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CHARACTERISTICS OF THE ANTARCTIC OZONE HOLE DERIVED FROM NIMBUS 7 TOMS DATA

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Abstract: Global total ozone has been mapped with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) instrument since November 1978. Very detailed daily maps are produced with this instrument which has a spatial resolution at nadir of 50 km. The data accuracy is better than 2% under all weather conditions as evaluated by comparison with Dobson spectrophotometer network stations. Coverage is complete at all sunlit latitudes including the poles during non-polar night months.

The general structure of southern hemisphere total ozone is a polar minimum surrounded by a circumpolar maximum. Over much of the year the gradients are quite small except for local midlatitude storms. However, during the spring months the difference between the minimum and the maximum grows with time. The boundary of the polar minimum is generally very sharp with a gradient of 10 Dobson units/100 km not uncommon, thus justifying the term "ozone hole" to describe this feature. A station in the boundary region will undergo very large changes in ozone as the position of the hole drifts and fluctuates. Finally, the ozone hole is destroyed as the polar vortex breaks down in November. These characteristics were illustrated during the Symposium in a motion picture of daily ozone maps for a complete year. A second motion picture shows the striking decrease of Antarctic ozone during each of the October months since 1979 to values near 140 Dobson units, far below the lowest (180 Dobson units) ever observed previously at any location. It is this decrease which is the subject of the current controversy over possible fluorocarbon effects on ozone.

The data from TOMS show that dynamics are critical in the formation of the ozone hole. Total ozone in the Antarctic region is found to be highly correlated with air temperature in the lower stratosphere.

1. Introduction

An extraordinary decrease in Antarctic spring total ozone in the past decade was reported by FARMAN *et al.* (1985). Subsequently, the observation was confirmed with data from the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) (STOLARSKI *et al.*, 1986). Several explanations have been proposed. The first by FARMAN *et al.* suggested that the closed polar night circulation of air in the polar vortex allowed slow chemical reactions to occur between chlorine sink molecules. The spring sunlight then photolyses the reaction products to form active chlorine which catalyses the destruction of ozone. A second explanation proposed that solar cycle modulation of thermospheric nitric oxide followed by polar night downward transport to the stratosphere was producing a solar cycle modulation of total ozone (CALLIS and NATARAJAN, 1986). A third hypothesis suggested that the growth of bromine compounds along with chlorine constituents synergistically produced destruction of odd oxygen (MCELROY *et al.*, 1986). Finally, the fourth theory proposed that enhanced ascending motion in the lower stratosphere has produced lower total ozone. The source of the increased vertical motion is not known, but a change in heating by polar stratospheric clouds and aerosols has been suggested (TUNG *et al.*, 1986).

Total ozone is one of the most variable atmospheric parameters. Data from Dobson spectrophotometer stations at Northern middle latitudes show day-to-day changes that exceed the amplitude of seasonal changes. The TOMS instrument was designed to spatially resolve the total ozone field. This capability has allowed the analysis of the horizontal structure in total ozone responsible for the remarkable variability of this gas and has spurred on investigations of the sources of this variability.

Total ozone is determined by measuring the radiance of the sunlit atmosphere at near-ultraviolet wavelengths that are weakly absorbed by ozone. The technique was originally proposed by DAVE and MATEER (1967) and first tested with data from the Nimbus 4 BUV instrument (MATEER *et al.*, 1971). The spatial variability in total ozone, however, was found to be greater than could be resolved with the nadir pointing BUV instrument and the TOMS instrument with a smaller field of view scanning the atmosphere below the spacecraft was proposed for the Nimbus 7 spacecraft. This instrument was designed to cancel sources of error in the BUV (and SBUV) instruments due to image motion during the sampling time and, therefore, produces very high quality data. The basic design is described in HEATH *et al.* (1975).

The Nimbus 7 spacecraft was launched on October 24, 1978 into a polar, 950 km, sun-synchronous orbit to produce full daily global coverage. The orbit is in a noon-midnight plane which results in TOMS observations near local noon at nadir. The full field of view includes a longitude range at the equator of 27 degrees in order that full contiguous coverage is possible at all latitudes. As a result the local time varies by about 2 h across the scan angles of the instrument. The 27 degree swath also serves to produce coverage of the polar cap beyond the inclination angle of 100 degrees. Thus when the poles are sunlit in spring and summer that point is viewed on each of the 13.8 orbits each day.

The accuracy of the TOMS data has been tested by internal consistency checks and by comparison with the Dobson spectrophotometer network stations (BHARTIA *et al.*, 1984) with the result that the TOMS data averaged 6% less than the Dobson data. The data are being reprocessed using recent U.S. National Bureau of Standards ozone cross section measurements. This has resulted in an improvement in agreement with a -1% bias remaining. The precision has been evaluated by determining the standard deviation of the difference between Dobson and TOMS coincident observations. In both versions of the processing algorithm, the standard deviation is near 2%. This implies that both TOMS and Dobson techniques produce data of precision better than 2%.

2. Structure of the Antarctic Ozone Hole

The total ozone in the south polar regions undergoes a simple annual cycle consisting of a maximum in November or December which decays steadily to a minimum in the next October (BOWMAN and KRUEGER, 1985). This characteristic is shown in Fig. 1 which illustrates the seasonal behavior of the total ozone at 70°S, 0°E taken from 1984 TOMS data. At this location the minimum of 207 Dobson units (DU) occurred in late October and the maximum of 360 DU was two months later in late December. The rapid reset in this cycle takes place near the time of the breakdown of the polar vortex and signals a clear change either in the vertical motion field in the lower stratosphere or in the horizontal transport to the pole. This behavior is similar at other polar longitudes but varies in detail in the timing and rapidity of the springtime reset of the cycle. During the polar night (the region of missing data near the center of the line in Fig. 1) the total ozone appears to decrease only slightly.

The spatial variations of total ozone during the Antarctic spring are illustrated in Fig. 2. The monthly mean total ozone for the months of September, October, November and December 1984 is shown on four Southern Hemisphere polar projection maps with the Greenwhich meridian at the right of each plot. In September through November a large wavenumber 1 modulation is present with a maximum at 130 to 160°E longitude and a minimum at 0 to 40°W longitude. The maximum, with values exceeding 400 DU, is centered near 55°S in September and October but shifts

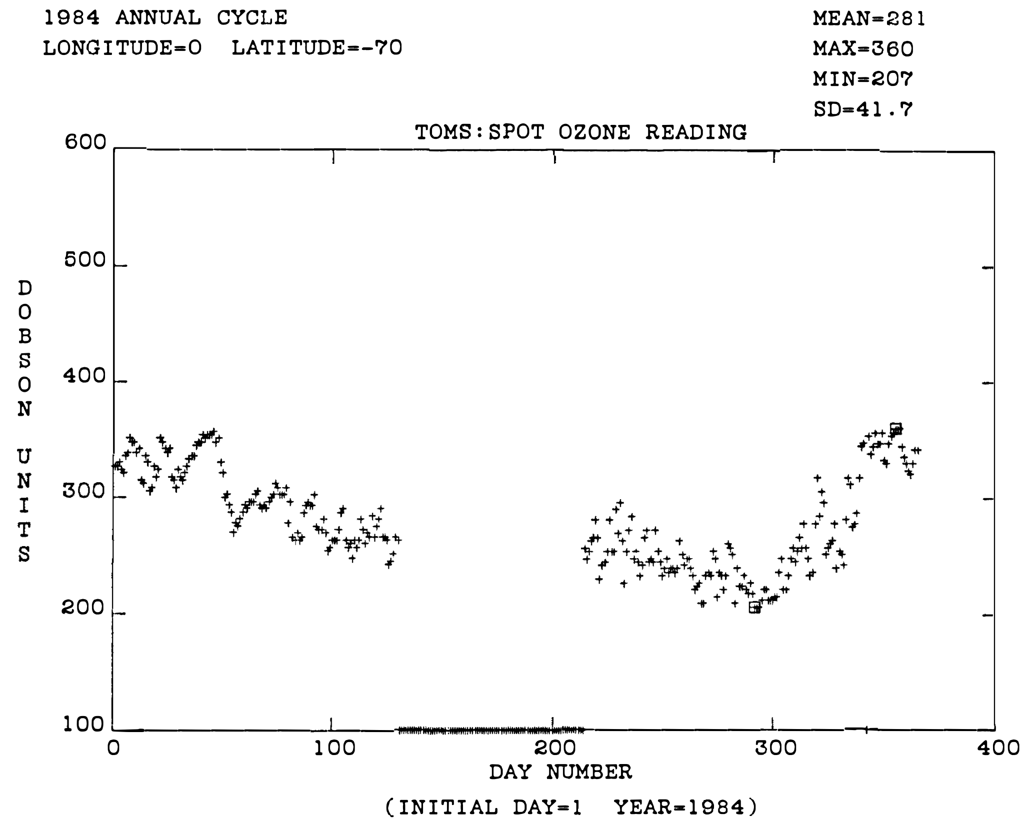


Fig. 1. Annual variation total ozone during 1984 at 70°S latitude, 0°E longitude from TOMS data. The missing segment near the center of the curve is polar night at this location.

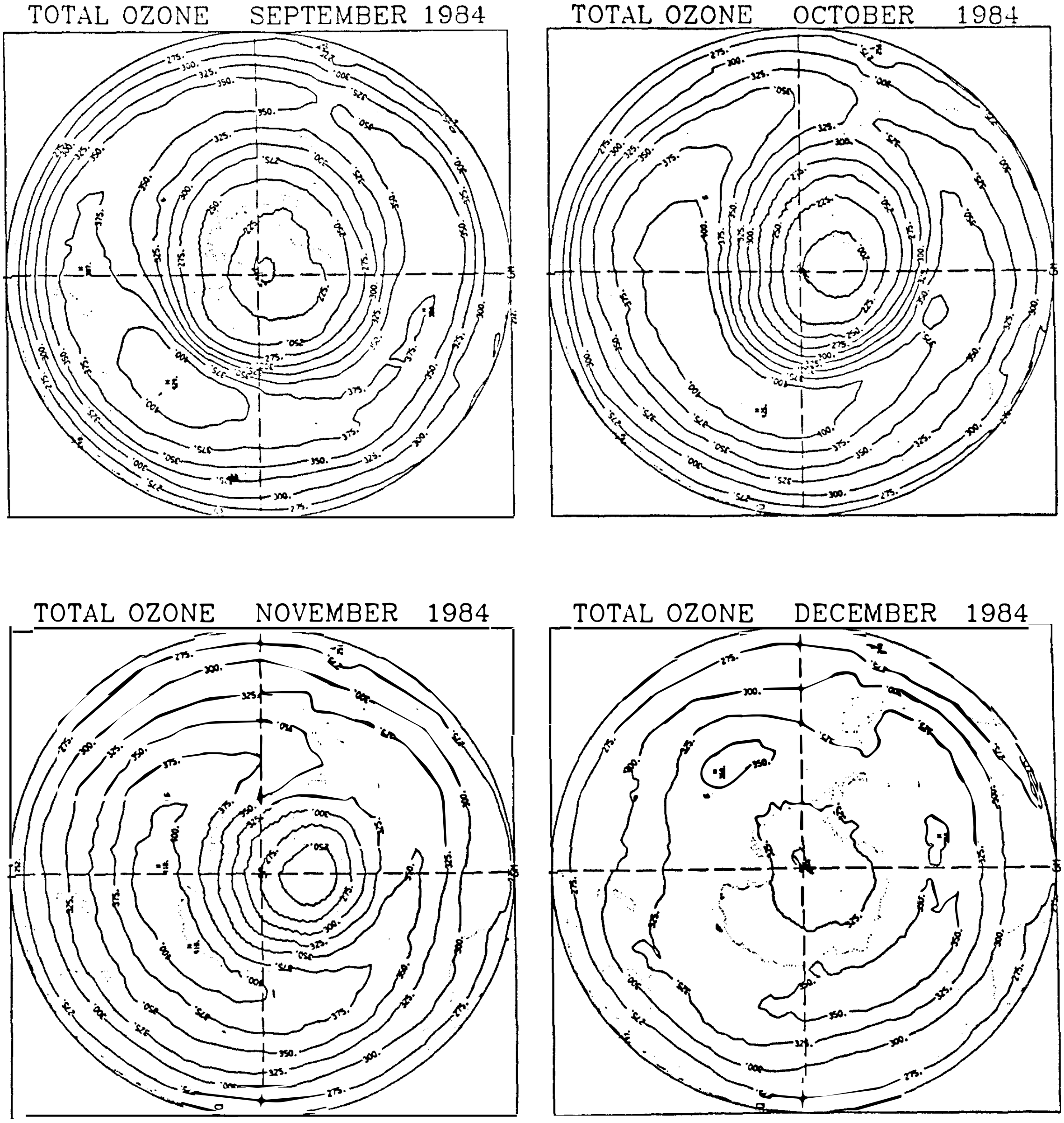


Fig. 2. Monthly average total ozone in the Southern Hemisphere for September–December 1984. Contours are shown with 25 DU intervals.

poleward to 65°S in November. The minimum is located at much higher latitudes, appearing to start almost at the pole in September and shifting to 80°S in October and November. The characteristic pattern of the Antarctic ozone hole is this oval minimum, surrounded by a semicircular maximum, with a steep intervening gradient present even in the monthly average maps. This pattern is unique to the Southern Hemisphere and is clear evidence for a stable circulation in the polar vortex.

The lowest contour in September, 200 DU, expands in area in October, but is replaced by 250 DU contour in November and the 325 DU contour in December. This is similar to the behavior illustrated in Fig. 1 which was selected to represent the longitudes of the ozone minimum. At the opposite side of the pole (180°E, 70°S),

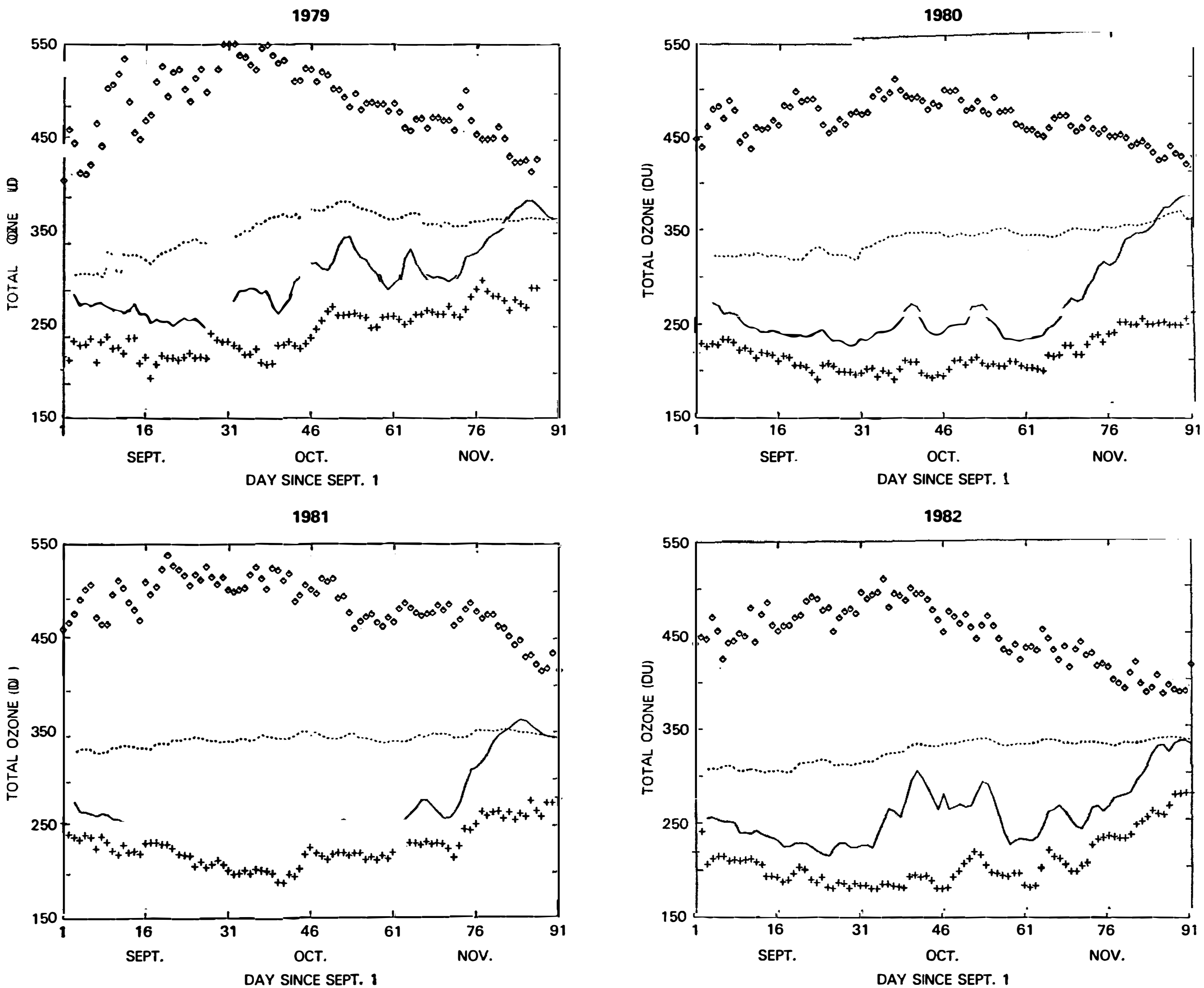


Fig. 3. *Change in the maximum (◇) and minimum (+) total ozone south of 44°S in 1979–1982 from* S*TOLARSKI and* S*CHOEBERL (1986). Daily values are plotted for September, October, and November of each year. The dotted line is the area-weighted average total ozone (44 to 90°S) and the solid line is the 78°S zonal mean total ozone.*

the ozone is much more variable and begins to increase immediately after the polar night ends.

3. Time Variations of Southern Hemisphere Total Ozone

The deepening of the polar minimum in September and October is accompanied by an increase in the area of the 400 DU maximum. Similarly, as the minimum fills in November the area of the maximum decreases. In December only a generalized polar minimum and circumpolar maximum remain as the steep gradient that distinguishes the ozone hole disappears. Complementary variations of the ozone maximum and minimum are also present in daily patterns, further suggesting that redistribution of ozone is an important part of the formation of the ozone hole. This is shown in Fig. 3 (STOLARSKI and SCHOEBERL, 1986) where the daily maximum and minimum values south of 44°S, and the zonal mean total ozone (solid line) at 78°S for September–November in 1979 to 1982 are plotted. Also plotted is the area weighted total ozone integral from 44°S to the pole (dotted line), a region containing the ozone hole and surrounding maximum. If ozone is chemically destroyed rather than redistributed by winds, the integral over this region is expected to show a decrease with time. The integral in each of the years, however, is constant or slightly increasing with time, indicating that there is no net destruction of ozone. If chemical destruction is indeed

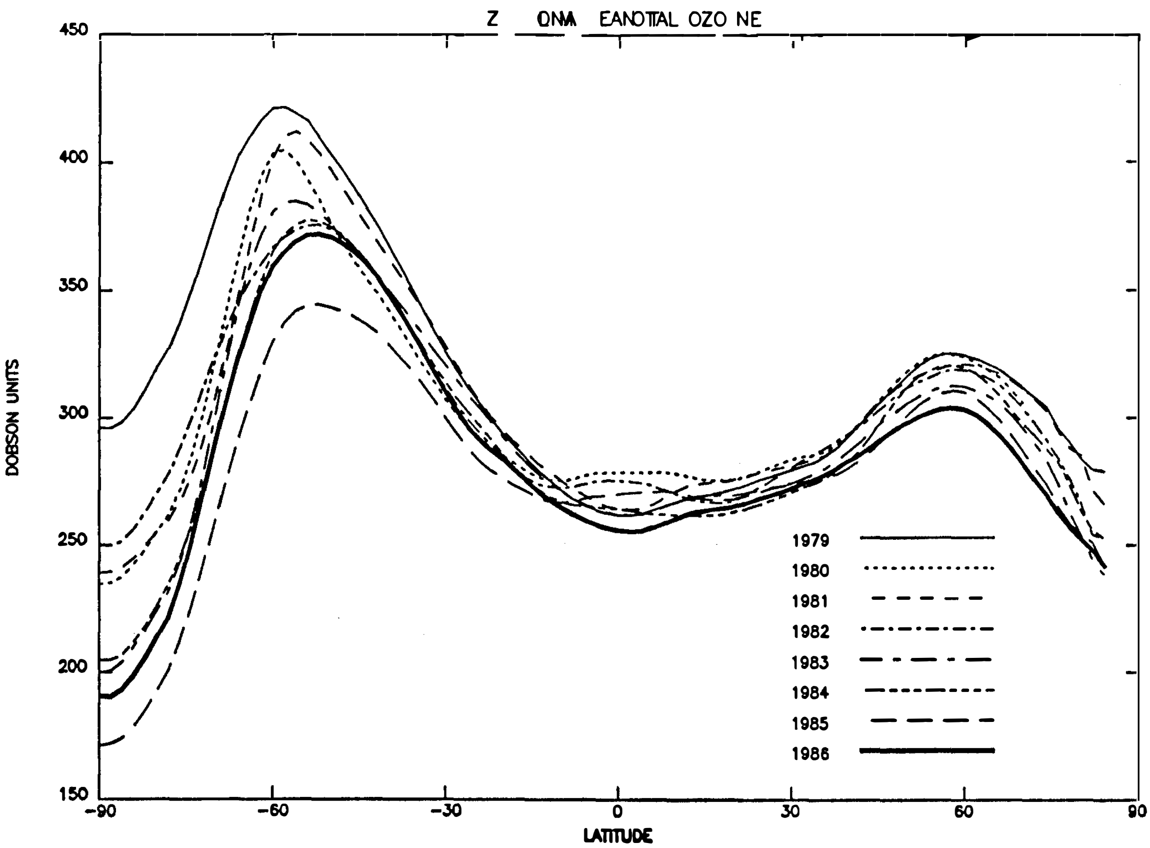


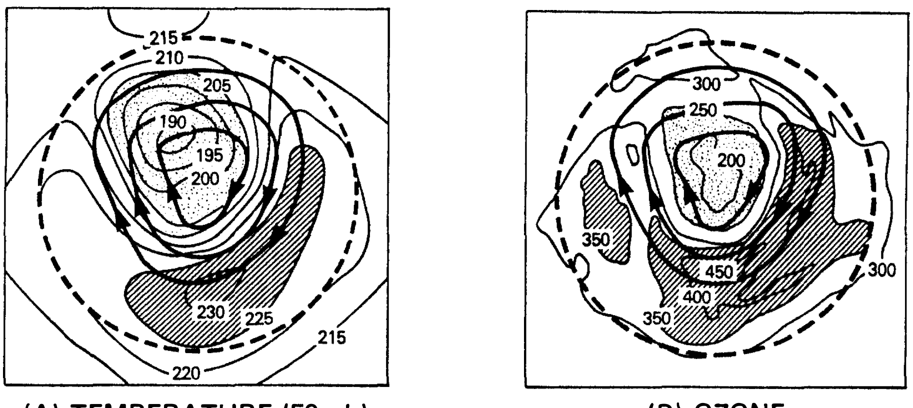
Fig. 4. Zonal mean total ozone vs latitude for the years from 1979 to 1986.

occurring it must be closely balanced by transport across the 44°S latitude boundary for the integrals.

Although the average polar ozone is approximately constant during each spring season, that amount has decreased since the TOMS data began in 1979. This is illustrated in Fig. 4 from SCHOEBERL *et al.* (1986) where the zonal mean total ozone for the eight Octobers from 1979 to 1986 is plotted as a function of latitude. The latitudinal variation with a midlatitude maximum and a polar minimum is apparent during each of the years. The ozone at the pole has clearly decreased from 280 DU in 1979 to 170 DU in 1985 in good agreement with the observations of FARMAN *et al.* (1985). However, the decrease is shown to extend over the entire hemisphere south of the tropical regions. Even the ozone at the 60°S maximum has decreased from 400 to 330 DU over this time period. Thus, the apparent secular trend in Southern hemisphere ozone is not restricted to polar night air (STOLARSKI *et al.*, 1986) and any chemical ozone loss processes either take place throughout the hemisphere or rapid mixing of polar air throughout the hemisphere must take place. However, rapid mixing is inconsistent with chemical ozone destruction mechanisms requiring long polar night conditions (*e.g.* FARMAN *et al.*, 1985; MCELROY *et al.*, 1986).

4. Relation Between Total Ozone and Air Temperature

A very close relation has been found between the air temperature at lower stratosphere altitudes and total ozone on both short and long time scales (CHUBACHI, 1986; STOLARSKI *et al.*, 1986; NEWMAN and SCHOEBERL, 1986; KOMHYR *et al.*, 1986). An example of the relation on a single day is given in Fig. 5 which shows the 50 mb air temperature on the left and total ozone on the right for October 3, 1982. Each plot is a south polar projection with 30°S shown as the dashed circle. The regions of low temperature (less than 205 K) and low total ozone (less than 250 DU) are shaded while the high temperature (greater than 225 K) and high ozone (greater than 350 DU) regions are hatched. While the ozone pattern is more structured due to higher



(A) TEMPERATURE (50mb) (B) OZONE

Fig. 5. South polar distribution of 50 mb air temperature and total ozone on October 3, 1982. Temperature contours are shown for each 5 K. Total ozone is in Dobson units. The heavy lines with arrows indicate the air parcel motions at 50 mb. The dashed circle is at 60°S latitude.

spatial resolution than in the temperature data, the correspondence is clear. Also shown in this figure by heavy solid lines with arrows are streamlines around the polar vortex derived from geostrophic winds. These streamlines are particularly interesting because they show that the air flows from low temperature and low ozone regions to high temperature, high ozone regions. The flow is adiabatic because at the observed wind speeds a circuit is completed in less than 4 days, a time much shorter than the radiative time constant. For adiabatic, steady state conditions the vertical motion is given directly by the temperature advection. Regions of cold advection (right-hand side of left panel) lead to sinking motion; warm advection produces rising motion.

5. Conclusions

Total ozone observations from the Nimbus 7 TOMS instrument are of high quality and can be used to diagnose the extraordinary decrease in Antarctic springtime total ozone in recent years. At middle latitudes spatial variations of total ozone are produced by vertical and horizontal air motions in the lower stratosphere. We believe that the changes in Antarctic total ozone are produced primarily by similar processes.

The TOMS observations show that Antarctic total ozone annually decreases from a maximum in November or December (late spring) to a minimum in the next October (early spring). The rapid transition from minimum to maximum values takes place about the time of the breakdown of the polar vortex. The recent extreme low values occur during the October minimum.

A high correlation is found between total ozone and lower stratosphere air temperature on time scales from daily to interannually in the Antarctic spring. On a daily scale the temperature and ozone patterns are displaced from the polar vortex center, indicating flow across the isopleths. This suggests that the ozone modulations are produced by vertical motions, similar to those found at midlatitude locations, and demonstrates that dynamical processes are important to the formation of the ozone hole. In fact, the integral of total ozone over the region south of 44°S is nearly constant as the hole forms and dissipates, thus demonstrating that the ozone is being redistributed rather than destroyed in a given year. The integrals, however, show a secular trend that is symptomatic of possible climate changes or a depletion due to chemical causes.

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