out of the system (11 kg ha^{-1} $year^{-1}$). If we neglect input from forest renewal, stemflow, throughfall, and aerial dust, the annual average concentration of Si and Al in the solution that leaches the litterfall is 5.65 and 0.65 μmol $liter^{-1}$, respectively. In consideration of solubility diagrams (*31*), we find that such a water is supersaturated with Si with respect to kaolinite for a pH of 5.1 or greater.

Thus, geochemical modeling of soil formation and weathering in equatorial areas must be considered (Fig. 2). Topsoil inputs of elements, especially Si and Al, are significant. They are added mainly in fine litterfall, larger litterfall (tree and branch felling), throughfall, and stemflow. The last two fractions may include an appreciable amount of atmospheric dust transported from great distances (*32*). In the top meter of the soil, microbiological activity leads to a dissolution of soil minerals, which increases Si and Al concentrations (*33*). As the solution percolates through the soil, the Al and Si concentrations are mainly controlled by root uptake and mineral-solution interactions. Kaolinite is stable in the upper part of the soil, and gibbsite precipitates in depth. These interactions should be included in models of soil water and stream-water chemistry.

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Record Low Global Ozone in 1992

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The 1992 global average total ozone, measured by the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus-7 satellite, was 2 to 3 percent lower than any earlier year observed by TOMS (1979 to 1991). Ozone amounts were low in a wide range of latitudes in both the Northern and Southern hemispheres, and the largest decreases were in the regions from 10°S to 20°S and 10°N to 60°N. Global ozone in 1992 is at least 1.5 percent lower than would be predicted by a statistical model that includes a linear trend and accounts for solar cycle variation and the quasi-biennial oscillation. These results are confirmed by comparisons with data from other ozone monitoring instruments: the SBUV/2 instrument on the NOAA-11 satellite, the TOMS instrument on the Russian Meteor-3 satellite, the World Standard Dobson Instrument 83, and a collection of 22 ground-based Dobson instruments.

The Nimbus-7 TOMS (Total Ozone Mapping Spectrometer) has observed the amount and distribution of atmospheric total column ozone since November 1978. From 1979 to 1991, the amount of total column ozone has decreased over most of globe (*1–3*). Small (3 to 5%) losses at mid-latitudes, larger (6 to 8%) losses at high latitudes, and no losses near the equator were reported (*2, 3*). The most dramatic ozone decease has been observed each year in the springtime Antarctic ozone hole region (*4*) and the 1992 ozone amounts there were about 50% of the 1979 amounts.

For latitudes between 65°S and 65°N, the average area-weighted ozone loss rate for all seasons (1979 to 1991), after correction for solar cycle and quasi-biennial oscillation (QBO) effects has been estimated to be 2.7 ± 1.4% per decade (*1–3*). Analysis of the 13-year ozone data shows that most of the ozone depletion has occurred at mid- and high latitudes (*2, 3*). In this report we examine the decrease in the global daily average ozone amount from 1992 into 1993. We show that the observed decrease is consistent with measurements from other satellite and ground-based instruments.

The TOMS data show that the 1992 daily global average (65°S to 65°N) total ozone amount is significantly lower than in any of the earlier 13 years. The daily global average ozone value during 1992 falls 2 to 3% below the range of ozone values observed in any of the preceding 13 years (Fig. 1). The amounts were outside the earlier range starting in March, and reached a maximum of 4.7% below the daily mean of the earlier measurements near the end of December. The low values continued into January 1993 (Fig. 1). For the last 9 months of 1992, the daily ozone values were more than two standard deviations below the 12-year mean. In 1985 and 1987 the ozone amounts fell briefly, for 2 weeks, to the 2 standard deviation level, but the 1992 ozone decrease was much larger and of considerably longer duration.

The largest decreases in ozone amounts were observed in the regions from 10°S to 20°S and from 10°N to 60°N (Fig. 2). Outside of these bands, except near the equator, the amounts of ozone were at the lower edge of the range of values measured during earlier years. In the equatorial region, ozone amounts were near or above their climatological average. In contrast, during fall of 1991, ozone levels were unusually low in the equatorial region, and near the 12-year minimum between 45°N and 65°N. These low values may have been the result of changes in stratospheric circulation induced by the presence of aerosols from the Mount Pinatubo eruption (5). After November 1991, ozone amounts near the equator returned to normal values.

Some decrease in the 1992 global average ozone amount relative to the 1991 amount would be expected because the solar output has been declining during the current phase of the solar cycle, and because of the phasing of alternating high and low values of ozone associated with the QBO cycle (3). In addition to these cycles, there is a linear trend that has been estimated to be $-2.7 \pm 1.4\%$ per decade (*1–3*). A statistical model including the effects of the seasonal cycle, QBO, 10.7-cm solar flux cycle, and a linear trend accurately reproduces the observed ozone variation from 1979 to 1991 (*1–3*). For 12 years of data, 1979 to 1990, this model accurately predicts the 13th year, 1991. However, when we fit the data through 1991 (13 years) and used the model to predict amounts through the end of 1992, the observed values were 1 to 2% lower than the predicted values (Fig. 3). Thus, this statistical model that adequately describes the first 13 years of TOMS data failed to predict accurately the observed data in 1992.

We evaluated several possible sources of error in the TOMS data. Nimbus-7 is in a nearly sun-synchronous polar orbit that has

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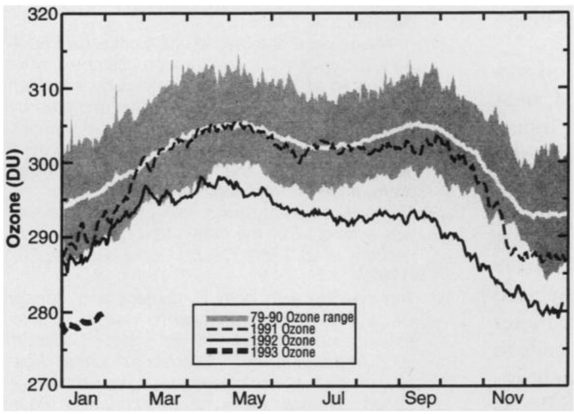


Fig. 1. Daily global average ozone amount (area-weighted 65°S to 65°N). The 1992 data are represented by the solid line. The range of ozone amounts for 1979 through 1990 are represented by the shaded gray area, and the daily average for the 12-year period is shown by the white line within the envelope.

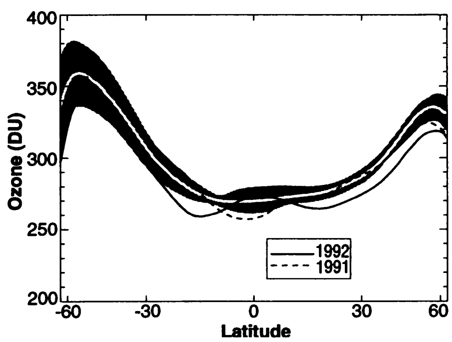


Fig. 2. Semiannual average zonal mean ozone amounts from 1 July to 31 December for 1991 (dashed line) and 1992 (solid line). The range of ozone amounts for 1979 through 1990 are represented by the shaded gray area and the daily average for the 12-year period is shown by the white line within the envelope. A 6-month average was chosen because it reflects a significant time period over which the global ozone is low.

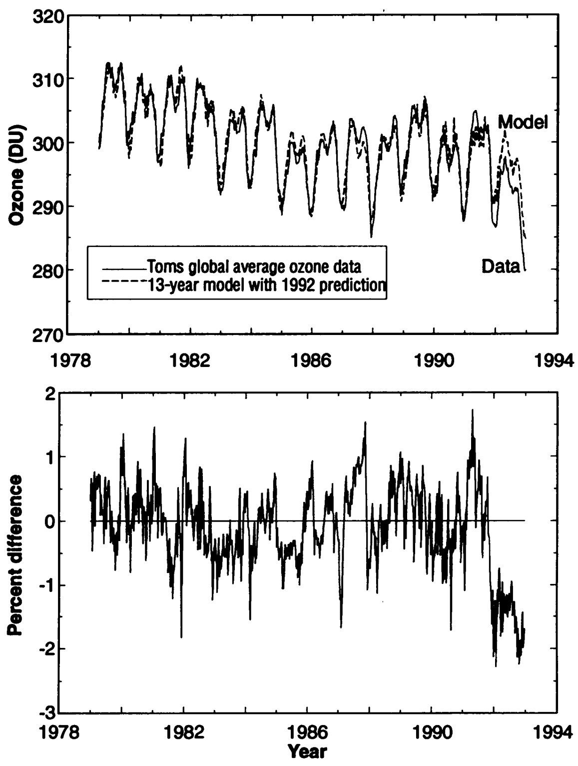


Fig. 3. (**Top**) The annual average ozone amount for the latitude range 65°S to 65°N for 1 January 1979 to 31 December 1992 shown as a continuous time series (solid line). Each data point is a 1-week average. The annual, solar, and QBO cycles are clearly evident. In addition to the measured ozone time series, a statistical model is shown (dashed line) fitted to the 1979 to 1991 time period and extrapolated for 1992. (**Bottom**) The percent difference between the measured global average ozone amount and the model.

slowly drifted from crossing the equator at noon to 10:45 a.m. over a period of 14 years. This relatively stable orbit means that observing conditions for Nimbus-7 TOMS have not changed significantly from year to year. The consistent observing conditions, and recent recalibration of Nimbus-7 TOMS (6), have permitted the determination of long-term trends in ozone amounts and relative year-to-year variation with high precision (*1–3*). The slow drift of the Nimbus-7 orbit, however, caused the diffuser plate used for in-flight instrument calibration to be partially shaded between February 1992 and September 1992. On 30 September 1992, the Nimbus-7 TOMS instrument reacquired the sun, and normal solar calibration procedures were resumed. For the period between February 1992 and September 1992 the TOMS instrument calibration was interpolated between the February and September solar measurements, and the interpolated calibration was verified by comparison with other satellite and ground-based instruments (see below).

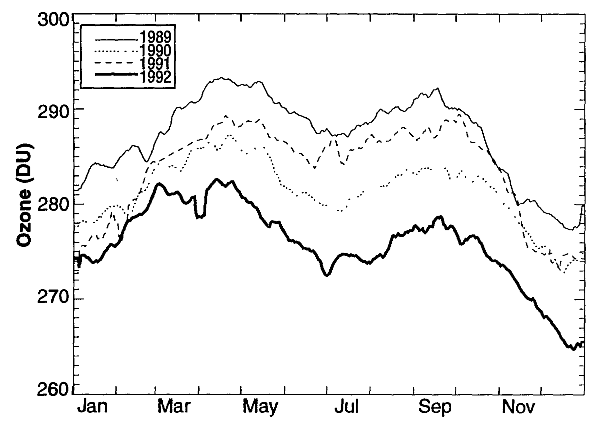
TOMS ozone data were affected by the stratospheric aerosol layer created by the eruption of Mount Pinatubo in June 1991. Radiative transfer calculations (*7*) show that a TOMS measurement at a single scan angle could have errors as large as 2% in low and mid-latitudes and up to 10% in high latitudes. However, these errors vary in both sign and magnitude over the range of scan angles. Their net effect is to cause a less than 1% overestimation of the zonal mean ozone in the low and mid-latitudes. At latitudes greater than 60°, the aerosol effect is less than 1% in summer, but it can cause a 5% underestimation of ozone amounts near the time of the winter solstice. We estimate that the overall effect of the aerosols on the global mean ozone shown in Fig. 1 is about 0.3%. We conclude that there has not been an undetected change in the instrument calibration or sensitivity to ozone amounts and that the observed ozone decrease is real and not caused by Nimbus-7 TOMS instrument error or artifact.

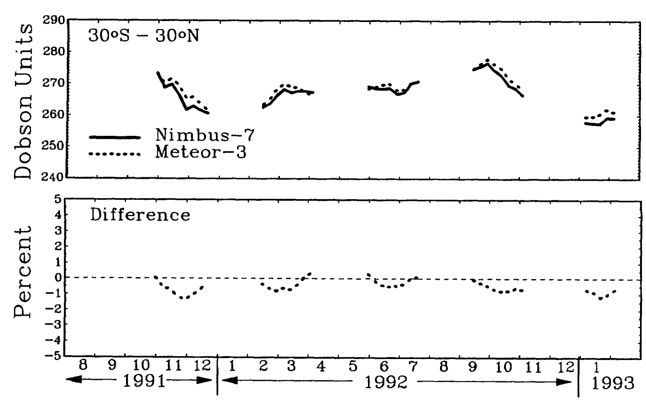
To confirm the long-term stability of the Nimbus-7 TOMS ozone data, we compared the data with similar ozone data sets from the NOAA-11 SBUV/2 (solar backscattered ultraviolet), from the Meteor-3 TOMS, and with data from the ground-based Dobson network. The SBUV/2 instrument, onboard the NOAA-11 polar orbiting satellite, measures ozone by the same backscattered ultraviolet technique as the TOMS instrument. This instrument, which has been operational since 1 January 1989, observes 12 ultraviolet wavelengths in order to measure both the ozone altitude profile and total column ozone amounts. From 1990 to 1992, evidence from the onboard calibration system suggests that the relative error of the SBUV/2 total ozone measurements is less than 1%.

As with the TOMS data, the SBUV/2 data are 2 to 3% lower in 1992 than in 1990, the previous lowest year (Fig. 4). In addition, the latitudinal distribution of the decrease in ozone amounts in 1992 observed by SBUV/2 is similar to the decrease observed by the TOMS instrument. This similar ozone decrease indicates that the TOMS calibration has not drifted significantly relative to the SBUV/2 calibration.

A second TOMS instrument is on the Russian Meteor-3 spacecraft, launched on 15 August 1991. Unlike the Nimbus-7, the Meteor-3 is in a precessing orbit with a 212-day period. As a result, the Meteor-3 TOMS data can be obtained with solar zenith angles comparable to those for Nim-

Fig. 4. Daily global average ozone amount (area-weighted 65°S to 65°N) from NOAA-11 SBUV/2. The 1992 data are represented by the thick solid line. The 1991 data are represented by the dotted line. The 1990 data are represented by the dashed line. The 1989 data are represented by the thin solid line.





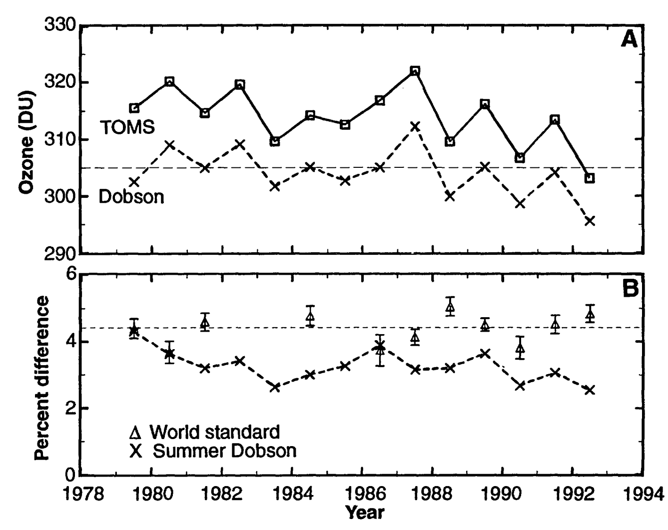


Fig. 5. (**Left**) Comparison of Meteor-3/TOMS and Nimbus-7/TOMS zonally averaged ozone data for latitude band 30°S to 30°N. The data are displayed from orbits with equator crossing times between 9 a.m. and 3 p.m. The lower plot shows the percent difference between Nimbus and Meteor for the same orbits. **Fig. 6.** (**Right**) (**A**) Comparison between TOMS and the average of 22 Dobson stations for the period from 1 June to 31 August for the years 1979 to 1992. The TOMS ozone amounts are for the nearest location to each Dobson station (within 1°) generated from the high-resolution TOMS data (50 by 50 km^2 at nadir view). The average time difference is 1 hour between the Dobson and TOMS observations. The dashed horizontal line is drawn at the 305 DU level to act as a visual aid. (**B**) The lower plot shows the percent difference between Nimbus-7/TOMS ozone amounts and average ozone amounts the World Standard Dobson Instrument and from the 22–Dobson station average. The dashed horizontal line is drawn at the 4.5% level to act as a visual aid.

bus-7 TOMS during periods when the Meteor-3 crosses the equator between 9 a.m. and 3 p.m. There have been five such periods of about 2 months each since its launch. During these periods (Fig. 5), the Nimbus-7 TOMS and Meteor-3 TOMS data show a consistent 1% bias. (In practice, the Meteor-3 TOMS data compare well with the Nimbus-7 TOMS data over a much wider range of equator crossing times.) The Meteor-3 comparison confirms that the interpolated calibration for the period February 1992 to September 1992 is accurate, and that the calibration did not shift in 1992.

The stability of TOMS is monitored relative to ozone observations made each summer at the Mauna Loa observatory with the World Standard Dobson Instrument 83 (I83) (8). The calibration of I83 has been maintained since 1962 to an accuracy of ±0.5% (9). These comparisons indicate that the TOMS ozone measurements have been stable relative to I83 to approximately 0.5% (Fig. 6). The TOMS-I83 comparison in July and August 1992 is consistent with the comparison in previous years. The I83 comparison is a good test of the aerosol sensitivity of the TOMS measurements. Dobson measurements, because they are done with a pair of wavelength pairs, are not sensitive to contamination by the presence of atmospheric aerosols. The consistency of the I83-TOMS comparison confirms our radiative transfer calculations that show that the aerosols have a small net effect on the TOMS measurement (6).

We also compared the TOMS data with a summer (June–August) average of 22 Dobson stations for which data were available through 1992 (Fig. 6). Only direct-sun Dobson observations were used, and all the data were adjusted to use the Bass and Paur ozone cross sections. Although there was a small trend in the TOMS-Dobson difference (possibly caused by increasing tropospheric ozone), there was not a significant change in 1992. The absolute offsets of 4.5% relative to I83 and of 3% relative to the 22-station average most likely result from an error in the original ground calibration of TOMS. Both the World Standard Dobson Instrument and the 22-station average confirm that the TOMS calibration in 1992 was consistent with that for earlier years and that the low observed ozone values are not a result of a shift in the instrument calibration.

In summary, the 1992 global average amount of ozone is 2 to 3% lower than the lowest values observed in earlier years. The largest 1992 decreases occurred during November and December, and were 3 to 4 standard deviations below the 12-year daily mean. The largest decreases occurred from 10°S to 20°S and 10°N to 60°N. Only in the equatorial region are the ozone values well within the envelope data from earlier years. It is significant that 1992 is the first time that ozone amounts observed by TOMS showed a simultaneous sustained decrease over a wide latitude range in both hemispheres.

The cause of the 1992 low ozone values is uncertain. Although the mechanism for ozone decrease is unknown, the understandable first guess would be that the decrease is related to the continuing presence of aerosol from the Mount Pinatubo eruption. There are three possibilities related to the presence of the aerosol: (i) direct chemical loss through increased heterogeneous processing (*10*); (ii) an aerosol-induced change in radiative heating which can directly affect ozone transport; or (iii) changes in photochemical production or loss rates caused by the temperature changes resulting from the aerosol heating. The size and timing of these potential effects of heterogeneous processing have been modeled by several groups (*11*). In general, these model simulations have not predicted the size or the timing of the observed ozone decreases for 1992 to 1993. Transport effects caused by aerosol-induced radiative heating were proposed (5) as the cause of the short-term tropical ozone loss observed immediately after the Mount Pinatubo eruption, but the mechanism responsible for the long-term ozone changes observed more than 1 year after the eruption remains unknown.

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Tectonics and Volcanism of Eastern Aphrodite Terra, Venus: No Subduction, No Spreading

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Eastern Aphrodite Terra, a deformed region with high topographic relief on Venus, has been interpreted as analogous to a terrestrial extensional or convergent plate boundary. However, analysis of geological and structural relations indicates that the tectonics of eastern Aphrodite Terra is dominated by blistering of the crust by magma diapirs. The findings imply that, within this region, vertical tectonism dominates over horizontal tectonism and, consequently, that this region is neither a divergent nor a convergent plate boundary.

Eastern Aphrodite Terra, the region on Venus between Alta and Thetis regiones, is approximately equal in size to the western North American cordillera, between Mexico and Alaska. This region on Venus is part of the Equatorial Highlands, which is characterized by large topographic relief and free-air gravity anomalies, intense tectonism, and volcanism (*1–3*). Its size and landforms make it an area important to the study of the tectonics of Venus. Using Pioneer Venus data, Schaber (4) suggested that this region recorded limited global extension, but others (5) proposed that it represents a zone of crustal divergence, analogous to terrestrial mid-ocean ridges. Data from the National Aeronautics and Space Administration–sponsored Magellan project have broadened the interpretation of this region. Eastern Aphrodite Terra has been interpreted as part of a circumglobal rift zone separating two major venusian

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