheric warming 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 at least in some altitude belts (Hofmann *et al.*, 1994, 1995).

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-centre from the pole (Herman *et al.*, 1995a), congruent with the polar vortex wind system, with a rotation period of about 2 to 3 weeks. When the oval is sufficiently elongated, it may even extend over the tip of South America. Reduced ozone values during the southern hemisphere spring up to 55°S have been observed (Stolarski *et al.*, 1991; Herman *et al.*, 1993; Herman and Larko, 1994), when the ozone hole region is elongated. For Australia and New Zealand, Atkinson *et al.* (1989) showed from TOMS data that there was a 30% depletion on 1-12 December, 1987, with decreases extending up to 30°S latitude. Using ground-based Dobson spectrophotometer daily values of total ozone, Kane (1991) showed that the Antarctic ozone hole of 1987 caused about 10% decrease at Buenos Aires (35°S) while later, during the Antarctic ozone holes in 1988, 1989 and 1990. Kane (1995) showed that depletions up to 10% were observed for latitudes up to 40°S. Kane (1994) reported
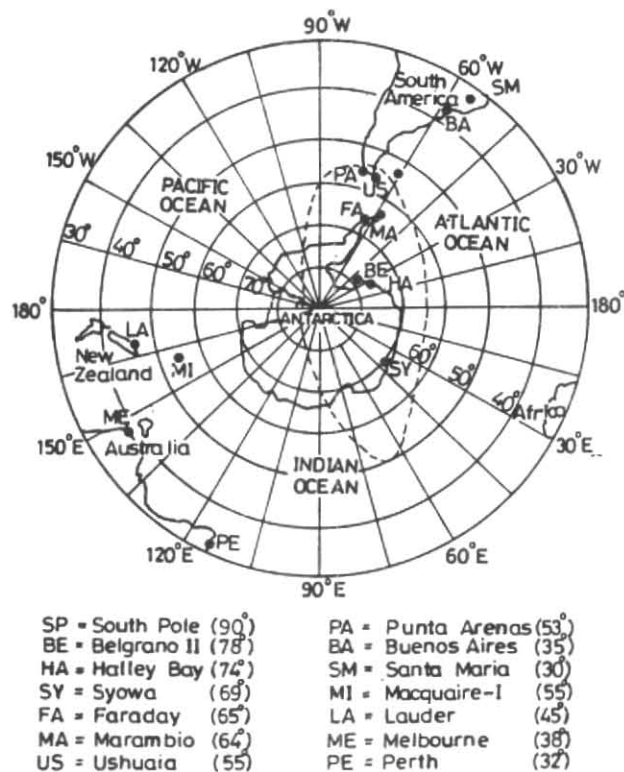
SP = South Pole (90°)   PA = Punta Arenas (53°)
BE = Belgrano II (78°)   BA = Buenos Aires (35°)
HA = Halley Bay (74°)   SM = Santa Maria (30°)
SY = Syowa (69°)   MI = Macquaire-I (55°)
FA = Faraday (65°)   LA = Lauder (45°)
MA = Marambio (64°)   ME = Melbourne (38°)
US = Ushuaia (55°)   PE = Perth (32°)

Fig. 1. Map of the southern hemisphere (polar view, 90°S to 30°S) with middle and high latitude stations marked. The dashed oval covering a part of the Antarctic represents the 220-DU contour of the 5 October, 1992 ozone hole (Herman *et al.*, 1995a)

that during these events, whereas the evolution in October was fairly uniform at the South Pole, fluctuations were observed at Syowa, McMurdo and Palmer, which could be indicative of the vortex wall passing in and out over these peripheral locations. Also, later in November, the vortex seemed to shift from the South Pole in different directions. These movements indicated *nonuniform* evolutions and dissipations of the Antarctic ozone holes. Downey *et al.* (1996) described the processes which led to the formation of the 1994 Antarctic ozone hole and compared these with those of earlier holes. 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. In this communication, ground-based Dobson daily values of total ozone are examined for the September, October, November of 1992, 1993, 1994 and 1995, mainly with a view to identify events which could be possibly due to rotating tongues. It will be necessary to distinguish between these and other types of ozone depletions *e.g.*, those 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 Challaghan, 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 al.*, 1995). Total ozone fluctuations may also result from planetary or Rossby waves (wavenumbers 1-3), which often accompany stratospheric warming events in polar winter and early spring (Allen and Reck, 1997, and references therein).

2. Data

Table 1 lists the locations (with their symbols, latitudes and longitudes) for which Dobson data were used. Most of the data were obtained from the publication "Ozone Data for the World", published by the Atmospheric Environment Service, Canada, in co-operation with WMO. Some data were obtained from publications (*e.g.*, data for Punta Arenas, Chile, from Kirchhoff *et al.*, 1997a,b; data for Santa Maria, Brazil from Kirchhoff *et al.*, 1996; plots for Faraday and Halley Bay for 1994 spring from Downey *et al*, 1996). Data for Brazilian locations were obtained privately from Dr. Kirchhoff and Dr. Sahai of INPE (Instituto Nacional de Pesquisas Espacias, Brazil).

Fig. 1 shows a map of the Antarctic region (centered at the South Pole), with middle and high latitude stations marked. The dashed oval demarcates the 5 October, 1992 ozone hole 220-DU boundary observed by TOMS (Herman *et al.*, 1995a) and seems to pass over the tip of South America.

3. Evolution and extension of the ozone holes

(A) *The 1992 ozone hole*

The Dobson daily ozone values over various regions during September-November 1992 are shown in Fig. 2, with values for South Pole at the top. Values below 300 DU are painted black. As can be seen, the South Pole values (available only from the middle of October onwards, when the sun appeared above the horizon) were not steadily low but oscillated between ~130-230 DU, with periods of ~10-12 days. Individual events were as follows:

(*i*) On 20 October, 1992, the ozone value at the South Pole was ~230 DU; but Belgrano (78°S) had ~100 DU and Marambio (64°S) had ~180 DU, indicating that the ozone hole *was not centered at the South Pole* and was shifted towards the Atlantic Ocean, in agreement with the dashed plot of the 220-DU contour in Fig. 1, and was possibly oscillating. Except for Syowa, the various ozone minima seem to tally within a day or two (shown by vertical joining lines), indicating
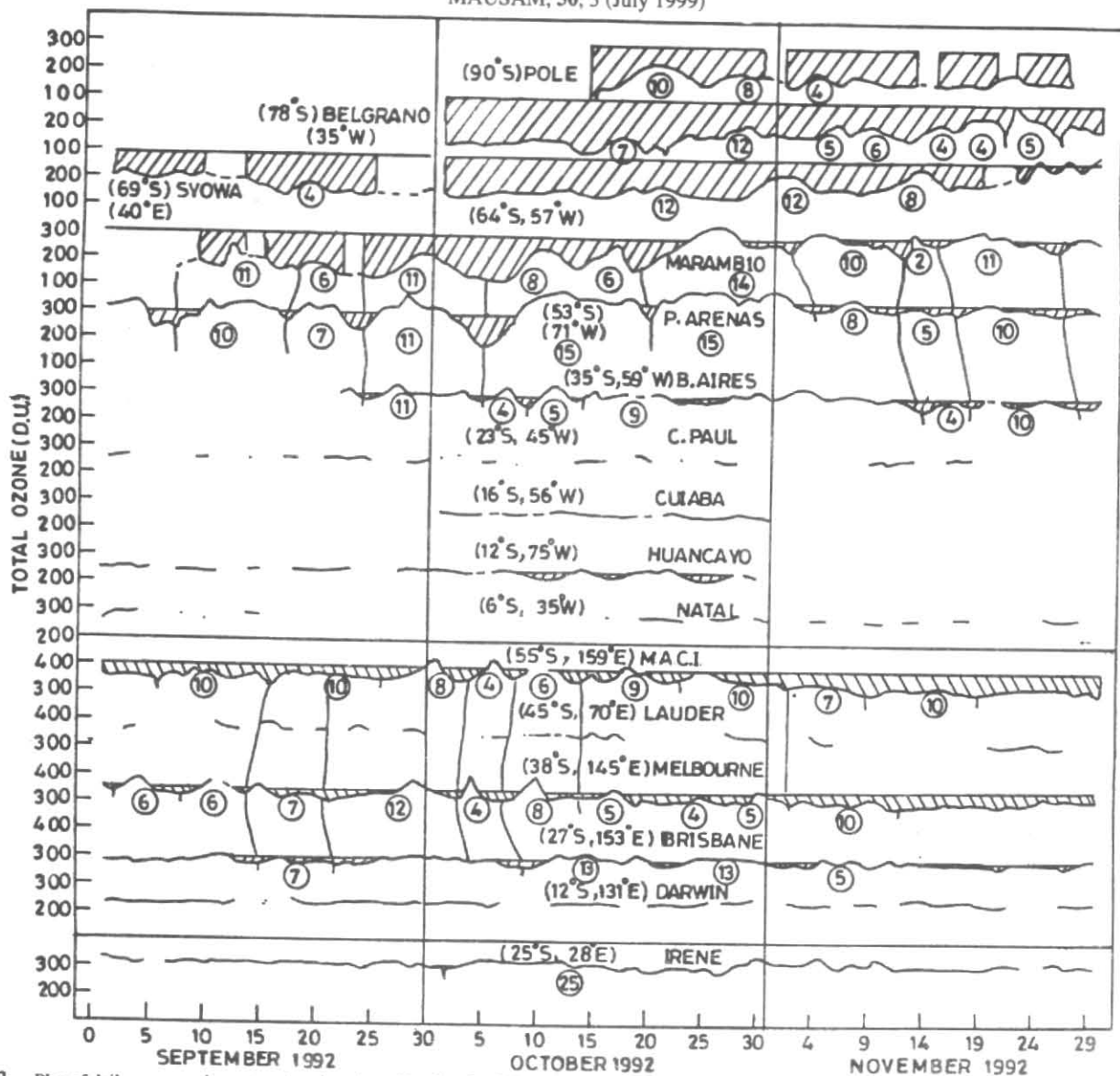
Fig. 2. Plot of daily ozone values at various locations (South pole, 90°S at the top) for the spring period 1 September-30 November1992. In the near polar region, values below 300 DU are painted black. The circled numbers indicate spacings in days between successive ozone minima

that we might be dealing here with one very elongated oval of the Antarctic ozone hole, sweeping over the various locations. With the rotation, the effects at about the same latitude but different longitudes would show a phase shift of a few days, as seems to have occurred for Syowa (40°E) in relation to Belgrano (35°W) or Marambio (57°W). On the other hand, locations in the same longitudes would show depletions almost simultaneously. The minima at Belgrano (78°S) seem to coincide with those of Marambio (64°S), Punta Arenas (53°S) and even Buenos Aires (35°S) within a day or two. In Fig. 1, the oval is shown for a 220 DU contour. Since we are considering values below 300 DU, the oval would be broader and longer. Thus, the simultaneous ap-

pearance at all these locations does indicate the passing of a single elongated oval over all of them. The shifted peak at Syowa indicates the rotation, at ~ 20 days rotation period. Henceforth, we will use the term *rotating tongues* for features of this type, where locations in roughly the same longitudes show ozone depletions almost simultaneously and locations at different longitudes show depletions with a few days shift (*e.g.*, Syowa, a few days earlier). Data for still lower latitudes (Cachoeira Paulista, Cuiaba, Huancayo, Natal) are intermittant and not of very good quality. The ozone hole effect at these locations is not at all obvious. In the Australian sector (~130°E-160°E), the effects are smaller and the minima hardly drop below 300 DU. The oscillating struc-
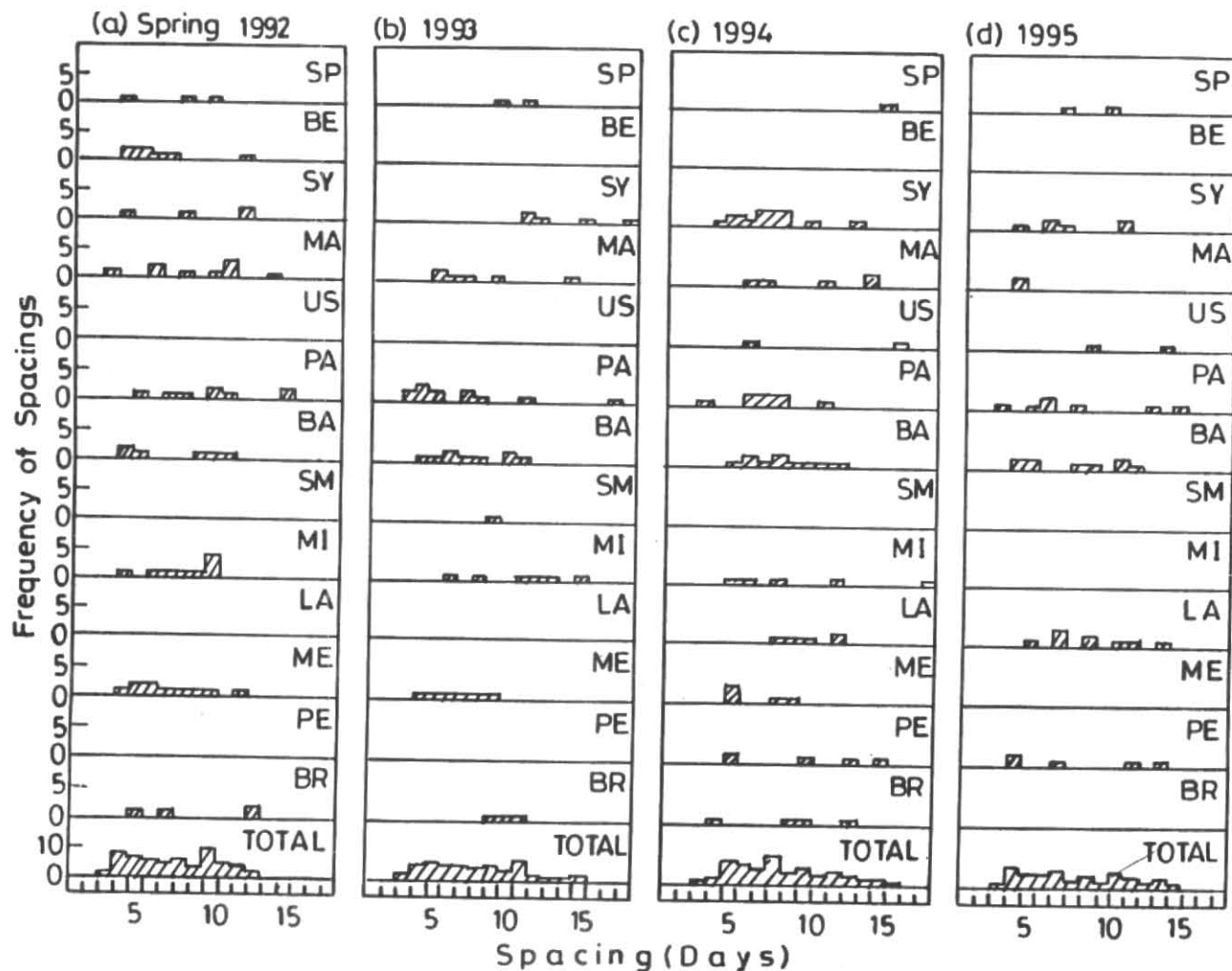
Fig. 3. Frequency distribution of the spacings of the minima at different locations for the spring (Sept.-Oct.-Nov.) periods of (a) 1992, (b) 1993, (c) 1994 and (d) 1995. The bottom plots are totals of plots for all locations

tures are seen; but the phase matching is not always good, especially for latitudes below ~30°S. At Darwin (12°S), effects are negligible. In the European sector, Irene (25°S, 28°E) shows negligible effects.

(*ii*) Besides the 20 October event, there are other events, notably near 24 September and 5 October, showing ozone depletions *simultaneously at several high latitudes at the same longitude*. Hence, these are also *rotating tongues*. Considering the 11-15 day separations, this is probably not the same extended oval edge going round and round in 2-3 weeks, as envisaged by Herman *et al.* (1995a) from the ~2 week rotation period of the elliptical ozone hole, related to the wave number 2 component of the south polar vortex wind system. These could be due to uneven boundaries of the vortex, not exactly circular or oval, but with

major corrugations. Thus, besides the elongation of the oval envisaged for the 20 October event, there were other elongated structures in other parts of the polar vortex, *i.e.*, other rotating tongues.

(*iii*) In each plot, there are other short-spaced peaks too. Fig. 3(a) shows the occurrence frequency of the spacings. As can be seen, a wide range of spacings is seen, though in the total for all locations (bottom plot), the maximum is for a spacing of 10 days. Thus, it is not just one elongated oval going round and round, with a rotation of 2-3 weeks. There are in-between corrugations (tongues) in the vortex wall, which may be steady structures or may be regions from which ozone-poor air may be leaking out and sweeping over low latitudes. The corrugations (tongues) ~ 10 days apart are fairly extensive in space and time and are probably other elongations of the oval.
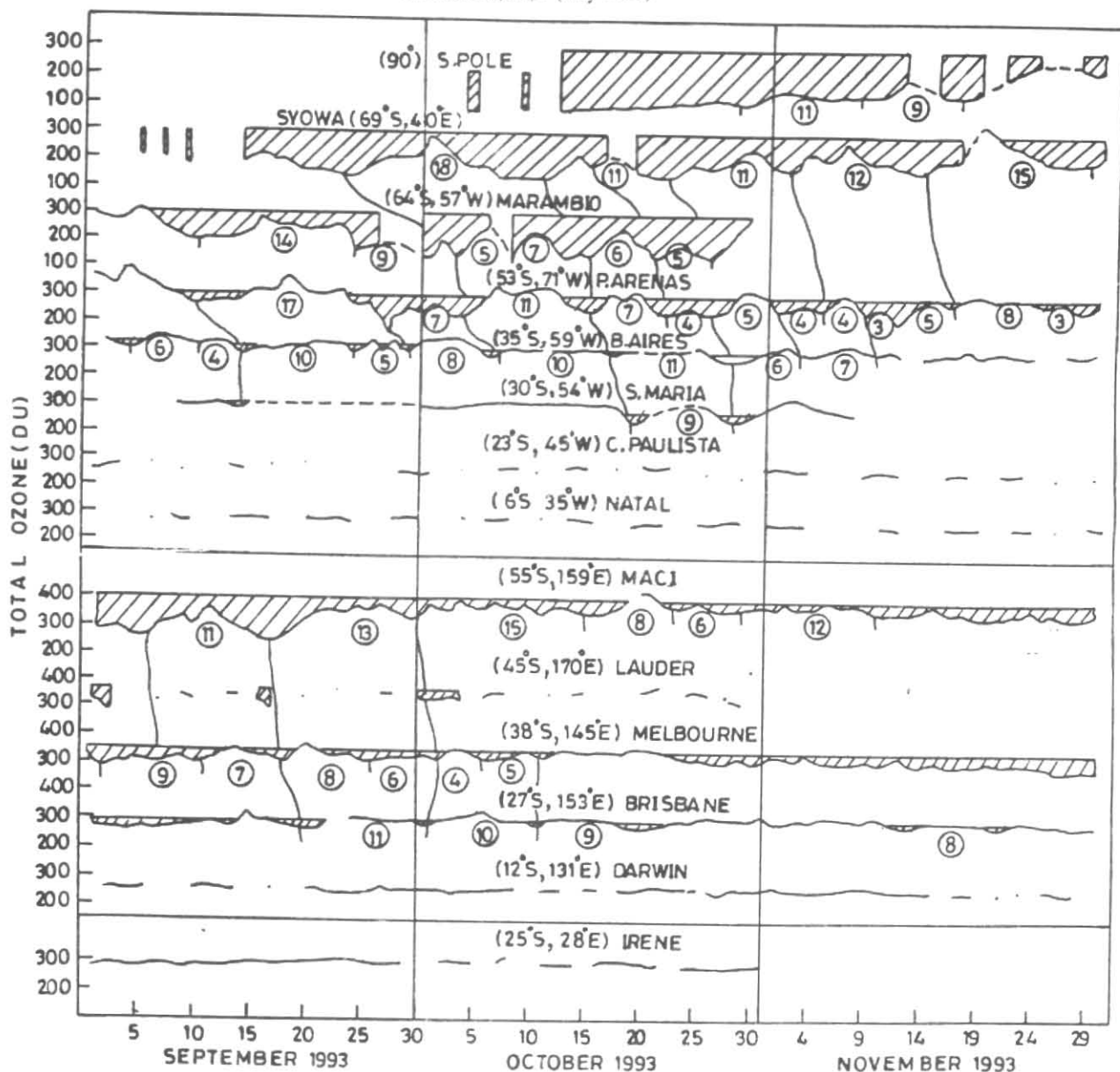
Fig. 4. Same as Fig. 2, for the spring 1 September-30 November 1993

The shorter-spaced depletions (5-8 days) are not always seen at all latitudes (in the same longitude) and might be related to planetary waves in the Antarctic, mentioned by Chandra and McPeters (1986) or to mini-holes (Newman *et al.*, 1988; Orsolini *et al.*, 1995), where air is being peeled off the polar vortex in a motion analogous to the planetary-scale breaking of Rossby waves in the upper stratosphere (Leovy *et al.*, 1985; McIntyre and Palmer, 1983) and the meridional transport of air off the polar cap occurs in preferred longitudes determined by an upper- tropospheric circulation (Kaye *et al.*, 1991; Rod *et al.*, 1992). Thus, several types of

large scale mixing might be occurring: strong intrusion of subtropical air into high latitude regions, peeling of the vortex accompanied by transport into the middle latitudes, or tongues of midlatitude air being stretched deep into the vortex (Orsolini *et al.*, 1995).

(*iv*) At lower latitudes, the various short-spaced peaks (5-10 days) may not be related to the ozone hole at all and may be indicative of ozone changes due to up and down motions of the tropopause, caused by synoptic disturbances. Schubert and Munteanu (1988) showed that the synoptic scale correlations between total ozone and tropopause pressure exceeded 0.6 at midlatitudes and

dropped rapidly towards lower latitudes but slowly towards higher latitudes, while large scale correlations were low (<0.6) everywhere.

(B) *The 1993 ozone hole*

Fig. 4 shows the ozone values for September-November 1993. The minimum ozone value at South Pole was ~85 DU, smaller than that for 1992 (~120 DU). The South Pole values do not show short period oscillations, indicating that South Pole was deep in the vortex; but Syowa values do show minima with spacings of 11- 18 days. Marambio, Punta Arenas and Buenos Aires (all in the same longitude) show many common minima; but there are small phase shifts, indicating that the depletions at different latitudes in the same longitude were not exactly simultaneous. Of particular interest are the ozone depletions at Santa Maria (30°S) in Brazil on 19 and 28 October, 1993. Kirchhoff *et al.* (1996) discussed these events in detail and examined TOMS data to show that a clear *tongue* of low ozone stretching from the Antarctic ozone hole to the south American continent (particularly southern Brazil) was responsible for these events. Obviously, the same tongues could not have caused these two events, only 9 days apart. Two tongue must have been involved. The small phase shifts of 2-3 days at different latitudes in the same longitude indicate that the tongues were stretching out slowly in a sort of Archimedes spiral. In latitudes lower than Buenos Aires, data are inadequate to draw any clear conclusions. In the Australian sector, the effect at Macquire Island (56°S) is very large near 5 and 15 September, when two clear minima occurred at a spacing of ~10 days (two different tongues?). The longitude difference between Macquire Island and Syowa is ~120°. Hence, the 15 September peak at Macquire Island, the 22 September peak at Syowa and later, the early October peaks at Marambio and Punta Arenas could all be attributed to the same tongue, rotating and passing over all these in succession. The same tongue might have gone round and come back over Macquire Island in early October, over Syowa by 10 October and over Marambio and P. Arenas by mid-October. Similarly, the 5 September peak at Macquire Island and the 11 September peak at P. Arenas could be due to another tongue. Obviously, the ozone hole was eccentrically shifted more towards Australia in September. The effects were seen at Melbourne also (38°S) but not clearly at Brisbane (27°S). In later months (October and November), the ozone hole effects were smaller in the Australian sector. As in 1992, the effects at Darwin (12°S, 131°E) and Irene (25°S, 28°E) were negligible. At Australian low latitudes, synoptic disturbances might have been more effective.

Fig. 3(b) shows the frequency distribution of the spacings. As before, the spacings are in a broad range. Fig. 5 shows the 220 DU boundaries obtained from TOMS data as given by Herman *et al.*, (1995a) for 9 September-18 November, 1993 at 7 day intervals. As can be seen, the shape of the ozone hole changed drastically in 7 days, from ovals of

different orientations to rough circles of different sizes, thus giving a corrugated shape to the oval boundary and producing ozone depletions as if these were due to multiple tongues.

(C) *The 1994 ozone hole*

Fig. 6 shows the ozone values for September-November 1994. Herman *et al.* (1995b) report that TOMS observed a value of ~90 DU on 28 September, 1994. For South pole, the data are available only in early October and show values near 100 DU. However, Syowa and Marambio do show low values even in September. On 17 October, severe depletions were seen at Marambio (64°S), Ushuaia (55°S) and Punta Arenas (53°S) but not at Buenos Aires (35°S). Thus, only the tip of a relatively small oval must have passed over the tip of South America. At Syowa, there was a peak a few days earlier and all these could be attributed to the same tongue. Syowa had a peak near 17 October also; but this was not seen with a phase shift later at Marambio. In the Australian sector, Macquire Island and Lauder showed considerable depletions but near 5 and 25 October *i.e.*, ~10 days earlier or later than 17 October. As the longitude difference between Australia and S. America is ~180°, these differences are compatible with a rotation period of ~20 days for the oval; but effects at Lauder (45°S) and Melbourne (38°S) indicate the possibility of the oval having a larger latitudinal extension in the Australian longitudes. Again, the short-spaced depletions at lower latitudes could be due to synoptic disturbances also. For this event, Maputo (26°S, 33°E), Mozambique (SE Africa) showed large ozone fluctuations. Some of these may be related to the ozone hole; but origin in synoptic disturbances is more probable.

Farman *et al.* (1985) were among the first ones to report about the Antarctic ozone hole, using data for Halley Bay (74°S, 77°W). However, data for this location as also for Faraday (65°S, 74°W), both operated by the British Antarctic Survey, do not seem to be available in the "Ozone Data for the World" catalogues. Jones and Shanklin (1995) mention a continued decline of total ozone over Halley Bay, Antarctic, since 1985. For the 1994 event, Downey *et al.* (1996) have shown the plots total ozone for Halley Bay and Faraday. In their Fig. 4, Halley Bay (74°S) ozone declined almost steadily from ~ 170 DU in September beginning to ~ 100 DU in September end and then recovered almost steadily to ~ 200 DU by 15 November, similar to the evolution at South Pole, as shown in our Fig. 6. Hoever in their Fig. 4, Faraday (65°S) shows violent fluctuations with minima (~150 DU near 30 September, 15 October and 30 October and recoveries in-between, with values near 20 October recovering to above 300 DU, similar to Marambio in our Fig. 6. Downey *et al.* (1996) used the METEOR 3 TOMS data to describe several attributes of the 1994 hole such as beginning in early September through maturity in the first week of October, development of a strong asymme-
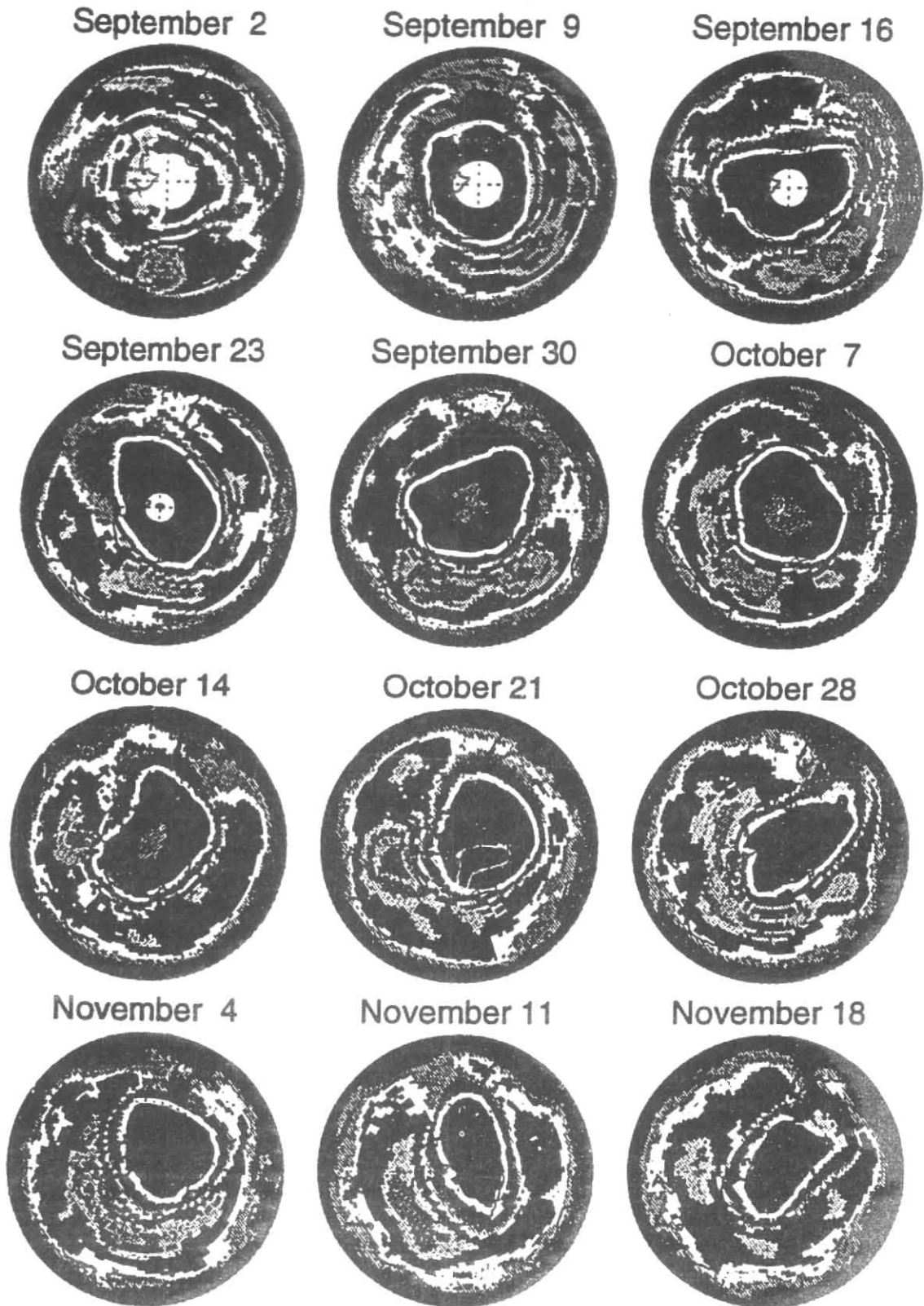
September 2   September 9   September 16

September 23   September 30   October 7

October 14   October 21   October 28

November 4   November 11   November 18

Fig. 5. The evolution of the Antarctic ozone hole during the spring 1993 (Herman *et al.*, 1995a). The white line indicates the 220-DU contour

try in late October, its decay and movement off the south pole in mid- November and its disappearance (in terms of total column ozone values) in early December. When the

October 1994 hole structure was examined by them as a departure from the mean October structure for the six years (1989-1994), a polar dipole was noticed which they attrib-
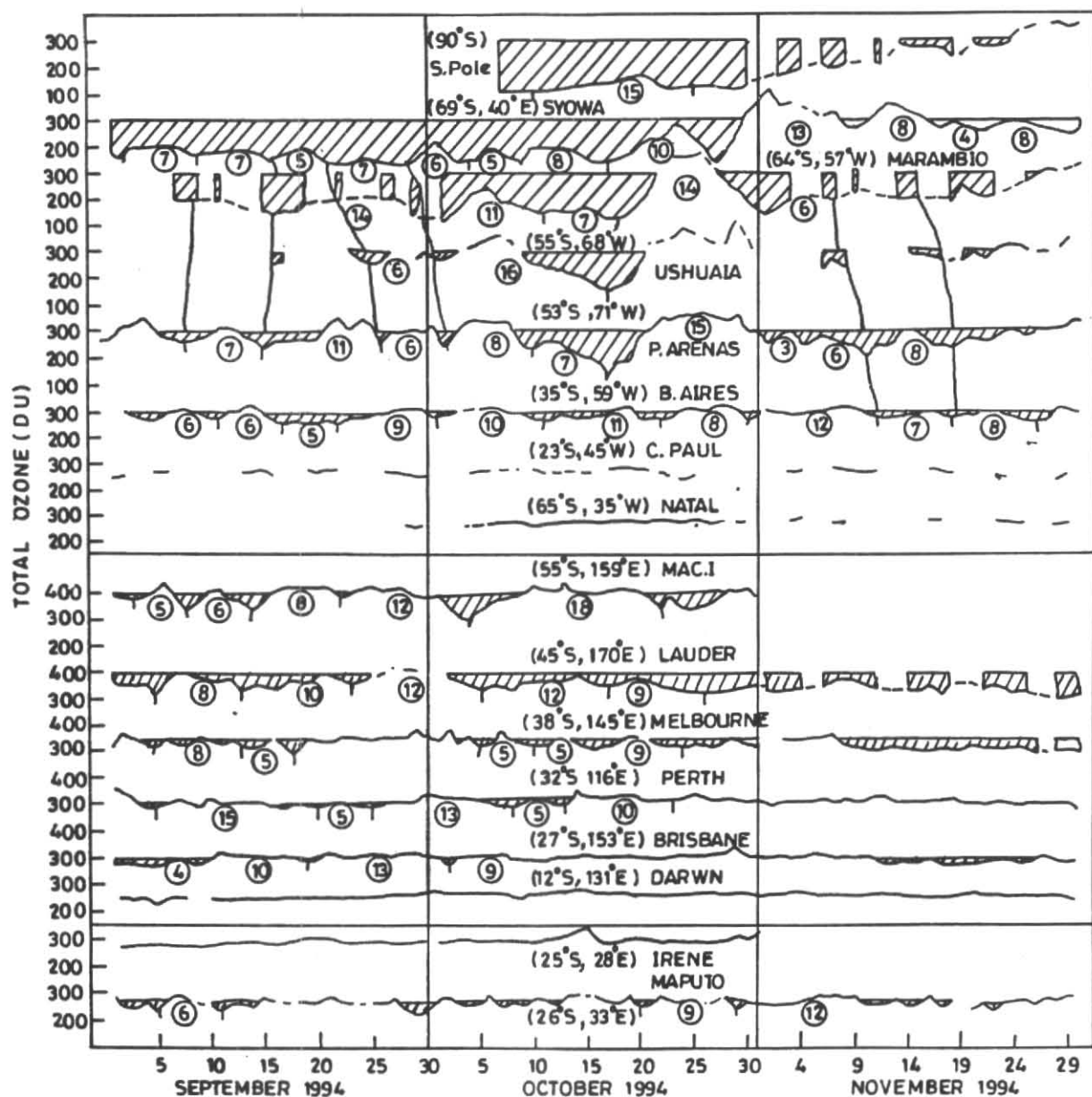
Fig. 6. Same as Fig. 2, for the spring 1 September-30 November 1994

uted to a particularly large wave number 1 perturbation to the polar vortex, with the vortex displaced towards the Atlantic Ocean. Strong anomalies were attributed to the fact that it was a region of strong ozone gradients (90°S-60°S) and relatively small changes in position of the vortex would give rise to large anomalies. The difference in Halley Bay and Faraday values was attributed to the slow rotation of the strongly asymmetric ozone hole. The 1994 hole was found to be similar to that of 1993 in areal size (~24×10⁶km²) and amount of ozone loss (values near 100 DU); but the distortion of the shape of the hole was different and the ozone depletion commenced earlier in 1994.

Fig. 3(c) shows the distribution of the spacings of the successive minima. Overall, there is a preference for spacings of 5-8 days.

(D) The 1995 ozone hole

Fig. 7 shows the ozone values for September-November 1995. Data are presently available for fewer locations and are largely intermittent. Hence, marking minima was not always easy and may be unreliable. However, amongst all these and also in the earlier plots for 1992, 1993, 1994, the best, continuous data seem to be for Punta Arenas, Chile, obtained from a Brewer spectrophotometer installed there under a joint project of INPE (Instituto Nacional de Pes-
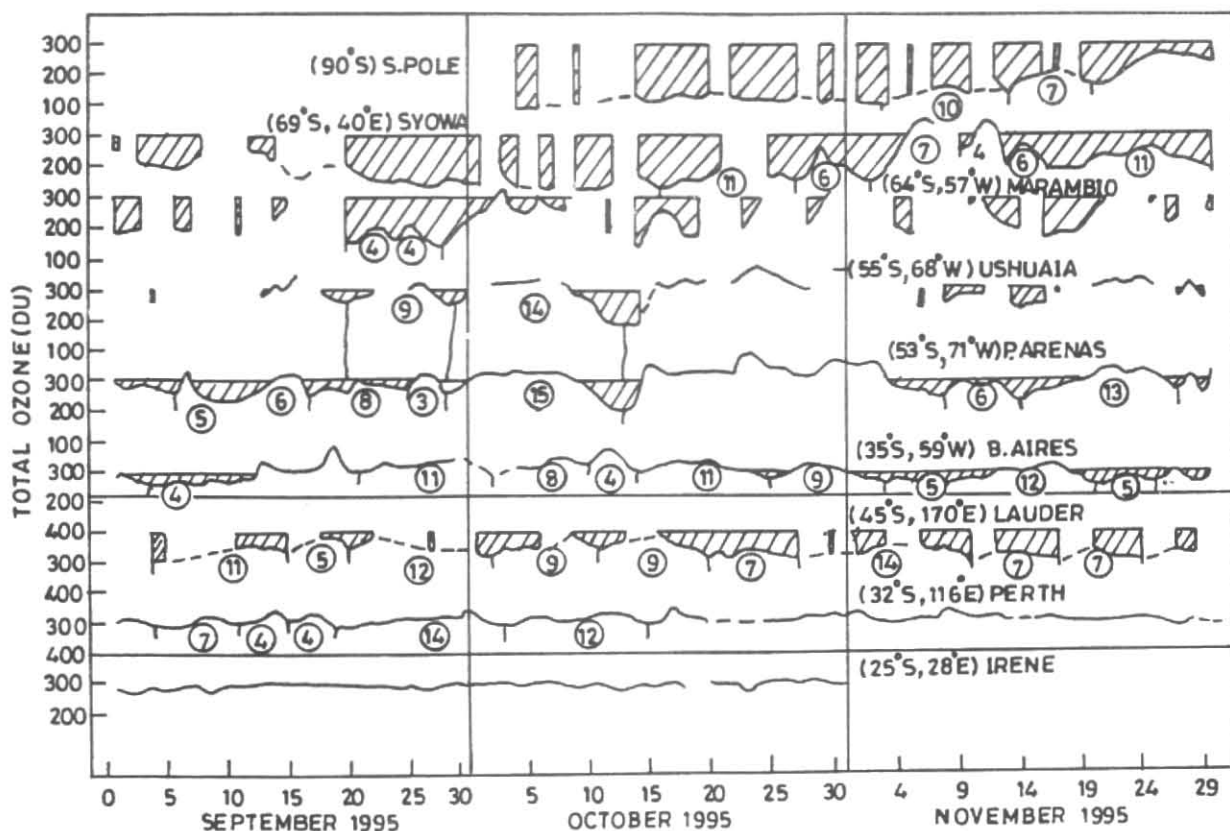
Fig. 7. Same as Fig.2, for the spring 1 September-30 November 1995

quisas Espaciais), Brazil and UMAG (Universidad de Magallanes), Chile. A larger network of such Brewer instruments is highly desirable. The major event in 1995 seems to be the ozone hole which passed over Punta Arenas and Ushaia during 12-14 October, though numerous smaller events occurred in September and November. Data at Maraimbo and Syowa were intermittent and hence, phase shifts cannot be studied. But one major tongue is indicated. Other smaller peaks could be due to mini-holes etc.

Fig. 3(d) shows the distributions of the spacings of the successive minima. Though not very reliable, the distributions are broad, indicating smaller spaced tongues, in addition to the broad rotating tongues.

4. Vertical structure evolution and dissipation

The ground-based 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-around 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 sulfuric 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, Hoffman *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 sulfate 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 zone-rich lower latitude air across the vortex wall, or shrinking of the vortex at the upper levels, was occurring. Since more that 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.

While the total ozone measurements were being conducted at Punta Arenas (53°S, 71°W) regularly, 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, 12-14 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 profile over Punta Arenas on 12-14 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.

In 1993, when two short-lived total ozone depletions were observed even at the low latitude location Santa Maria (30°S, 54°W), RS, Brazil, on 19 and 28 October 1993, Kirchhoff *et al.* (1996) conducted balloon flights on 26 and 28 October, 1993 from Santa Maria 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.

5. Skin cancer related solar UVB

Since ozone absorbs UVB (280-320 nm) which has damaging effects on terrestrial life, the ozone hole has a scaring effect. In the Antarctic, UVB increases would be substantial during severe hole conditions (Frederick and Snell, 1988; McKenzie *et al.*, 1991), with implications of damage to living systems (*e.g.*, Lubin *et al.*, 1992). In the Antarctic, human population is very small and concentrated in the various research stations; but ocean life systems could be affected by large UVB changes. For example, Phytoplankton blooms are initiated during the maximum ozone hole conditions (Lubin *et al.*, 1992). The largest human population near the Antarctic is in the southern tip of South America and Kirchhoff *et al.* (1997a,b,c) have been using Brewer spectrophotometer at Punta Arenas, Chile for UVB measurements in the 290-325 nm range. During severe ozone hole events, UVB increased by a factor of 22 at 295-297 nm. When integrated for 290-325 nm and weighted by the CIE erythermal action spectrum, the intensity in the October events was double than normal and was comparable with the average summer intensities that follow in December-January. Thus, doses received normally in summer only are received in some days of the preceding spring also, not a very disastrous situation, especially considering the fact that the increased UVB levels at Punta Arenas (53°S) are still below the normal UVB levels at low and equatorial latitudes, *e.g.*, at Natal (6°S). This is not to say that there is no danger. UVB levels, even at their present level all over the globe, seem to be large enough to initiate skin cancer. Hence, precautions are necessary to avoid excessive exposures.

6. Conclusions and discussion

The extension to lower latitudes of Antarctic ozone holes during the springs of 1992, 1993, 1994 and 1995 was

examined, using data from ground-based Dobson spectro-photometers. The following was noted:

(i) In the South Pole region, the ozone hole evolution was mostly smooth, a monotonic decrease up to 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 centre was oscillating near the South Pole.

(ii) In latitudes near 65°S, considerable fluctuations were seen, often compatible with the notion of an eccentric and/or noncircular vortex, having the vortex edge at these latitudes and sweeping over these areas like extended tongues, with a rotation period of about 15-20 days.

(iii) However, there were instances when at these latitudes (65°S), narrower structures (extra tongues) appeared to be sweeping and moving towards lower latitudes beyond the edge of the vortex, even up to ~30°S.

(iv) These structures could spread non-uniformly in different longitudes, sometimes strongly in the Australian sector and weakly in the South American sector, but more often, *vice-versa*. Their speed and extent to low latitudes could be different from event to event.

(v) Besides these, there were other shorter-spaced (5-8 days) depletions which are not due to of fullfledged tongues but probably depict effects of synoptic disturbances and/or transient mini-holes caused by changes in the upper-tropospheric circulation.

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 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. For example, 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 radioactively cooled descending motions ("containment vessel" hypothesis), or whether the air is rapidly flushed through the votex (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 (*e.g.*, 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 (*e.g.*, 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 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 radioactive 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, 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 radioactive 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 2-3 weeks. In a finer way, the oval shape gets distorted often and becomes corrugated, giving the effect of multiple rotating tongues.

Acknowledgements

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