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## Low ozone amounts during 1992–1993 from Nimbus 7 and Meteor 3 total ozone mapping spectrometers

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**Abstract.** The global distribution of ozone during the October 31, 1978, to May 6, 1993, observing lifetime of the Nimbus 7 total ozone mapping spectrometer (TOMS) is described, with emphasis on the low ozone amounts observed during 1992 and 1993. Ozone amount time series are extended beyond May 6, 1993, to the end of July 1993 using preliminary Meteor 3 TOMS data. Time series for zonally averaged ozone amounts show that there has not been a significant shift in the seasonal patterns of ozone maxima and minima caused by the Mount Pinatubo eruption or by the onset of very low ozone values during 1992 and 1993. There has been a relatively slow, nearly linear decrease in the amount of ozone over the entire globe from 1979 to the end of 1991, with rates ranging from no change at the equator to a 4–6% decrease per decade at midlatitudes and a 10–12% decrease per decade at higher latitudes. After the eruption of Mount Pinatubo during June 1991, the ozone amount decreased in the equatorial latitudes (10°S to 10°N) for about 6 months (–10 Dobson units (DU) between 0° and 10°S and –3 DU between 0° and 10°N). During 1992 and continuing into 1993, the rate of ozone decrease deviated from the previously linear trend with the onset of changes that were large in comparison with the historical range of ozone values from 1979 to 1991. The first of the large decreases in ozone amount occurred earlier, in February 1990 to May 1990, at 50°–70°N. At high northern latitudes, the 1993 decreased ozone amounts were about 12.5% below the envelope of historical values; at midlatitudes they were about 7% lower; and at low latitudes they were about 4% lower. Area-weighted averages in the northern and southern hemispheres show that most of the 1992–1993 ozone losses have occurred in the northern hemisphere. The 1993 global average (70°S to 70°N) ozone amount is 3% below the 1979 to 1991 minimum, 5% below the historical envelope in the northern hemisphere, and near the lower boundary of the historical envelope in the southern hemisphere. In the 70°–60°S latitude band, the ozone losses between 1979 and 1993 have reduced the annual minimum amount to values below those seen in the equatorial regions.

### Introduction

Since November 1978 the amount and distribution of ozone observed from the Nimbus 7 total ozone mapping spectrometer (TOMS) has changed substantially over the entire globe [Gleason *et al.*, 1993; Herman *et al.*, 1991a, b, 1993; Stolarski *et al.*, 1991, 1992a, b; Stolarski, 1992; Angell, 1988; Bojkov *et al.*, 1990; J. R. Herman and D. Larko, Global ozone change as a function of latitude and longitude, January 1979 to December 1991, submitted to Journal of Geophysical Research, 1993, hereinafter referred to as HL]. The most dramatic of these changes has been the continuing development of the springtime Antarctic ozone hole region (first reported by Farman *et al.* [1985]; see also Chubachi [1984]), with a 1992 ozone depletion of about 50% relative to 1979 amounts. From 1979 to 1988 there was a nearly linear decrease in the springtime Antarctic ozone minimum measured by TOMS, from 200 to 118 Dobson units

(DU) (HL). After 1988 the Antarctic ozone hole minimum leveled out at  $118 \pm 8$  DU. However, the total area of the ozone hole region (220-DU ozone contour) has continued to increase though still bounded by the south polar vortex wind system.

Both the detailed Antarctic ozone morphology and likely mechanisms for producing the observed ozone hole depletions, high ClO and low NO<sub>2</sub> amounts, are discussed by Solomon [1988], Stolarski *et al.* [1991], Watson *et al.* [1988], Prather *et al.* [1990], and review discussions in several World Meteorological Organization reports [e.g., World Meteorological Organization, 1990]. Similar changes have not been observed from TOMS in the Arctic region during the spring [Krueger and Schoeberl, 1987] even with recent increases in the amount of ClO [Waters *et al.*, 1993]. At other latitudes the rates of ozone loss are smaller, and changes can be most easily seen in plots of the long-term ozone trend versus latitude.

Between 1979 and 1991 there was about a 7% per decade rate of ozone loss in both hemispheres for latitudes between 30° and 60° during the winter and spring months, with smaller

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loss rates during autumn (3% per decade) and almost no losses during summer [Stolarski *et al.*, 1991; Herman *et al.*, 1993]. Between  $\pm 20^\circ$  there has been no measurable long-term ozone loss. The largest sustained equatorial ozone loss occurred for a few months after the June 1991 eruption of Mount Pinatubo [Chandra, 1993; Schoeberl *et al.*, 1993]. Since March 1992 there have been substantial decreases between  $10^\circ$  to  $30^\circ\text{N}$  and  $10^\circ$  to  $30^\circ\text{S}$ , with the largest decrease between  $10^\circ$  and  $20^\circ\text{S}$  [Gleason *et al.*, 1993]. There is still no long-term change in ozone amount for the latitude band between  $\pm 10^\circ$ .

For latitudes between  $\pm 65^\circ$ , the average area-weighted ozone loss for all seasons (1979–1991) has been about  $2.6 \pm 1.5\%$  per decade [Herman *et al.*, 1991a]. Analysis of the 13-year ozone trend for global changes [Herman *et al.*, 1991b, 1993] based on continuous satellite measurements from the Nimbus 7 TOMS shows that most of the ozone decrease occurred after 1984 at middle and high latitudes. The observed decrease in ozone amounts included solar cycle effects in the ozone time series. After the solar cycle effects are removed, the rates of decrease at most latitudes are approximately linear from 1979 to 1991. The details of ozone decrease rates based on TOMS data have been discussed in a series of papers [Herman *et al.*, 1991b, 1993; Stolarski *et al.*, 1991, 1992a, b; Niu *et al.*, 1992; Herman and Larko, unpublished data, 1993] as a function of latitude, longitude, and month for the period 1979 to 1992.

The larger high-latitude ozone losses during the 1979 to 1993 Nimbus 7 observing period are correlated with the introduction of relatively large amounts of active chlorine and bromine (ClO and BrO) into the stratosphere from the photolytic breakdown of both natural and anthropogenic source gases. When heterogeneous chemical processes decrease the ratio of  $\text{NO}_2$  to ClO, the large amounts of ClO can readily remove ozone from the polar regions. The likelihood of this mechanism contributing to ozone losses outside of the south polar vortex region is enhanced by recent observations of large quantities of ClO during the Arctic and Antarctic winters from the upper atmosphere research satellite [Waters *et al.*, 1993].

Outside of the regions where heterogeneous chemical destruction of ozone is known to occur for sustained periods (Antarctica), the total amount of atmospheric chlorine and bromine is not sufficient to explain the observed ozone amount changes over the past 14 years [Herman and McQuillan, 1985]. The sensitivity of ozone amounts to the atmospheric dynamical state is seen in the relatively short-period changes induced by the  $\sim 2.3$ -year quasi-biennial oscillation (QBO), the 11-year solar cycle effects [Herman *et al.*, 1991b; Stolarski *et al.*, 1991; Zerefos *et al.*, 1992], and the dominant dynamically driven seasonal changes. The observed changes in ozone amount at middle and high latitudes in both hemispheres suggest that there have been changes both in chemical mechanisms (active chlorine and heterogeneous chemistry at high latitudes) and in the seasonal transport of ozone from low to high latitudes [Tung and Yang, 1988]. Heterogeneous chemical reactions on sulfate aerosols may also have contributed to the observed changes in the global ozone amounts after the Mount Pinatubo eruption [Granier and Brasseur, 1992]. Global and local ozone amounts are also dependent on changes in the solar ultraviolet flux. For example, the relative maxima and minima of the 11-year solar cycle are well correlated with the

1979 to 1991 deseasonalized global-average ozone minimum during 1984 to 1985, with relative maxima during 1979 and 1991 [Herman *et al.*, 1991b], and with the recent decrease in ozone amounts during 1992 and 1993 [Gleason *et al.*, 1993].

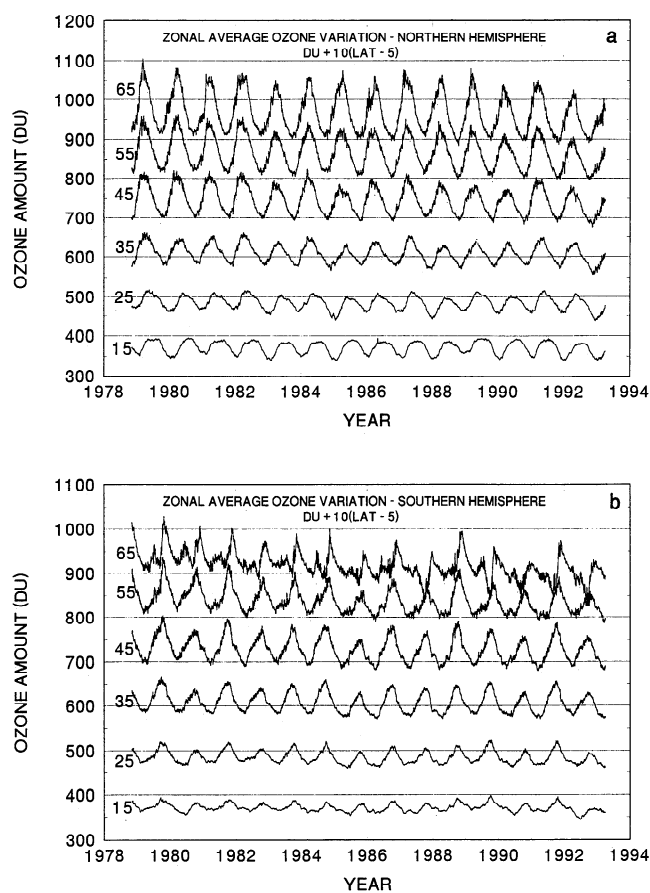
This paper examines some of the changes in ozone time series and the latitudinal distribution of ozone that have occurred during 14.5 years of observations from the Nimbus 7 TOMS satellite instrument (October 1978 to May 6, 1993). The zonally averaged ozone time series is extended through July 1993 using data from Meteor 3 TOMS (launched in August 1991). Until the end of the data record on May 6, the Meteor 3 TOMS ozone data have been shown to agree closely with ozone amounts from Nimbus 7 TOMS [Gleason *et al.*, 1993]. The Meteor 3 TOMS extension of the Nimbus 7 TOMS ozone time series beyond May 6, 1993, uses an extrapolated in-flight solar calibration between definitive in-flight solar calibrations once every 15 weeks [Herman *et al.*, 1992].

The latitudinal dependence of the seasonal phases and amplitudes in ozone amount is discussed for both northern and southern hemispheres. Asymmetries between the hemispheres are discussed for both absolute ozone amounts and the long-term rates of decrease. The year-to-year variability of ozone is examined by using a Fourier transform low-pass filter on the zonally averaged ozone time series in  $10^\circ$  latitude bands. This analysis is applied to the very low ozone values observed from late 1991 to 1993 as well as to the 1979 to 1991 period to show both the evolution and the latitudinal distribution of ozone amounts. Hemispheric averages are examined to show that most of the changes have occurred in the northern hemisphere at middle and high latitudes. Long-term trends in ozone are computed from the seasonal maxima and minima, which show a nearly linear rate of decrease at most latitudes between  $\pm 70^\circ$ , with only a small modulation by solar cycle effects. We show that the first large northern hemisphere decreases occurred during spring of 1990 and compare the size of the decrease with those occurring during 1992 and 1993. Using the data from the Meteor 3 TOMS, it is also shown that the northern hemisphere ozone decreases have continued into the summer months. Ozone decreases below the historical envelope during June and July 1993 should further increase the amount of UV radiation reaching the ground at a time when UV radiation is near its usual seasonal maximum. The increase relative to that in previous years would be in cumulative exposure over a period of time long enough to provide an average over variable meteorological conditions or in clear-sky exposure.

## Zonal Average Ozone Morphology

Some of the key features of global ozone distribution can be described by using zonal averages to remove the large longitudinal variability within a latitude band. In Figures 1 to 3, the zonally averaged daily ozone data are given for 14 latitude bands from  $70^\circ\text{N}$  to  $70^\circ\text{S}$  in  $10^\circ$  latitude bands for the northern and southern hemispheres for the period from January 1979 to May 1993. The same ozone data are plotted in different ways to emphasize various aspects of the latitudinal relationship between seasonal phases and amplitudes and to show the effects of atmospheric circulation on the seasonal ozone amounts.

As shown in Figures 1 and 2, the northern hemisphere



**Figure 1.** Zonally averaged ozone time series for 10° latitude bands in the (a) northern and (b) southern hemisphere. The ozone data have been shifted vertically to show the ozone variation within each latitude band without overlap. The vertical shift is calculated by taking the measured ozone amount in Dobson units (DU) and adding 10 (latitude – 5°). The latitude bands are labeled with their middle values.

ozone amount amplitudes range from  $\pm 75$  DU at 55° and 65°N to  $\pm 20$  DU at 15°N, with a very small phase shift of the ozone maxima and minima as a function of latitude. The southern hemisphere behavior is similar up to 45°S if the phase is shifted for the 6-month difference in seasons and if a smaller seasonal amplitude change, e.g.,  $\pm 50$  DU is allowed for at 55° and 65°S. The extreme springtime lows in 1987, 1989, 1990, 1991, and 1992 at 65°S correspond to the very low ozone values within the Antarctic ozone hole region during those years. The effects of the smaller ozone hole during spring 1988 (September and October) and the high ozone amounts during November, December, and January are visible in the 65°S zonal averages. There is an alternating pattern in the annual ozone maxima and minima in both hemispheres at all latitudes associated with the QBO surrogate, the 30-mb Singapore wind cycle [Herman *et al.*, 1991b, 1993]. The alternating pattern is more evident in the maxima than in the minima except near the equator. Since this cycle's period is not an integer multiple of years ( $\approx 2.3$  years), only some of the six QBO cycles in the TOMS data period show enhancements of the annual ozone maxima and minima.

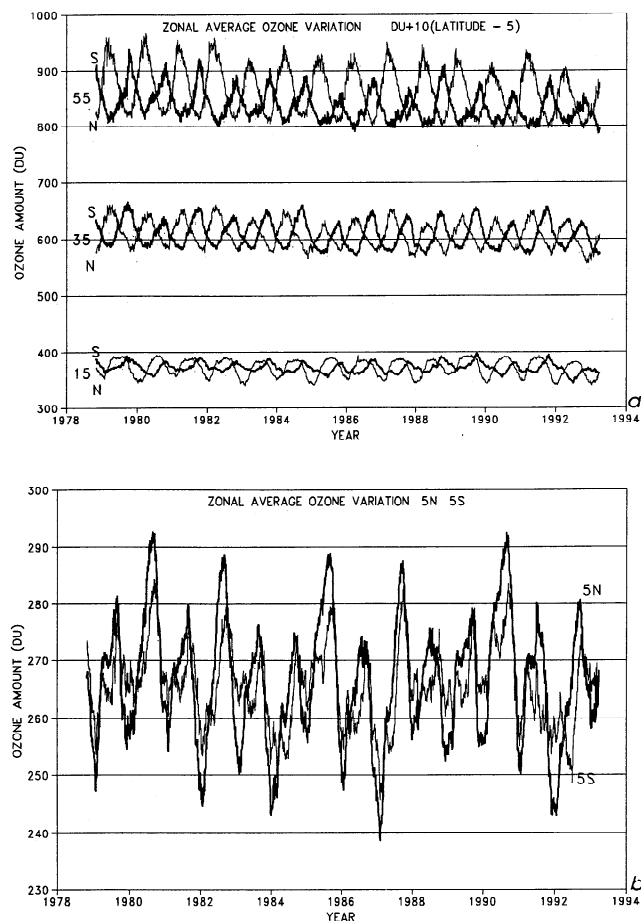
Part of the year-to-year variability in zonally averaged ozone at 65°S arises from the growing size of the slowly

rotating oval Antarctic ozone hole region (arbitrarily defined by the 220-DU ozone contour line). Since 1987 the 220-DU oval has extended over the tip of South America for periods of a few days during October as it rotates longitudinally with about a 2-week period. Figure 1 shows the increasing loss of ozone in the 55° and 65°S latitude bands as well as at 55° and 65°N. Smaller long-term decreases occur at lower latitudes, but they are not evident before removal of the annual cycle from the time series.

Figure 2a shows the ozone time series from six latitude bands ( $\pm 55^\circ$ ,  $\pm 35^\circ$ , and  $\pm 15^\circ$ ) superimposed in pairs to show the interhemispheric phase and amplitude relationships. The  $\pm 55^\circ$  ozone variations are almost 6 months out of phase, corresponding to the interhemispheric seasonal differences in equator-to-pole transport of ozone. A comparison of midlatitude data shows an obvious additional phase shift relative to  $\pm 55^\circ$  of about 1.5 months during northern winter but almost no additional phase shift during northern summer. In the equatorial zone (from 20°N to 20°S) the ozone is nearly in phase for all seasons with approximately equal amplitude. An expanded view of the ozone time series for 5°N and 5°S is given in Figure 2b, which shows that the amplitude is smaller at 5°S than at 5°N for most years (there is a distinct change after 1988). At all latitudes the QBO effects on ozone are significant [see Herman *et al.*, 1991b], but there is a change from positive to negative correlation between the equatorial and midlatitude regions. The appearance of low 1992 and 1993 ozone values can be seen most easily in the northern hemisphere ozone amount data (Figures 1a, 1b, and 2a).

Figures 2a, 2b, 3a, and 3b show seasonal asymmetries in the ozone time series between the hemispheres at all latitudes between  $\pm 70^\circ$ . Three obvious asymmetries are (1) the different cyclic behavior of the equatorial region, which extends further north ( $\approx 25^\circ$ N) than it does south ( $\approx 15^\circ$ S); (2) the amplitudes of the annual cycles, which are smaller in the southern than in the northern hemisphere; and (3) the seasonal maximum ozone amount, which increases from the equator to the polar regions in the north but peaks at about 45°S in the south and then decreases toward the south polar region. The extreme springtime lows in 1987, 1989, 1990, 1991, and 1992 at 65°S correspond to the very low ozone values within the Antarctic ozone hole region during those years. The effects of the small ozone hole during spring 1988 (September and October) are visible in the 65°S zonal averages; very high ozone amounts followed during November, December, and January. Figures 3a and 3b combine the data in Figures 1a and 1b into a three-dimensional view of ozone amount versus latitude and time. This view emphasizes the much larger amounts of ozone at high latitudes in the northern hemisphere than in the southern hemisphere and the different behavior of the winter-spring equator-to-pole transport of ozone in each hemisphere.

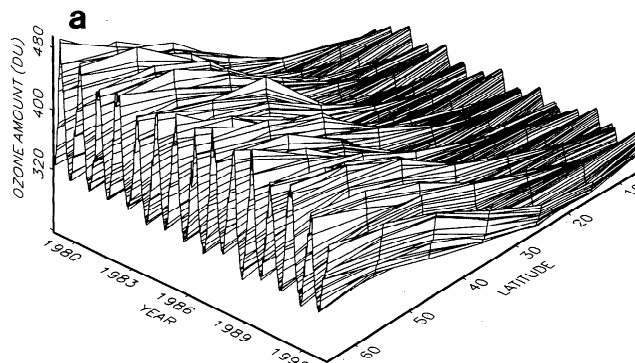
Between 45°S and 90°N, the largest rates of ozone loss occur during the winter and spring months, corresponding to the annual maximum in ozone amounts (see Figures 4 and 5). Until 1993, the winter-spring ozone losses had very little practical impact on long-term integrated exposure to UV radiation reaching the ground compared to the smaller ozone losses during the summer months. Ozone losses of a few percent per decade have not caused the middle- and high-latitude column ozone amounts to fall to values that are historically normal for lower latitudes. Even with the lower



**Figure 2.** (a) Ozone time series for the latitude bands centered on  $\pm 55^\circ$ ,  $\pm 35^\circ$ , and  $\pm 15^\circ$ , showing the approximately 6-month seasonal phase shift between northern and southern midlatitude ozone data and almost no seasonal phase shift near the equator. The ozone time series for the northern and southern hemispheres shift phase relative to each other with increasing latitude until by  $\pm 35^\circ$  they are 6 months out of phase. The darker lines are for the southern hemisphere. (b) Ozone time series for the latitude bands centered on  $\pm 5^\circ$ . The QBO effect is nearly the same size as the annual ozone variation. The darker lines are for the northern hemisphere.

1992–1993 ozone amounts, the ozone annual minima at northern middle and high latitudes still exceed the ozone amounts at low latitudes ( $0^\circ$  to  $20^\circ$ N) (see Figures 3a and 3b), where there have been no long-term losses.

In the southern hemisphere high-latitude regions ( $55^\circ$  to  $90^\circ$ S), ozone losses have been much larger. Because the south polar vortex wind system interrupts the equator-to-pole transport of ozone, southern hemisphere ozone amounts reach a maximum near  $45^\circ$ S instead of near  $90^\circ$ S as in the northern hemisphere. The result is that historical values for ozone amounts are almost 100 DU below high-latitude northern hemisphere values. This increases the importance of the large observed ozone loss rates during the high-latitude southern hemisphere spring, where current ozone amounts can be comparable to equatorial amounts. For example, at  $65^\circ$ S the amount of ozone decreased from about 325 DU during the 1979 minima to 250 DU during the 1992 minima. The corresponding decrease for  $55^\circ$ S is 320 to

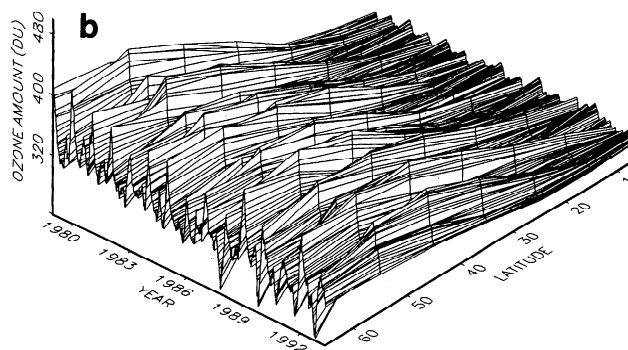


**Figure 3a.** Surface plot of the northern hemispheric zonal average ozone time series, showing relative magnitude and variability as functions of latitude and time (November 1, 1978, to March 31, 1993). The data are weekly averages.

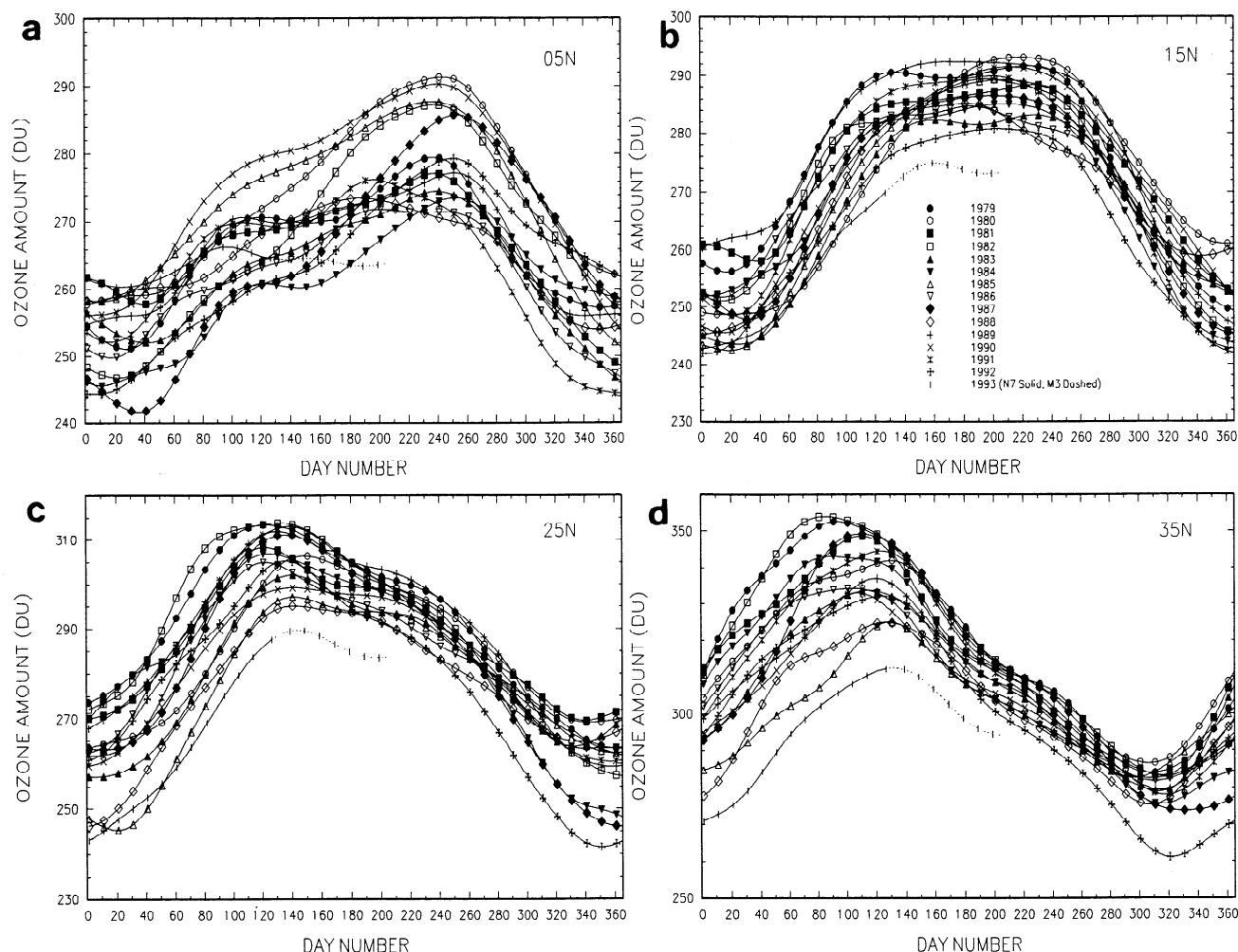
300 DU. The equatorial ozone amount at  $5^\circ$ S has been a nearly steady 250 to 260 DU from 1979 to 1993.

The alternating minimum-maximum seasonal behavior of ozone amounts at high latitudes outside of the Antarctic polar vortex region is mostly caused by transport of ozone from the equatorial to the polar regions along with seasonally dependent upward or downward motions arising from the temperature structure of the atmosphere [Reed, 1950; Tung, 1986; Mahlman and Fels, 1986; Rosenfield and Schoeberl, 1986; Rosenfield et al., 1987; Tung and Yang, 1988]. The reasons for the global ozone variation shown in Figures 3a and 3b are qualitatively well explained by the extensive discussions of Tung and Yang [1988].

Even though most of the stratospheric ozone is produced in the equatorial region, there is an equatorial relative minimum in total column ozone as a function of latitude. The minimum (shown in Figures 3a and 3b) is caused by transport of air away from the equator, driven by the large amount of radiative heating in the presence of low temperatures in the tropical lower stratosphere. The heating causes the air to rise and flow toward higher latitudes, where there is downward flow. This reduces the column ozone content in the equatorial regions and increases it at higher latitudes. The high-latitude seasonal dependence of the ozone amount is caused by variations in the diabatic circulation in the lower stratosphere that cause the downward circulation to be



**Figure 3b.** Surface plot of the southern hemispheric zonal average ozone time series, showing relative magnitude and variability as functions of latitude and time (November 1, 1978, to March 31, 1993). The data are weekly averages.



**Figure 4.** A comparison of the behavior of the zonally averaged annual ozone time series for 10°-wide latitude bands from 5° to 65°N (Figures 4a to 4g) and from 5° to 65°S (Figures 4i to 4o). Each part of the ozone time series is smoothed with a 50-day Fourier transform low-pass filter. Figures 4h and 4p are the area-weighted averages from 0° to 70°N and 0° to 70°S, respectively, constructed from the preceding latitude band plots. Day number 1 corresponds to January 1.

stronger in the winter than the summer. The diabatic circulation in the stratosphere above 20 km has a rising motion during the summer and a falling motion during the winter, with reversal occurring during the spring and fall.

When both the upper and lower stratospheric motions are downward, the high-latitude ozone tends toward a maximum. After the upper circulation pattern reverses along with a weaker lower circulation pattern, the transport of ozone to higher latitudes is reduced, leading to a minimum in ozone amount. According to *Tung and Yang* [1988], the low ozone values that occur in the Antarctic region during the southern hemisphere autumn are prolonged throughout the winter (see Figure 5a) by the presence of the polar vortex winds partially isolating the region from equator-to-pole ozone transport [see *Schoeberl and Hartmann*, 1991]. Since the equator-to-pole transport stops at the edge of the polar vortex region, the spring maximum caused by downward flow also occurs at latitudes near the vortex edge (see Figure 3b). Within the south polar vortex, the low winter ozone amount is further deepened into the Antarctic ozone hole during the spring by heterogeneous chemistry [*Solomon*,

1988, 1990], leading to conditions (large amounts of ClO and low amounts of NO<sub>2</sub>) that can rapidly remove ozone.

### Smoothed O<sub>3</sub> Time Series

In addition to zonal averaging, smoothing of the ozone time series in each latitude band can be used to reveal some of the general medium- and long-term variations in ozone amounts. The ozone time series are smoothed using a fast Fourier transform low-pass filter with a 50-day window (the smoothed ozone data are available from the authors upon request; 0.8 Mbytes). The 50-day window was selected to remove all short-term ozone variability while leaving the variation with periods of 1 month or longer. The following topics are discussed by using daily values of smoothed ozone data: (1) the day numbers of the ozone maxima and minima as a function of latitude; (2) the year-to-year ozone change as a function of latitude, day number, and year, with emphasis on the comparison of very low ozone values observed during 1991 to 1993 with those observed during previous years within 10° latitude bands from 65°S to 65°N; and (3) long-term ozone loss rates at the seasonal maxima and minima.

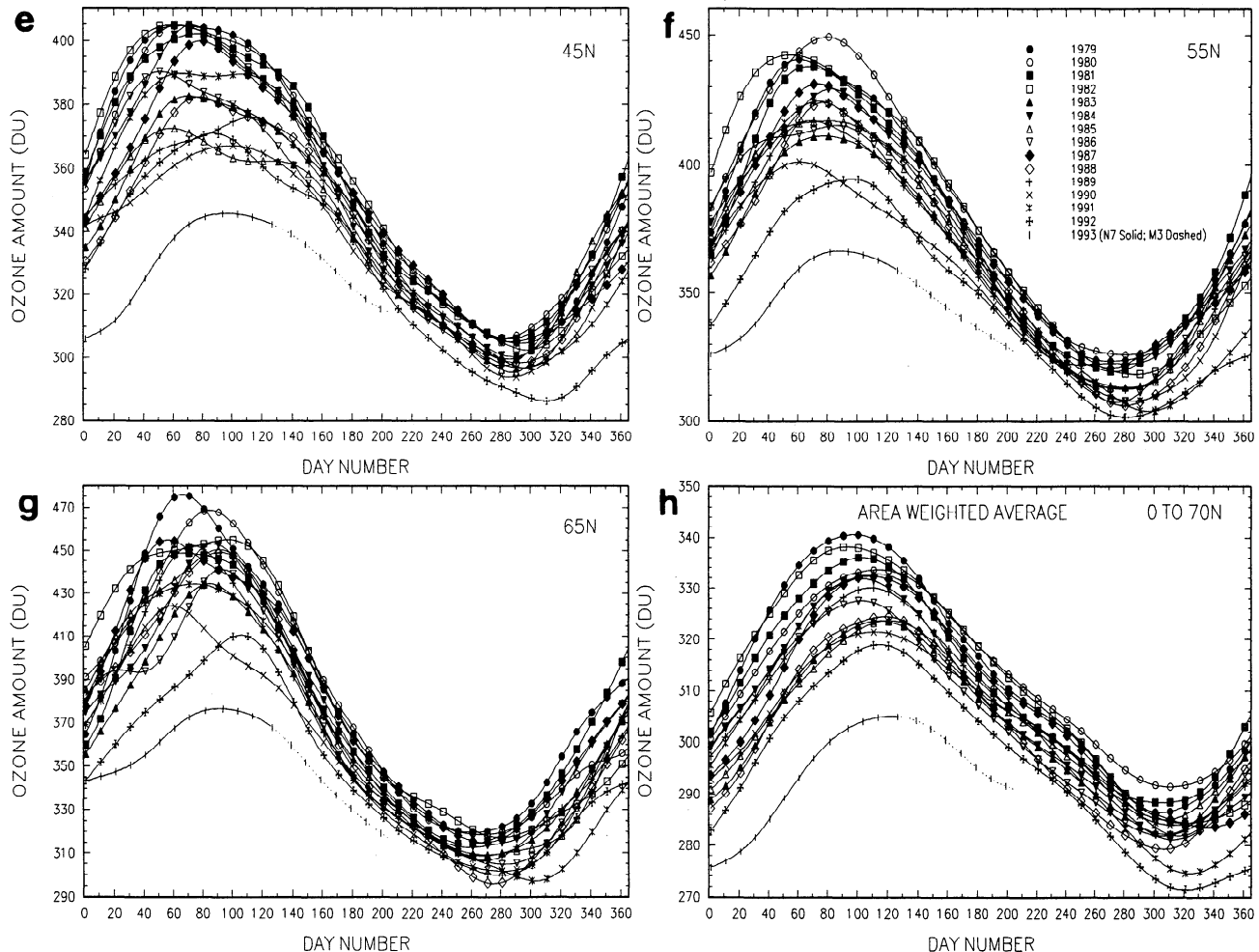


Figure 4. (continued)

The long-term zonal-average ozone time series in each hemisphere have maxima and minima about  $180^\circ$  (6 months) apart (see Figures 1–3). The specific day numbers for the maxima and minima depend on the latitude and year (see Table 1). For most latitudes, after smoothing there is a 1- to 2-week standard deviation about the average from year to year with no significant trend. Exceptions to this are mostly in the southern hemisphere and are caused by the rotation and shape changes in the springtime Antarctic ozone hole region. At  $65^\circ\text{S}$  there are no well-defined autumn minima near day 80 that correspond to the  $65^\circ\text{N}$  minima near day 270 (see Figure 4). At  $65^\circ\text{S}$  and to a lesser extent at  $55^\circ\text{S}$ , the irregular springtime ozone behavior is caused by the longitudinal rotation of the off-center, time-changing, oval south polar vortex wind system. The ozone amounts shown at  $65^\circ\text{S}$  in Figures 2b and 4 are near the edge of the polar vortex wind region. Since 1987, portions of the springtime Antarctic ozone holes have frequently extended into this latitude band, causing the large minima shown in 1987, 1989, 1990, 1991, and 1992. Prior to 1987, the extent of the Antarctic ozone within the 220-DU contour line was small enough that it did not extend into the  $70^\circ$  to  $60^\circ\text{S}$  latitude band. The boundary of the Antarctic ozone hole is selected at 220 DU to be near the center of the large ozone gradient between about  $80^\circ\text{S}$

and the region outside of the south polar vortex wind system.

At  $65^\circ\text{N}$ , the smoothed ozone amount variation is roughly sinusoidal (1-year period), with an average  $445 \pm 20$  DU maximum around day  $77 \pm 12$  (spring) and an average  $311 \pm 10$  DU minimum around day  $264 \pm 9$  (autumn), both near an equinox. For low latitudes ( $15^\circ\text{N}$  to  $30^\circ\text{S}$ ) the minima (south) and maxima (north) tend to have more variability and are less well defined (broader) from year to year than at higher latitudes. There is an asymmetry in the seasonal cycle between the hemispheres at low latitudes. The characteristic equatorial cycle extends further north ( $25^\circ\text{N}$ ) than south ( $15^\circ\text{S}$ ) (see Figure 4). The time series for the southern hemispheric latitude bands are more irregular than their northern counterparts. At midlatitudes ( $30^\circ$  to  $50^\circ$ ) the southern hemisphere behavior is similar to the northern hemisphere oscillating annual variability but is about 6 months out of phase. For those latitudes with well-defined minima and maxima, there have been no significant systematic changes in phase over the 1979 to 1993 period. Significant phase changes would be driven by systematic changes in the dynamical state of the atmosphere.

Before the beginning of 1992 and especially before the June 1991 eruption of Mount Pinatubo, the year-to-year

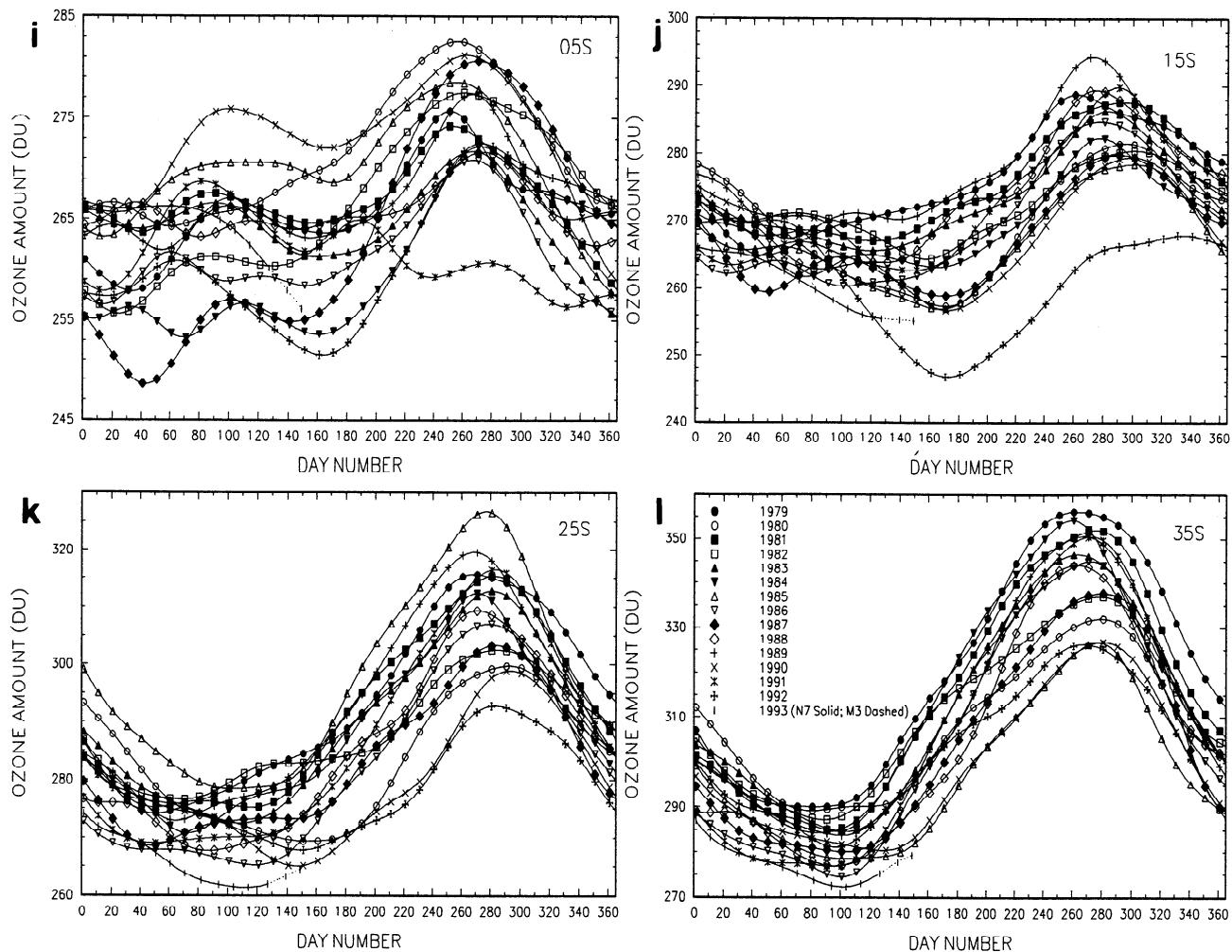


Figure 4. (continued)

ozone variation was within a fairly narrow envelope. Changes in ozone amounts between successive years can be a large fraction of the envelope width. However, these changes usually last for only a few months, take place within only a few latitude bands, and may be of opposite signs in different bands. For example, during 1990, ozone values were unusually low compared to those in previous years. At  $65^{\circ}\text{N}$ , ozone amounts were low from March to May 1990 and returned to values well within the envelope for the rest of the year. Similar behavior is seen at  $55^{\circ}$  and  $45^{\circ}\text{N}$ , but by  $35^{\circ}\text{N}$  the 1990 ozone values are near the middle of the envelope for most of the year. In the southern hemisphere the 1990 ozone values are within the envelope except briefly at  $25^{\circ}$  and  $15^{\circ}\text{S}$ . Within the region bounded by the Antarctic springtime polar vortex wind system, 1990 had exceptionally low ozone values compared with most previous years.

Over a longer time period, it can be seen that there has been an overall gradual downward trend in ozone amount at middle and high latitudes and no decrease near the equator (except immediately after the Mount Pinatubo eruption). The specific linear least squares rates of decrease for each latitude band and month have been discussed for the period from January 1979 to December 31, 1990 [Herman *et al.*, 1993]. Figure 5 and Table 2 also show the long-term (1979 to 1993) decrease in ozone amount calculated by following

changes at the times of the ozone maximum and minimum for each latitude band between  $\pm 65^{\circ}$ . The latitude and seasonal ozone amount decreases are consistent with those reported earlier by Stolarski *et al.* [1992a], Herman *et al.* [1993].

The panels in Figure 5 have been drawn with the same scale for corresponding northern and southern hemisphere latitudes to facilitate the comparison of absolute ozone amounts and loss rates (slopes). The hemispheric asymmetry in equatorial ozone amount can easily be seen in the panels for  $15^{\circ}\text{S}$  to  $15^{\circ}\text{N}$ . The northern ozone amount maximum to minimum amplitudes are larger than southern amplitudes, and the northern ozone amount minima are less than the southern minima. The small ozone loss rates between  $15^{\circ}\text{S}$  to  $15^{\circ}\text{N}$ , indicated in Table 2 and Figure 6, are within the error limits and are therefore not significantly different from 0. At  $25^{\circ}\text{S}$ ,  $35^{\circ}\text{S}$ ,  $25^{\circ}\text{N}$ , and  $35^{\circ}\text{N}$  the winter ozone amount maxima are approximately equal, as are the loss rates. For these four latitude bands, the minima in the north are less than the minima in the south. At  $45^{\circ}\text{N}$  the ozone loss rate is significantly higher than at  $45^{\circ}\text{S}$  (see Table 2). At higher latitudes the effects of the springtime Antarctic ozone depletion contribute to the observed loss rates. The result is that the springtime southern hemisphere rate at  $65^{\circ}\text{S}$  is about three times the rate at  $65^{\circ}\text{N}$ , while the summer-autumn rates are



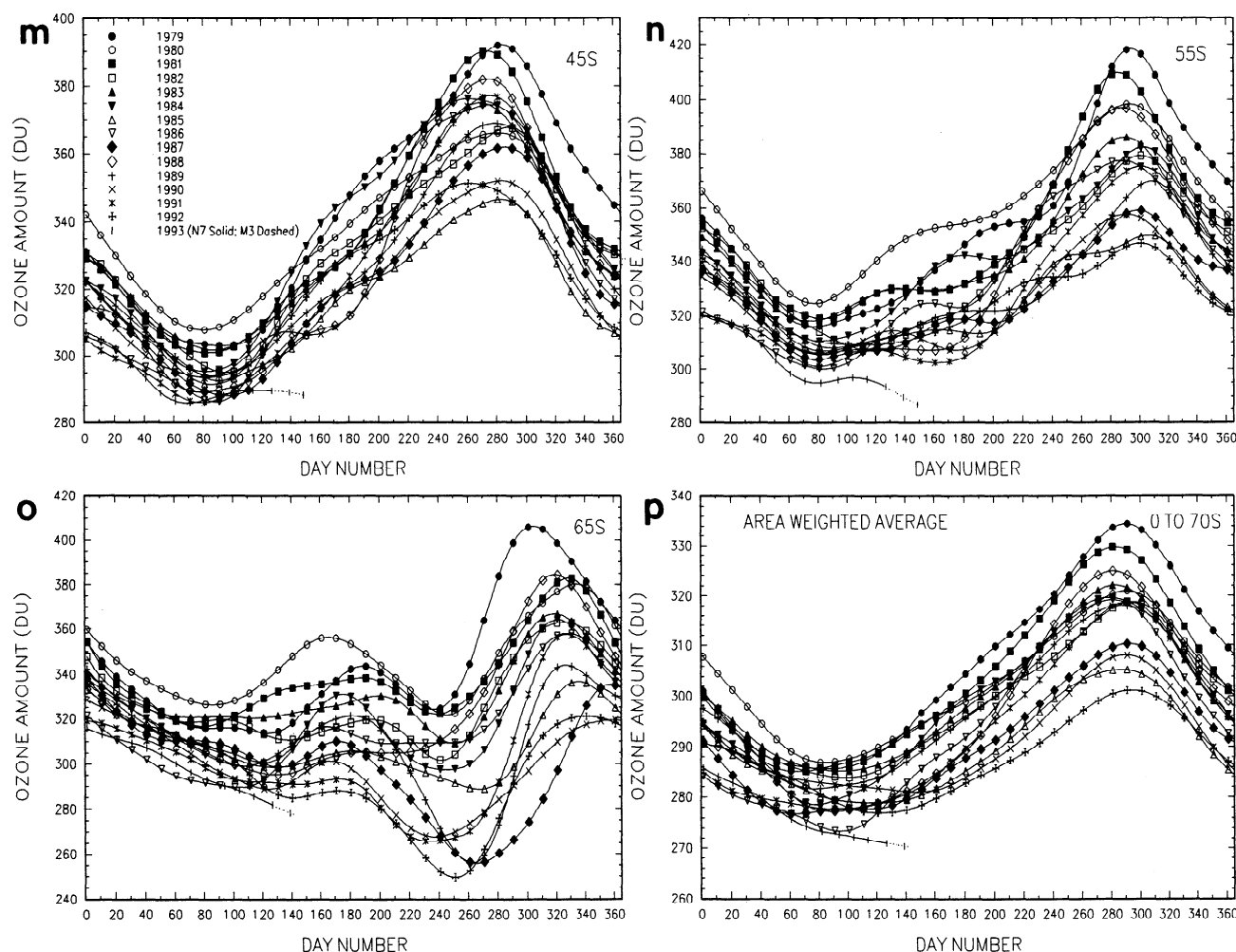


Figure 4. (continued)

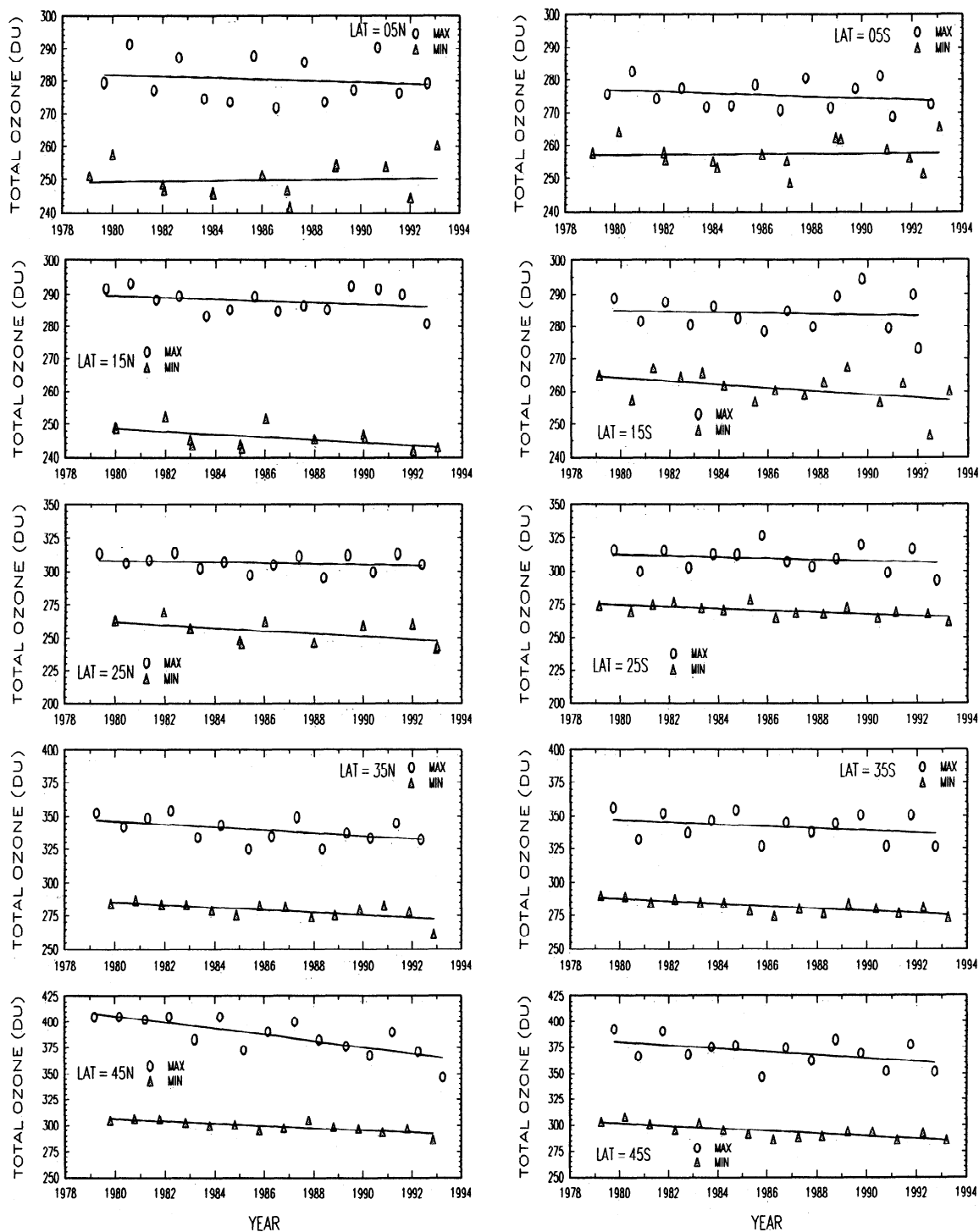
approximately comparable. If area-weighted averages are formed for the northern and southern hemispheres, then both the average ozone amounts and the rates of ozone loss are approximately equal within the range of their error estimates.

### 1992–1993 Ozone Decrease

After the beginning of 1992, the character of the annual ozone cycle appears to have changed so as to produce unusually low values over a wide range of latitudes and time. The result has been a large percentage decrease in the global average ozone amount below any values seen previously (see Figure 7) [Gleason *et al.*, 1993; Bojkov *et al.*, 1993]. The changes are correlated with but not necessarily caused by the global redistribution of aerosols from the June 1991 Mount Pinatubo eruption, the decreasing portion of the 11.5-year solar cycle, the current phase of the 2.3-year QBO, and the El Niño–southern oscillation (ENSO) [Zerefos *et al.*, 1992]. If the ozone time series for January 1979 to December 1991 are represented by a functional least squares fit composed of terms for the annual cycle, solar cycle, QBO, linear rate of decrease, and ENSO, the 1992–1993 observed ozone changes are larger than those predicted from the time series. Gleason *et al.* [1993] show an example of a comparison

between the observed data and the model prediction without the ENSO term, showing a difference that is much larger than expected. The accuracy of the Nimbus 7 TOMS ozone data used in the time series analysis has been assessed by comparison with data from other satellites (Meteor 3 TOMS and NOAA 11/SBUV 2) and from ground-based Dobson stations [Gleason *et al.*, 1993]. The Nimbus 7 TOMS ozone data have been shown to agree very closely with ozone amounts determined by Meteor 3 TOMS when the Meteor 3 polar orbit has equator-crossing times between 0900 and 1500 LT (i.e., not near the day–night terminator). Worst-case disagreements during the 1993 period were when the zonally averaged ozone data from Meteor 3 TOMS were 6 DU higher than Nimbus 7 TOMS data from near the terminator crossing of March 31, 1993, and 5 DU lower on January 15, 1993.

Since the end of the Nimbus 7 TOMS data record on May 6, 1993, the northern hemisphere ozone time series have been extended through July 1993 with preliminary Meteor 3 TOMS data (dotted extensions in Figures 4 and 7), using an extrapolated in-flight solar calibration. Even though the differences between the final and preliminary data are expected to be small, the accuracy of the preliminary Meteor 3 TOMS data has not been established since the last in-flight calibration period in March and April 1993. The dotted



**Figure 5.** Ozone amounts (in Dobson units) for each year computed from the seasonal maxima and minima within each  $10^\circ$  latitude band from  $65^\circ\text{S}$  to  $65^\circ\text{N}$  for the period from January 1979 to May 1993. The straight lines are linear least squares fits used to determine the trends listed in Table 2.

extensions are included only as indicators of the continuing low ozone values during the summer of 1993. During this time, Meteor 3 TOMS does not provide coverage of the southern hemisphere because of the location of its precessing orbit (212-day precession period).

The observed ozone amount decreases during 1992 are correlated with observations of elevated amounts of ClO at

high latitudes [Brune *et al.*, 1988; Levi, 1992] produced from increasing amounts of chlorofluorocarbons in the atmosphere and the presence of low temperatures in northern hemisphere winter and spring [Newman *et al.*, 1990]. The low temperatures are necessary for the formation of polar stratospheric clouds and the heterogeneous chemical processing of some of the high-latitude air to reduce the amount

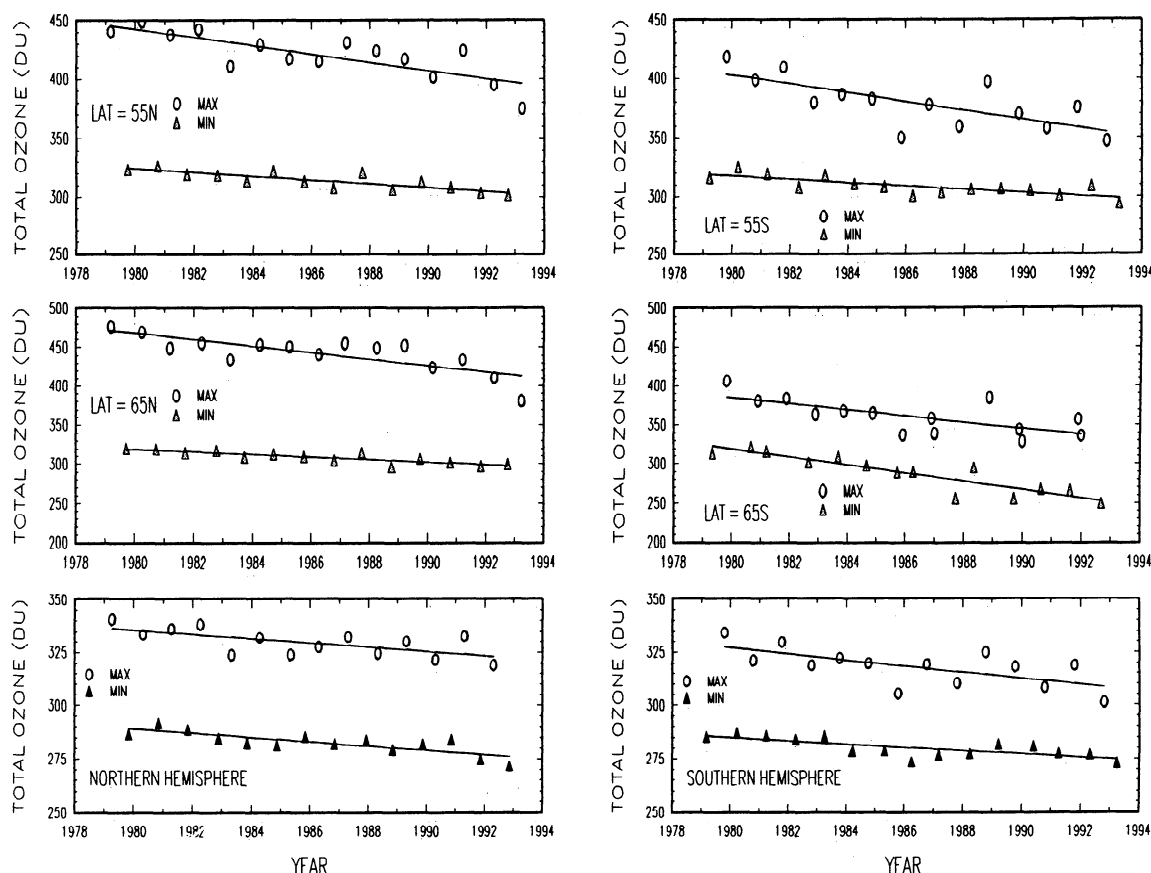


Figure 5. (continued)

of ozone. When heterogeneous chemical processes decrease the ratio of  $\text{NO}_2$  to  $\text{ClO}$ , the large amounts of  $\text{ClO}$  can readily remove ozone from the polar regions.

Recently, large quantities of  $\text{ClO}$  have been observed during the Arctic and Antarctic winters from the Upper Atmosphere Research Satellite (UARS) as reported by Waters *et al.* [1993]. According to Waters *et al.*, ozone destruction-associated high  $\text{ClO}$  in the northern hemisphere was limited because of a coincident lower stratospheric warming to temperatures above the polar stratospheric cloud limit. In

the southern hemisphere, ozone decreases were associated with the largest  $\text{ClO}$  concentrations, beginning in about mid-August. Waters *et al.* conclude that their  $\text{ClO}$  observations may imply increased ozone loss outside of the Antarctic

**Table 1.** Twelve-Year Average Latitude Dependence of Day Number With Standard Deviation for Ozone Maxima and Minima

Latitude	Mean Day Number $\pm$ Standard Deviation			
	North		South	
	Minimum	Maximum	Minimum	Maximum
65°	264 $\pm$ 9	77 $\pm$ 12	322 $\pm$ 13	none
55°	270 $\pm$ 10	69 $\pm$ 9	290 $\pm$ 8	87 $\pm$ 26
45°	284 $\pm$ 5	67 $\pm$ 15	272 $\pm$ 8	82 $\pm$ 7
35°	307 $\pm$ 8	105 $\pm$ 16	265 $\pm$ 8	89 $\pm$ 8
25°	361 $\pm$ 11	133 $\pm$ 17	273 $\pm$ 8	88 $\pm$ 36
15°	4 $\pm$ 8	198 $\pm$ 20	279 $\pm$ 13	110 $\pm$ 45

**Table 2.** Ozone Losses at Seasonal Maxima and Minima

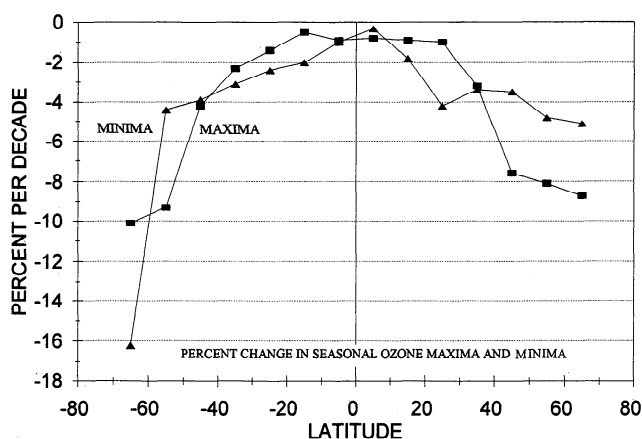
Latitude	$\text{O}_3$ Loss, %/Decade, $\pm 1\sigma$	
	Maximum	Minimum
5°S	0.9 $\pm$ 1.2	1.0 $\pm$ 1.3
15°S	0.5 $\pm$ 1.5	2.0 $\pm$ 1.3
25°S	1.4 $\pm$ 2.1	2.4 $\pm$ 1.0
35°S	2.3 $\pm$ 2.1	3.1 $\pm$ 1.0
45°S	4.2 $\pm$ 2.3	3.9 $\pm$ 1.1
55°S	9.3 $\pm$ 2.6	4.4 $\pm$ 1.2
65°S	10.1 $\pm$ 3.1	16.2 $\pm$ 2.3
Southern hemisphere	4.5 $\pm$ 1.6	2.6 $\pm$ 0.9
5°N	0.8 $\pm$ 1.8	0.32 $\pm$ 1.5
15°N	0.9 $\pm$ 1.1	1.8 $\pm$ 1.0
25°N	1.0 $\pm$ 1.5	4.2 $\pm$ 1.9
35°N	3.2 $\pm$ 1.8	3.4 $\pm$ 1.3
45°N	7.6 $\pm$ 1.8	3.5 $\pm$ 1.0
55°N	8.1 $\pm$ 1.8	4.8 $\pm$ 1.1
65°N	8.7 $\pm$ 2.0	5.1 $\pm$ 1.1
Northern hemisphere	3.1 $\pm$ 1.2	3.4 $\pm$ 1.0
Global average	2.8 $\pm$ 0.9	4.0 $\pm$ 1.0

tic region and that continued high levels of ClO may contribute to longer-term losses.

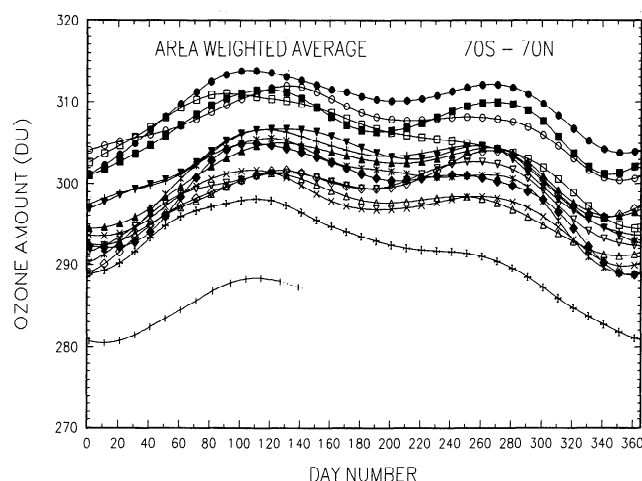
Figure 7 shows that the 1993 ozone amounts are 10 DU (3%) below the bottom of the historical envelope (1979–1991), or 5% below the historical mean. As was shown previously by Gleason *et al.* [1993], the low ozone values begin to deviate from the historical envelope in about March or April 1992. The ordering of the yearly values shows the generally steady loss of ozone between 1979 and 1993, with some deviations. In general, 1979–1982 are near the top of the envelope, 1983–1989 (excepting the low 1985 values) are near the middle, and 1990–1993 (excepting the high 1991 values) are near the bottom.

Figure 8 shows the global average trends (1979–1993) produced from the maxima and minima of the smoothed data shown in Figure 7. Because the global average ozone data tend to have two peaks, corresponding to the spring values in both hemispheres, the trends are computed from the usually larger maximum derived from the northern hemisphere spring ozone amounts. The minima are from December (winter and summer) in contrast to the autumn minima associated with the individual latitude bands. The rates of ozone decrease computed from the maxima and minima are  $2.8 \pm 0.9\%$  and  $4.0 \pm 1\%$  per decade without solar cycle corrections, respectively. The errors are  $1\sigma$  estimates, including both instrumental and least squares error estimates. These approximately agree with previous estimates [Herman *et al.*, 1991b; Stolarski *et al.*, 1991]. Because they occur in only 1 year of 14, the low ozone values in 1992 do not significantly affect the calculated trends.

At high northern latitudes ( $65^\circ\text{N}$ ) the ozone decreased well below the envelope of all previous ozone values measured by the Nimbus 7 TOMS instrument (January 1979 to December 1990). As is shown in Figure 4, the  $65^\circ\text{N}$  decrease started in September 1991 and continued through July 1993 (the



**Figure 6.** Total ozone amount loss rates (percent per decade) obtained from the smoothed seasonal maximum and minimum regression lines shown in Figure 5. The maxima are from late winter to early spring, and the minima are from late summer to early autumn. An exception is at  $65^\circ\text{S}$ , where the seasonal cycle is distorted by the low ozone values within the springtime Antarctic vortex wind system. Numerical values are given in Table 2 along with  $1\sigma$  error limits, including both instrumental and least squares error estimates.

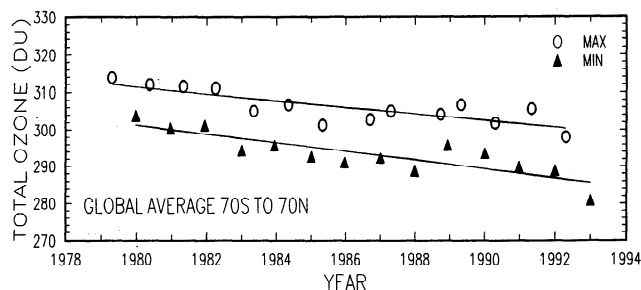


**Figure 7.** Smoothed ozone time series from an area-weighted average for the latitude range  $70^\circ\text{S}$  to  $70^\circ\text{N}$  for the years 1979–1993.

latest data available). By the end of the Nimbus 7 TOMS data record in May 1993, ozone values were about 50 DU below the bottom of the envelope. If the bottom of the envelope is taken to be about 400 DU, then the decrease is 12.5% below the previously observed variability. Extending the Nimbus 7 TOMS ozone data using preliminary Meteor 3 TOMS data indicates that the summer ozone values through the end of July 1993 are still outside of the historical envelope. Similar large decreases are seen from  $55^\circ$  to  $35^\circ\text{N}$  (see Figure 4), with a smaller decrease at  $25^\circ\text{N}$  starting in March 1993. At  $15^\circ\text{N}$  the 1992 values were low but within the normal range. Values at both  $15^\circ$  and  $5^\circ\text{N}$  appear to fall below the historical envelope, starting in March and July, respectively. There is a strong QBO influence in the equatorial zone that produces alternating years of low and high ozone amounts. During the present half of the 2.3-year QBO period, lower latitude ozone values tend to be higher than they were during the other half of the period. This may mean that low-latitude ozone values will again fall below the envelope during 1994. At higher latitudes the QBO effect is in the opposite direction, but the relative ozone amount change produced by the QBO is much smaller.

Ozone amounts in the equatorial latitude bands ( $10^\circ\text{S}$  to  $10^\circ\text{N}$ ) have not decreased outside of the historical envelope during the 1992 to 1993 period. The only decrease seen has been during the months immediately following the June 1991 Mount Pinatubo eruption (see Figure 4), when there were large amounts of injected  $\text{SO}_2$  and subsequent formation of  $\text{H}_2\text{SO}_4$  aerosols at altitudes near the ozone maximum. As the aerosol concentrations were reduced by redistribution to higher latitudes and lower altitudes, their effect on equatorial ozone decreased. Although the TOMS instrument is affected by the presence of aerosols near the altitude of the ozone maximum, it has been shown that the zonal averages have less than a 1% error induced by the aerosols [Bhartia *et al.*, 1993; Herman *et al.*, 1993].

In the southern hemisphere at high latitudes, the orderly pattern of maxima and minima is distorted by the development of the September–November Antarctic ozone hole. At its maximum extent, the ozone depletion region can extend



**Figure 8.** Change in the ozone amount (Dobson units) for the area-weighted 70°S to 70°N average computed at the seasonal maxima and minima (see Figure 7) for the period 1979–1993.

out to about 60°S, the edge of the oval, rotating (with approximately a 2-week period) south polar vortex wind system. At both 65° and 55°S, the ozone values dip below the historical envelope for part of 1992 and 1993. At 25°, 35°, and 45°S the ozone amounts are well within the envelope until February or March. In the 10°-wide latitude band centered on 15°S, the 1992 ozone decrease below the historical envelope (April–December) is about 11 (4%) of 270 DU, while the width of the envelope is about  $\pm 9$  DU (see Figure 4). The Nimbus 7 TOMS-derived 1993 values are again within the envelope. Because of the strong QBO effect at 15°S, the longer-term behavior will not be known until sometime in 1994. Meteor 3 TOMS did not provide ozone values in the southern hemisphere much beyond the end of the Nimbus 7 TOMS data record (May 6, 1993), because its 212-day-period precessing orbit was approaching the day-night terminator near the June 21 solstice.

The 1992–1993 reduction for the area-weighted global average ozone amount between  $\pm 70^\circ$  latitude has been discussed by Gleason *et al.* [1993]. Briefly, the ozone amount started to decrease in April of 1992 and has continued to decrease to the end of the data record near the beginning of June 1993. Figures 4h and 4p show the 1992–1993 reduction in ozone for the northern and southern hemispheres (0° to 70°) separately. Most of the 1993 ozone reduction is occurring in the northern hemisphere. In 1991, ozone reduction below the historical envelope (1979 to 1990) started in late August as an apparent direct response to the Mount Pinatubo injection of SO<sub>2</sub> into the stratosphere (25 km) and subsequent conversion of SO<sub>2</sub> into H<sub>2</sub>SO<sub>4</sub> aerosols. The panels for 5°S, 5°N, and 15°N show that the direct volcanic effect was mostly confined to these latitude bands and that it dissipated by the end of 1991. However, by April 1992 the ozone amounts were below the historical envelope within several latitude bands (15°S, 70°S, 35°N, 45°N, 55°N, and 65°N). For 55° and 65°N the ozone amount decrease started in September 1991 and continued into mid-1993. A possibility is that the Pinatubo eruption affected stratospheric temperature distribution enough to perturb the equator-to-pole ozone transport and cause the long-lasting high-latitude ozone decrease. During the winter and spring months, the low temperatures may have created conditions suitable for ozone destruction by heterogeneous chemistry acting on stratospheric particulates.

The year-to-year time series show that there has not been

an orderly progression from higher to lower ozone amounts even when the  $\sim 2.3$ -year QBO is taken into account. For the southern hemisphere spring, the lowest ozone values are in the years 1987, 1990, 1985, and 1992. The other years are grouped about 25 DU (about 8%) higher. For the northern hemisphere spring, the yearly progression is more orderly but shows a much larger decrease from 1992 to 1993 than between previous years.

## Conclusion

For the period November 1978 to May 1991, there was a steady, nearly linear decline in the amount of ozone over most of the globe, according to the data obtained from Nimbus 7 TOMS. Exceptions were at equatorial latitudes ( $\pm 10^\circ$ ), where almost no decrease was observed. During the past 2 years, July 1991 to May 1993, the rate of ozone loss has sharply increased. At high northern latitudes the 1993 ozone amounts were about 12.5% below the envelope of historical values, at midlatitudes they were about 7% below, and at low latitudes they were about 4% below. The first increased loss rates started during July in the equatorial zone after the June 1991 eruption of Mount Pinatubo [Chandra, 1993; Schoeberl *et al.*, 1993; Herman *et al.*, 1993]. There were also increased ozone losses at 55° and 65°N (and to a lesser extent at 45°N) that started in September 1991. The largest 1991 posteruption ozone decrease was observed at 5°S (0° to 10°S latitude band), with substantial decreases at 5° and 15°N (see Figure 4).

At 55° and 65°N the increased ozone loss rate started during February 1990 to May 1990. This implies either that changes in the equator-to-pole diabatic circulation occurred or that the increasing amounts of stratospheric ClO and lower temperatures have enabled ozone to be removed by heterogeneous chemical processes over a wide geographical area. During 1992 there were larger springtime losses of ozone in the northern hemisphere than during 1990. In the first half of 1993, the ozone amount decreased below the historical envelope over a wider latitude range, 20° to 70°N, encompassing most of the highly populated areas in the northern hemisphere. Use of the Meteor 3 TOMS preliminary data shows that the low ozone amounts are likely to have persisted in the northern hemisphere through the last data considered (July 1993). The area-weighted average of ozone amounts in the northern hemisphere shows that 1993 values are exceptionally low and widespread compared to values for all previous years since ozone observations started. However, current ozone values at northern middle and high latitudes are still above historically minimum ozone amounts in the equatorial and low-latitude regions (0° to 20°N).

Ozone losses in the months immediately after the Mount Pinatubo eruption were larger at low latitudes in the southern hemisphere (see Figures 4a and 4i) than in the northern hemisphere. During 1992 the largest change was at 15°S, smaller decreases occurred at 25°S, and almost no decreases below the historical envelope occurred at higher latitudes. During 1993 there have been small decreases below the historical envelope from 25° to 55°S. Compared with the northern hemisphere decreases, these are not particularly large. The area-weighted average of ozone amounts in the southern hemisphere shows moderately low values during the winter and spring of 1992 and values within the envelope

during the summer and early autumn of 1993. In the latitude band centered on 65°S, the long-term ozone losses are significant in that current values are below southern hemisphere equatorial ozone amounts.

Ozone trends computed from the seasonal maxima and minima of the annual smoothed time series are in approximate agreement with trends computed from the entire original time series. The ozone values at the summer minima decrease in a nearly linear manner with only a small variance, as is shown in Figure 5. Because of the increased atmospheric wave activity during the winter-spring ozone maxima, the variance about the linear least squares trend line is larger than the summer variance, but the ozone amount decrease appears to be linear.

Until 1992 the latitudinal average distribution of ozone and the latitudinal rates of decrease in ozone amount were symmetric between the hemispheres. Outside of the Antarctic ozone hole region, the largest seasonal ozone amounts and largest loss rates occur in the 40°–90°N latitude band during late winter and early spring. Except in the high-latitude southern hemisphere (65°S), the observed ozone decreases have not reduced ozone amounts below levels in the equatorial region ( $\pm 20^\circ$ ). Area-weighted averages (70°S to 0°, and 0° to 70°N) show that the overall hemispheric amounts of ozone and the average rates of decrease are approximately equal. Since the onset of large ozone losses in 1992, mostly in the northern hemisphere, there is no longer an average symmetry between the hemispheres.

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