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83 The evolution of the Antarctic ozone hole is illustrated for 1985-1990 springs. A detailed study for 1986-1989 and 1990 events indicates that the evolution, which occurs in early October, is fairly uniform over the South Pole. Hence the fluctuations observed at Syowa, McMurdo and Palmer during this period are mostly due to the vortex wall passing in and out over these periferial locations. However, later in November when the hole is dissipating, the vortex may shift from the South Pole in any direction and may also come back or intensify on South Pole before finally disappearing. At South Pole, the recovery started by October end in 1985, 1986 and 1988 but later in 1987 (November end), 1989 (November beginning) and 1990 (November end).
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88 TOMS
88 TOTAL OZONE MAPPING SPECTROMETER
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*Mausam*, (1994), 45,1, 23-28

551.510.534(99)

# Non-uniform dissipation of the Antarctic ozone hole

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(*Received 26 March 1993*)

सार — इस शोध पत्र में वर्ष 1985–1989 और 1990 की बसंत ऋतु की अवधि के दौरान अंटार्कटिका में ओज़ोन छिद्र के उद्‌भव के बारे में विस्तार से बताया गया है। वर्ष 1986–1989 तथा 1990 के दौरान किए गए विस्तृत अध्ययन से यह पता चला है कि अक्तूबर माह के आरंभ के उद्‌भव दक्षिणी ध्रुव पर काफी हद तक एक समान होते हैं। अतः स्योवा, मैक मर्डो तथा पामर में इस अवधि में दिखाई देने वाली अस्थिरता मुख्यतः इन परिधीय स्थानों में अंदर-बाहर गुजर रही भ्रमिलपर्त के कारण है। तथापि बाद में नवम्बर में जब ओज़ोन छिद्र समाप्त होता है तब भ्रमिल दक्षिणी ध्रुव से किसी भी दिशा की ओर खिसक सकता है और पूर्णतः लुप्त होने से पहले वहां वापस भी आ सकता है। दक्षिणी ध्रुव में 1985, 1986 तथा 1988 में अक्तूबर के आखिरी दिनों में इसकी वापसी शुरू हो गई किंतु 1987 (नवम्बर के अंत में), 1989 (नवम्बर के आरंभिक दिनों में) तथा 1990 में (नवम्बर के अंत में) इसकी वापसी बाद में ही हुई।

ABSTRACT. The evolution of the Antarctic ozone hole is illustrated for 1985-1989 and 1990 springs. A detailed study for 1986-1989 and 1990 events indicates that the evolution, which occurs in early October, is fairly uniform over the South Pole. Hence the fluctuations observed at Syowa, McMurdo and Palmer during this period are mostly due to the vortex wall passing in and out over these periferial locations. However, later in November when the hole is dissipating, the vortex may shift from the South Pole in any direction and may also come back or intensify on South Pole before finally disappearing. At South Pole, the recovery started by October end in 1985, 1986 and 1988 but later in 1987 (November end), 1989 (November beginning) and 1990 (November end).

**Key words** — Antarctic ozone, Total Ozone Mapping Spectrometer (TOMS), Ozone depletion.

## 1. Introduction

The Antarctic ozone hole manifests itself as a deepening of the polar minimum values in the month of September. From a study of Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) satellite data, Krueger *et al.* (1988, 1989) reported that the polar minimum is accompanied by a growth of mid-latitude (30°-60°S) ozone maximum levels. By mid-October, the ozone hole is a 4000 km broad minimum with steep gradients along the edges. The hole is supposed to retain its integrity until it fills in or drifts out of the polar region into mid-latitudes at the time of the final stratospheric warming. Several details of the hole evolution and comparisons for different years have been reported by Krueger *et al.* (1987, 1988, 1989), Deshler *et al.* [1990 (a & b)], Deshler and Hofmann (1991), Hofmann *et al.* (1987, 1989), Lubin and Frederick (1990), Newman *et al.* (1990, 1991), Schoeberl *et al.* (1989) and Stolarski *et al.* (1990). In this note, we examine whether the total ozone changes observed at some ground locations can be attributed solely to the displacement of the ozone hole (edge effects) or could be due to changes in the hole magnitude also.

## 2. Data and discussion

Fig. 1 shows a map of the Antarctic region with locations of some international observatories. For our study, we used ozone data at South Pole (90°S), Syowa (69°S, 39°E), Palmer (65°S, 64°W) and McMurdo (78°S, 167°E).

Fig. 2 shows a plot of the daily means of total ozone at South Pole (Amundsen-Scott) and Syowa for the six consecutive months September-February for 1985 onwards up to 1990. For the South Pole, data were available only from about the middle of October. The hole magnitudes, expressed as negative percentage deviations from the final recovery level in November-December, are indicated in Fig. 2 and given in Table 1. However, these refer to total ozone only. Vertical profiles show that the percentage decrease was much larger (in some years, almost 100%) in the 12-20 km region (Komhyr *et al.* 1988, Hofmann *et al.* 1989). The minimum values (DU) shown in Table 1 mostly represent the residual tropospheric and upper stratospheric ozone (Stolarski *et al.* 1990).

The following features may be noted :

(*i*) The percentage drops at Syowa are generally lesser (by a few per cent) than those at South Pole probably because Syowa is farther away from the main vortex centre (the pole itself ?).

(*ii*) The final recovery levels are chosen somewhat subjectively but do seem to vary a lot from year-to-year, probably due to a quasi-biennial oscillation (Garcia and Solomon 1987).

(*iii*) The 1988 ozone hole was the weakest but only by a slight per cent, as compared to earlier and

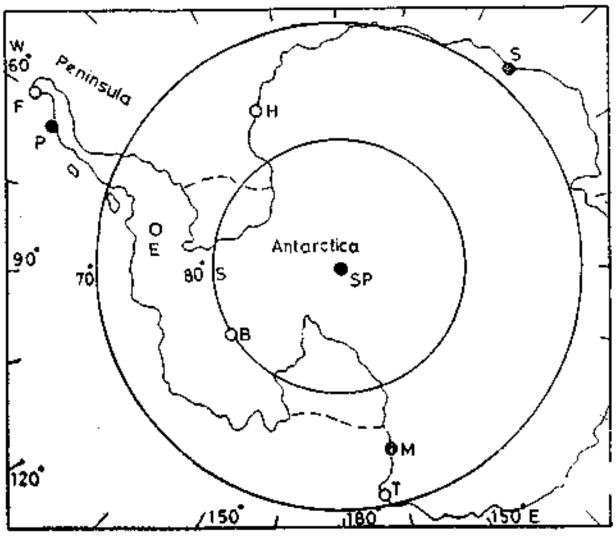



Fig. 1. Map of the Antarctic continent and peninsula with locations of some international observatories [F—Ferraz, P—Palmer, E=Eights, H—Halley, B—Byrds, SP—South Pole, M—McMurdo, T—Hallett, S—Syowa]

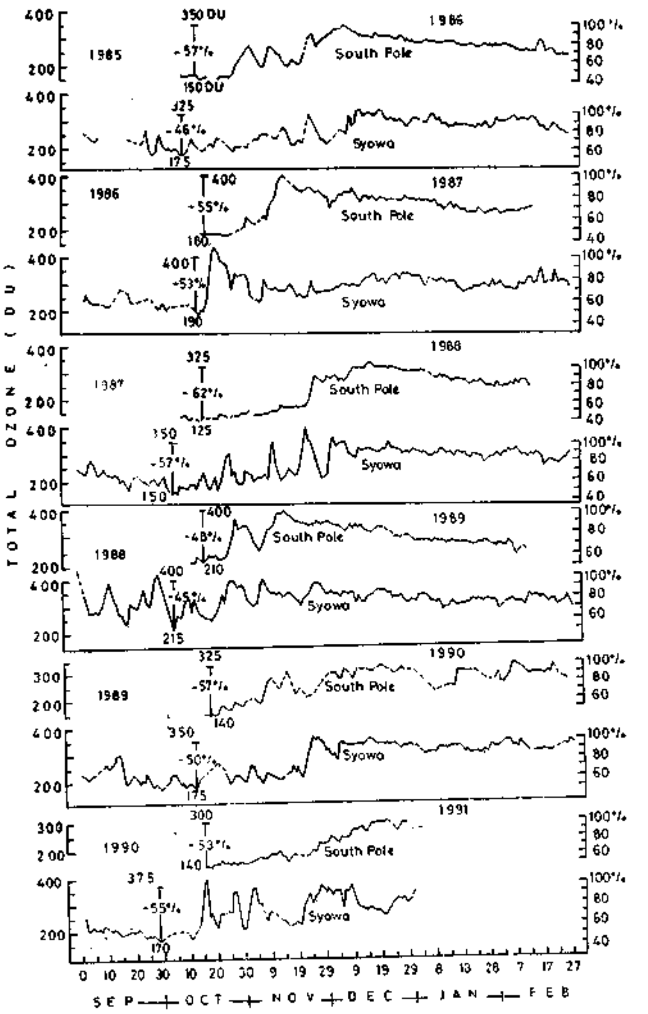



Fig. 2. Total ozone daily means at South Pole (90°S) and Syowa (69°S, 39°E) during Sep, Oct, Nov, Dec and Jan, Feb of next year, for 1985-1989 and 1990. The base levels and percentage drops from the same up to the minimum levels (generally in October) are indicated

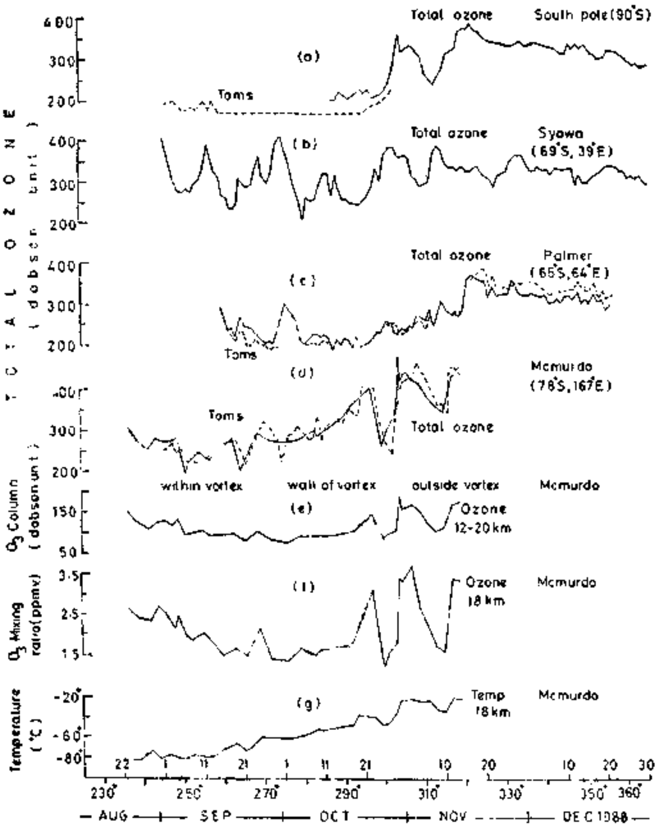
**TABLE 1**

**Antarctic ozone depletions at South Pole and Syowa**

| Year | S. Pole(90°S) Base level (DU) | S. Pole(90°S) Min (DU) | S. Pole(90°S) % drop | Syowa (69°S) Base level (DU) | Syowa (69°S) Min (DU) | Syowa (69°S) % drop |
|---|---|---|---|---|---|---|
| 1985 | 350 | 150 | —57 | 325 | 175 | —46 |
| 1986 | 400 | 180 | —55 | 400 | 190 | —53 |
| 1987 | 325 | 125 | —62 | 350 | 150 | —57 |
| 1988 | 400 | 210 | —48 | 400 | 215 | —46 |
| 1989 | 325 | 140 | —57 | 350 | 175 | —50 |
| 1990 | 300 | 140 | —53 | 375 | 170 | —55 |

later years. The absolute value (~210 DU) was larger than the ones for other years; but the base level (400 DU) was also higher.

(*iv*) In 1986, 1987 and 1990, the South Pole ozone recovered rather smoothly from mid-October to mid-November. However, in 1985, 1988 and 1989 there were large fluctuations during the recovery. South Pole can go out of the hole but only in the end stages. Hence, in between fluctuations are probably indicative of changes in the strength of the hole. At Syowa also, there were very large fluctuations. Some of these should be edge effects; but some might be due to hole strength fluctuations. Some events are very spectacular. In November 1985, South Pole showed large fluctuations in the early part and Syowa in the later part. In October 1986, South Pole showed no variations; but Syowa showed a very sharp rise during 18-21 October, followed by a gradual fall in the next 30 days. In October-November 1988, the fluctuations at South Pole and Syowa were similar except for a phase difference of ~5 days (Syowa occurring earlier). The November 1989 fluctuations at South Pole were not accompanied by fluctuations at Syowa. In 1990, South Pole ozone hole recovered steadily from mid-October to mid-December; but Syowa showed large fluctuations throughout this period.




Figs. 3 (a-g). Total ozone values for Aug-Dec 1988 at : (a) South Pole (the dashed curve is for TOMS 30°S-90°S minimum value), (b) Syowa (69°S, 39°E), (c) Palmer (65°S, 64°E), (d) McMurdo (78°S, 167° E) with TOMS values (dashed lines) appropriate to these locations, (e) and (f) show McMurdo ozone for 12-20 km and 18 km respectively, (g) 18 km temperature above McMurdo

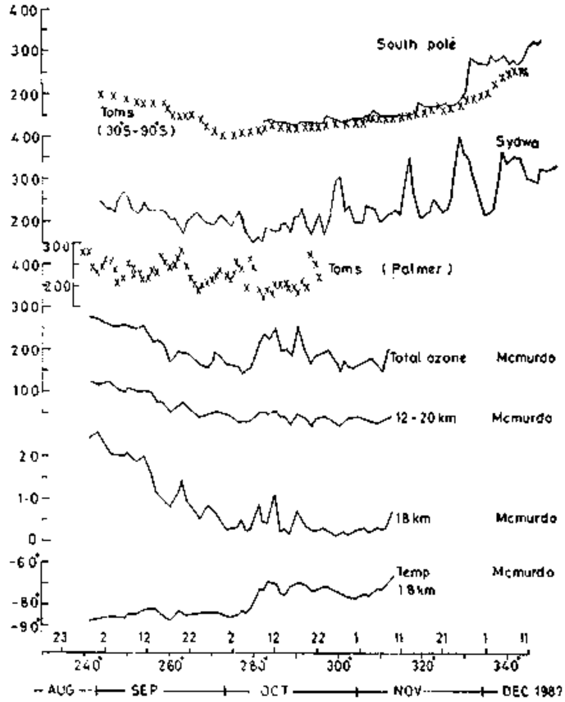



Fig. 4. Total ozone values for Aug-Dec 1987 at South Pole, Syowa and McMurdo and ozone at 12-20 km and 18 km and temperature at 18 km at McMurdo

### 3. The 1988 ozone hole

Since the discovery of the Antarctic ozone hole by Farman *et al.* (1985), considerable effort has gone into the detailed study of this phenomenon. Krueger *et al.* (1987, 1988) presented TOMS observations for the 1986 and 1987 Antarctic ozone holes. Krueger *et al.* (1989) and Schoeberl *et al.* (1989) compared the 1988 Antarctic ozone hole wth previous year depletions. In 1986, 1987, 1988, 1989 and 1990, balloon-borne measurements of ozone and temperature were made at McMurdo station (78°S,167°E) [Hofmann *et al.* 1987, 1989; Deshler *et al.* 1990 (a & b), Deshler and Hofmann 1991]. Also, Lubin and Frederick (1990) reported column ozone measurements for 1988, 1989 from Palmer station (65°S, 64°W). Thus, for the 1988 event data can be compared for four widespread locations (full dots in Fig. 1). Fig. 3 shows the plots. Fig. 3(a) (full lines) shows a plot for total ozone at South Pole. The dashed curve shows TOMS values of *minimum* ozone poleward of 30°S as reported by Krueger *et al.* (1989). Fig. 3(b) shows total ozone at Syowa. Figs. 3 (c & d) (full lines) show total ozone at Palmer station (Lubin and Frederick 1990) and McMurdo station [Deshler *et al.* 1990 (a & b)]. The dashed lines show the TOMS values appropriate to these locations. Fig. 3(e) shows ozone content in the 12-20 km region, Fig. 3(f) shows ozone at 18 km altitude and Fig. 3(g) shows the 18 km temperature, all above McMurdo.

The following features may be noted :

(1) Fig. 3(a) shows very little fluctuations of the ozone hole up to 20 October 1988, in the TOMS as well as South Pole data. Thus, the ozone hole was fairly constant during this period. Syowa shows very large fluctuations indicating that the location was in and out of the ozone hole frequently. The Syowa peak in late September and early October almost matches with a similar peak 2 days later at Palmer and 2-3 days earlier at McMurdo. However, the other prominent peaks at Syowa are not reflected at Palmer or McMurdo. The larger fluctuation at McMurdo during 23-31 October is explained by Deshler *et al.* 1990(b) as movements of the vortex wall back and forth over McMurdo.

(2) The most spectacular feature is the large ozone decrease at South Pole during 29 October-7 November and the subsequent recovery.

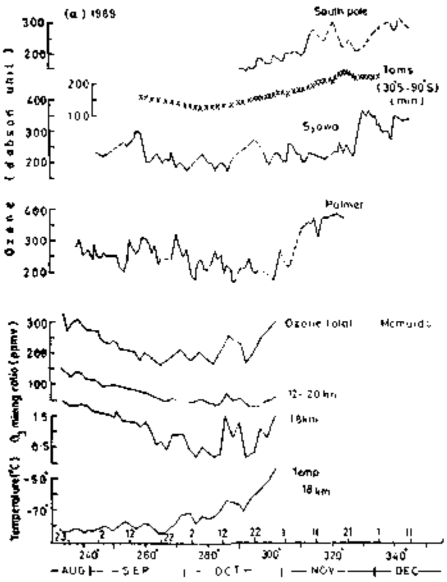



Fig. 5(a). Total ozone values for Aug-Dec 1989 at South Pole, Syowa, Palmer and McMurdo and ozone at 12-20 km and 18 km and temperature at 18 km at McMurdo

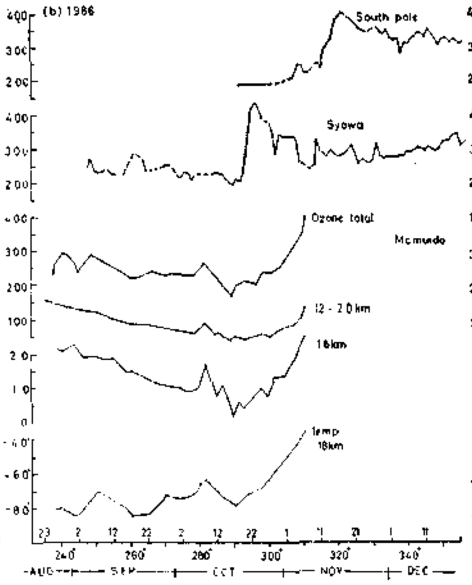



Fig. 5(b). Total ozone values for Aug-Dec 1986 at South Pole, Syowa and McMurdo and ozone at 12-20 km and 18 km and temperature at 18 km at McMurdo

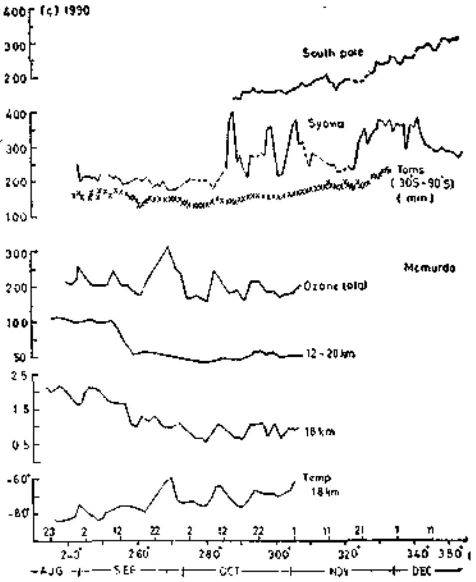



Fig. 5(c). Total ozone values for Aug-Dec 1990 at South Pole, Syowa and McMurdo and ozone at 12-20 km and 18 km and temperature at 18 km at McMurdo

This feature is seen at Syowa and McMurdo, but not at Palmer. Krueger *et al.* [1989, Fig. 5(a)] have shown in polar orthographic projections (with the South Pole at the centre and the equator as the outer circle) a sequence of TOMS daily southern maps for selected days, *viz.*, 27 August, 26 September, 5, 15 and 31 October, 1988. For the last date (31 October 1988) they mention that the ozone minimum was *dissipating* as the high total ozone region (eastern sector) was pressing (westward) across the South Pole toward the Antarctic Peninsula, resulting in values as low as 230 DU in the south polar region (including Palmer) while value at the South Pole itself rose to ~350 DU. Figs. 3 (a-c) confirm these findings. However, for periods after 31 October, Krueger *et al.* (1989) provide no information. No information is available in Schoeberl *et al.* (1989) either Krueger *et al.* (1989) mention that the minimum ozone poleward of 30°S quickly rose to above 200 DU on 23 October and the residual polar minimum *retained its integrity* through mid-November when it finally was absorbed in the mid-latitudes. However, they make no mention of the 31 October-7 November decrease and subsequent recovery. The minimum values near about 7 November 1988 were ~250 (7 November) at South Pole, ~300 DU (5 November) at Syowa, ~ 250 DU (8 November) at Palmer and ~350 DU (10 November) at McMurdo. However, at McMurdo, the 7-10 November minima were very conspicuous in the 12-20 km altitude range and at 18 km in particular. Using the circumpolar wind maximum at 70 hPa to delineate the polar vortex, Deshler *et al.* [1990 (a & b)] indicated the timings when McMurdo was inside, at the edge of, and outside the vortex. The Fig. 3(d) indicates these intervals and accordingly, the above interval (31 October-7 November) is mentioned as *outside* the vortex. Deshler *et al.* [1990 (a)] suggest that the relative ozone deficit during 29 October-6 November probably resulted from the entrainment of ozone poor air outwardly from the ozone cavity. We suggest the two possibilities. First possibility, the vortex which had started moving towards the Antarctic Peninsula and passed over South Pole in late October, probably *reversed* its direction of displacement and came back over South Pole, Syowa and McMurdo during 31 October-7 November and later on, either moved back westward and/or weakened and dissipated by November end. In this case, Palmer should have shown increased levels of ozone during 31 October-7 November. There is some indication of this to have occurred. Second possibility, for some reason the ozone hole intensified during 31 October-7 November and later weakened. In this case, all locations would show a decrease. South Pole, Syowa and McMurdo did show the decreases; but Palmer had a mixed pattern, *viz.*, an increase during 31 October-7 November, a decrease on 8 November followed by an increase on 9-10 November followed by a decrease during 10-14 November and later, a sharp recovery by 17 November. It is difficult to judge which of the two possibilities really occurred. An additional complication is that on 22 November and 12 December, Syowa reached low ozone levels comparable to those of 4 November. Would this imply *reformation* of ozone holes in November and December above Syowa ? Similar depressions were not observed at South Pole or Palmer. For McMurdo, no data were available.

In their detailed study of vertical profiles of ozone, Deshler *et al.* [1990 (a & b)] reported that ozone depletion was caused by a sink between 12-20 km and measurements at the edge of the vortex (McMurdo) displayed ozone *layering* and exchange of ozone rich and poor air across the vortex wall in the 12-20 km layer. Most of the fluctuations seen in Fig. 3 are probably of such an origin. However, some changes could be due to changes in the strength of the ozone hole itself. Deshler *et al.* 1990 (a) mention that the 1988 event corroborates earlier suggestions that regions of ozone depletion are related to temperatures conductive to the formation of polar stratospheric clouds. Fig. 3(g) shows the temperature at 18 km above McMurdo. The temperature was about —80°C up to mid-September and then rose steadily to about —50°C, which is interpreted as the vortex *wall* reaching over McMurdo. From 21 October onwards, the temperature remained above —55°C but small temperature variations match the large ozone variations. On day 300 (26 October) and day 315 (10 November), the 18 km ozone level at McMurdo was very low, almost comparable to that of late September. But the temperatures on these days (—54°C and —40°C) were much higher than the September end temperatures (—64°C). It would thus seem that low stratospheric temperatures are not the sole guiding factors controlling ozone changes.

#### 4. The 1989 ozone hole

Fig. 5(a) shows the plots for the 1989 event where data for South Pole, Syowa, Palmer and McMurdo are plotted. South Pole showed a structure during recovery, *viz.*, peaks on 10 November and 16 November 1989 of 275 DU and 300 DU respectively. On these dates, Syowa values were lower, ~225 DU and the recovery started only later on 22 November. In contrast, Palmer ozone had already recovered to ~350 DU by 6 November. Thus, the ozone hole had left the South Pole — Palmer axis and shifted towards Syowa. It would be interesting to confirm the shift from TOMS data for grid points above these locations separately. Data for McMurdo do not extend to November. In October, McMurdo total ozone showed an *increase* during 11-17 October (days 284-290) which was reflected in the ozone in the 12-20 km region as also in ozone and temperature at 18 km. The feature was seen a few days later at Syowa and probably a few days earlier at Palmer, probably indicating displacement of the vortex back and forth.

#### 5. The 1986, 1987 and 1990 ozone holes

For these events, data were available for South Pole, Syowa and McMurdo only and some TOMS data (Deshler and Hofmann 1991, Newman *et al.* 1991). Fig. 5(b) shows the plots for 1986. At South Pole, the hole seems to have disappeared by 16 November but reappeared partially by 3 December and dissipated later. At Syowa, there was an enormous increase during 17-22 October (from 200 DU to 430 DU) which was not seen either at South Pole or at McMurdo. Thus, during 17-22 October, the ozone hole must have moved away from Syowa, towards South Pole and McMurdo. From 22 October to 4 November, Syowa ozone decreased from 430 DU to 240 DU while McMurdo ozone increased rapidly from 200 DU to 400 DU. Thus, the ozone hole swung back to the Syowa region, away from McMurdo and South Pole. Thus, large displacements along the 180° -0° meridian seem to have occurred. In the latter half of November, ozone at South Pole decreased from ~400 DU on 16 November to ~275 DU on 3 December while Syowa ozone remained below 300 DU. Thus, a weak ozone hole seems to have covered South Pole and Syowa. Whether this covered McMurdo also cannot be checked as data are not available. At McMurdo, 18 km ozone and temperature in October showed similar variations indicating that McMurdo was often in and out of the ozone hole vortex.

Fig. 4 illustrates the 1987 event. At South Pole, the formation and subsequent dissipation of the ozone hole was fairly smooth. During 24-27 November, the ozone level recovered from ~175 DU to ~275 DU, remained at that level up to 9 December and later rose to ~325 DU. In contrast, Syowa showed very large fluctuations, probably indicating encounters with the vortex wall. Particularly interesting is the level during 27 November-3 December when South Pole ozone had recouped to ~275 DU but Syowa ozone decreased from ~400 DU to ~220 DU. This would imply that the ozone hole still existed but shifted from South Pole towards Syowa. Unfortunately, there are no McMurdo data to check such a movement. Krueger *et al.* (1988) showed a plot of TOMS observations for latitudes south of 30° S, which we have reproduced in Fig. 4. During the above interval TOMS values were lower than South Pole values and similar to those at Syowa. Their polar orthographic plot for 29 November 1987 shows that the ozone hole weakened and formed an *elongated oval* which seems to miss South Pole but enclosed Syowa. Thus, features like this seem to be mainly due to distortions and displacements of the ozone hole vortex. At McMurdo, a peculiar feature occurred during 4-20 October, when the ozone level rose from ~150 DU with two peaks on 12 October and 17 October. Similar peaks occurred in ozone and temperatures at 18 km above McMurdo but not at South Pole or Syowa. Hofmann *et al.* (1989) attributed these fluctuations to entry and exit of McMurdo from the vortex wall. The feature was not reflected in the TOMS values appropriate for Palmer as given by Margitan *et al.* (1989) and reproduced in Fig. 4.

Fig. 5(c) shows the plots for 1990. The ozone hole dissipation at South Pole was more or less smooth. Syowa showed violent fluctuations, ozone levels reaching above 350 DU on 16, 27 October and 3 November, obviously due to Swoya going out of the ozone hole. Similar fluctuations were seen at McMurdo but not on the same dates. In particular, McMurdo total ozone increased considerably (from 175 DU to 300 DU) from 19 September (day 262) to 27 September (day 270). Surprisingly, the increase was not seen in 12-20 km range or at 18 km, but the 18 km temperature showed a similar change. Thus, the increase was not due to McMurdo going outside the vortex but due to mid-latitude (ozone rich) air entering in the levels above 20 km (Deshler and Hofmann 1991).

#### 6. Conclusions

The Antarctic ozone hole dissipation is not uniform Apart from the displacements and distortions of the vortex during the course of the dissipation when the vortex shape may change from circular to an elongated oval and may even tilt so that some layers may be out of the vortex while some may still be in [Krueger *et al.* 1989, Deshler *et al.* 1990 (a & b)], the ozone hole strength may increase (*i.e.,* ozone level may decrease) again for a few days during recovery. Also, the displacements may not be necessarily from east towards west (from Antarctic continent towards Antarctic Peninsula) but may be in other directions also. The displacement may not be steadily in any one direction. It may even *reverse* and the ozone hole may come back over the South Pole and change strength before finally disappearing.

These characteristics of the ozone hole are not surprising. Though ozone depletion is mainly of chemical origin (Chlorine chemistry, Solomon 1988, Anderson *et al.* 1989), changes in other parameters like temperature and water vapour (which affect the polar stratospheric clouds) and nitrogen oxides could be important (Turco *et al.* 1989). Also, the dynamic situations which set up conditions favourable for the chemical depletions are dependent on vertical motions which would be affected by wave structures which would distort, displace and/or modify the circumpolar vortex (Krueger *et al.* 1989, Newman *et al.* 1990). Ozone *layering* caused due to exchange of ozone rich and poor air across the vortex wall in the 12-20 km layer has been demonstrated by Deshler *et al.* [1990 (a & b)]. It would be interesting to study these features in greater detail by using TOMS data at various latitude-longitude grid intervals on a *daily* basis.

*Acknowledgements*

Data for South Pole and Syowa ozone were obtained from *Ozone Data for the World.* This work was partially supported by FNDCT, Brazil under contract FINEP 5373 CT.

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