A Global Climatology of Total Ozone from the Nimbus 7 Total Ozone Mapping Spectrometer

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A global climatology of total column ozone has been computed from 4 years of daily observations by the total ozone mapping spectrometer aboard the Nimbus 7 polar-orbiting satellite. Observations were made at local noon; no observations are available in polar regions during the polar night. The orbital data have been area averaged onto a regular 5° by 5° latitude-longitude grid. The global coverage is more than 90% complete during the last 3 observing years (October 1979 to September 1982) and approximately 70% complete during the first year (October 1978 to September 1979). Global maps of the temporal mean and rms variance and the amplitude and phase of the annual and semiannual harmonics are presented. Similar analyses of the zonal mean values are given along with a time-latitude section of the zonal-mean total ozone. This climatology should be useful both for validating numerical models and for inspiring theoretical analyses.

INTRODUCTION

Because ozone strongly absorbs solar ultraviolet (UV) radiation through photodissociation, it provides an internal source of heat in the middle and upper atmosphere and forms a crucial link between atmospheric radiation, chemistry, and dynamics. For this reason alone the distribution of ozone in the atmosphere is of interest, but ozone serves a second important function: it protects living things at the earth's surface from the harmful effects of UV radiation. In recent years, concern has arisen that mankind may be affecting atmospheric ozone by releasing photochemically active substances, such as fluorocarbons or nitrous oxides, into the atmosphere. Because of the possible health effects, this concern has provided a very practical reason for studying the chemical and dynamical processes controlling ozone.

Observations of the ozone distribution in the atmosphere are needed for several purposes. The observed ozone distribution is used as an external parameter in some dynamical and radiative models, and in the lower stratosphere, where chemistry is less important than transport, ozone may serve as a tracer of atmospheric motions. Model studies of ozone itself require thorough and accurate observations of ozone and other chemically active species to verify that the models can reproduce the existing distributions of these constituents. Experiments may then be performed with the models to determine the sensitivity of ozone to various perturbations. A review of the current understanding of ozone transport and the annual cycle of ozone can be found in Rood [1983].

Ozone has been observed from the ground for many years with Dobson spectrophotometers, which measure the differential absorption of solar UV radiation at different wavelengths by the ozone [Dobson, 1931]. However, Dobson instruments are concentrated in northern hemisphere land areas and provide poor global coverage. In recent years, many new instruments have been developed to measure ozone both in situ and remotely. The ability to provide global coverage and the advantages of using a single instrument have led to development of several satellite-borne devices for measuring ozone. Hilsenrath et al. [1979], Hilsenrath and Schlesinger [1981], and Tolson [1981] have analyzed data from the backscattered ultraviolet (BUV) instrument on Nimbus 4. Because the BUV was a nadir viewer (nonscatterer), sampling was sufficient only to determine monthly and zonal means. The BUV data also have many hiatuses. Nimbus 4 also carried an infrared interferometric spectrometer (IRIS), from which temperature and total ozone in the stratosphere could be estimated [Prabha-kara et al., 1976]. Use of infrared wavelengths allows ozone retrievals at night, unlike the backscattered ultraviolet method, but the inversion of IR radiance data is considerably more difficult than the BUV measurements.

The Nimbus 7 satellite carries two BUV instruments: the solar backscattered ultraviolet spectrometer (SBUV), a nadir viewer, and the total ozone mapping spectrometer (TOMS), a scanner. Vertical profiles of ozone and total column amounts have been obtained from the SBUV [Nagatani and Miller, 1984; McPeters et al., 1984]. The TOMS instrument measures only total ozone but provides high spatial resolution. This paper presents a global climatology of total ozone based on the 4 years of TOMS measurements processed to date. The global coverage and sampling frequency of this data is superior to anything currently available.

METHODS

The TOMS Data Set

Nimbus 7 was launched in October 1978 in a near-polar, sun-synchronous orbit and makes approximately 13.8 orbits per day. TOMS observations are made on the ascending node of the orbit at ground times near local noon. The TOMS scans perpendicular to the orbit track to provide measurements over the entire sunlit portion of the earth once per day. Because the instrument measures backscattered solar radiation, no measurements are available in regions of polar night. The diameter of the field of view ranges from 50 km at nadir to 250 km in the farthest off-nadir scan tracks. Because the length of the scan across the orbital track is ~3000 km, scan swaths from different orbits overlap in middle and high latitudes, allowing multiple measurements during 1 day.

The spectrometer measures the intensities of direct and backscattered solar ultraviolet radiation in six wavelength channels. Two channels free of ozone absorption are used to determine the effective background albedo. The remaining

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four channels are used in pairs to provide two estimates of the total column ozone by the differential absorption method. The algorithms used to compute the total ozone are described in Fleig et al. [1982] and addenda.

For this analysis of the large-scale features the ozone data were area averaged onto a regular 5° latitude by 5° longitude grid from higher-resolution gridded data [Huang and Lee, 1983]. For each day in the observing period, each 5° by 5° grid cell was assigned an ozone value $\Omega$ and a weight $w$. All ozone values are in Dobson units (milli-atmosphere centimeters). The weight is the area within each cell for which measurements are available on that day. If there were no good measurements, $w$ was set to zero, and $\Omega$ was left undefined. Ozone values were not interpolated in either space or time. All of the available data has been used in the analyses shown in the following sections.

Intercomparison of the TOMS data with ground-based ozone measurements has shown the precision of the TOMS retrievals to be better than 2% [Bhartia et al., 1984]. On the average the TOMS measurements are 6.6% smaller than Dobson spectrophotometer measurements. Most of the bias appears to be caused by differences in the ozone absorption coefficients used to calculate the ozone amounts. Processing and calibration differences exist between data years but are less than 1%.

The observing year for this study runs from October 1 to September 30. Four years of gridded data are presently available (October 1978 through September 1982). The fraction of the globe for which measurements are available on each day in the 4-year period is shown in Figure 1. Only one day of data is available during October 1978. From October 31, 1978, through June 12, 1979, the TOMS was operated approximately 5 days out of 6. During June 1979, the instrument was inoperative for 6 consecutive days (June 13–18). After
June 19, when the instrument began to function again, it was operated continuously. Therefore from July 1979 to the end of the data set the data coverage is very high. The semiannual periodicity apparent in Figure 1 after the first observing year is caused by the loss of data during the alternating polar nights in the two hemispheres.

The spatial coverage of the data for the entire 4-year period is shown in Figure 2. The major systematic features are the decrease in data availability toward the poles caused by the polar nights and the oval region of lower data availability straddling the dateline. This oval feature is an artifact of gridding the data onto daily maps by whole orbits. The highest data availability is in middle latitudes, where multiple measurements during 1 day are possible and no polar night occurs.

**Statistical methods**

Area-weighted zonal means $\Omega_j$ and global means $\bar{\Omega}$ were computed by using the standard formula for weighted means:

$$[\Omega_j] = \frac{\sum_i w_{ij} \Omega_{ij}}{\sum_i w_{ij}} \quad (1a)$$
RMS DEVIATION OF DAILY OBSERVATIONS (DU)

Fig. 4. Root mean square deviations of the daily values of total ozone from the time mean (Dobson units).

\[ \Omega = \sum_{i} \sum_{j} w_{ij} \Omega_{ij}/\sum_{i} \sum_{j} w_{ij} \]  

where \( i \) is the longitude index and \( j \) is the latitude index.

The time mean ozone amount and the amplitudes and phases of periodic components of the ozone variations were estimated by assuming that the time dependence of \( \Omega \) could be represented by

\[ \Omega(t_n) = \Omega_0 + \sum_{n=1}^{L} \Omega_n \cos(\omega_n t_n - \phi_n) + \epsilon_n \]  

where \( n \) is time index, \( \ell \) is the harmonic number, \( \omega_n = 2\pi/1 \) year, and \( \epsilon_n \) is the residual error. The residual errors are assumed to have zero mean and to be uncorrelated in time. The amplitudes \( \Omega_n \) and phases \( \phi_n \) were calculated with a weighted least squares method by minimizing the total weighted squared error

\[ E_L^2 = \sum_{n} w_n \epsilon_n^2 / \sum_{n} w_n \]

This curve-fitting approach allows for the irregular distribution of missing data; as a result the weighted cosine basis functions are not orthogonal over the domain \( t_n \). Therefore, adding new harmonics changes the amplitude and phase of the other components slightly. Harmonics higher than the semiannual were found to contribute very little to the total variance, so results presented are for \( L = 2 \). The contribution of higher harmonics will be discussed below. Outside the tropics the autocorrelation time of the residuals is much shorter than the semiannual period. Because these time scales are well separated, (2) should be valid for estimating the annual and semiannual harmonics. Anomalies persist longer in the tropics, which renders the assumption that the residuals are uncorrelated less realistic, but the annual and semiannual harmonics still appear to be well defined.

Confidence intervals for \( \Omega_0 \), \( \Omega_n \), and \( \phi_n \) can be calculated with standard formulas [Anderson, 1971] by assuming that no data are missing. This assumption is valid outside of the polar regions, where generally less than 10% of the data are missing. In polar regions the systematic loss of data in the winter probably produces much larger errors than those caused by sampling, so error bars have been omitted poleward of 70° latitude.

RESULTS

Global Fields

A global map of the time-mean total ozone \( \Omega_0 \) is plotted in Figure 3. For comparison the time-mean total ozone as interpreted by London and Oltmans [1978/1979] from Dobson and M83 observations is reproduced in Figure 3.

The TOMS analysis shows a number of features that differ from ground-based analyses of total ozone. These differences may have a number of sources: (1) errors in either the TOMS instrument or retrieval algorithm or in the Dobson/M83 measurements, (2) subjective errors in the hand analysis of the ground-based measurements, (3) sampling errors, or (4) a real change in the ozone content between the observing period of the ground-based measurements (1957–1975) and that of the TOMS (October 1978 to September 1982). Because the results of Bhartia et al. [1984] indicate small relative errors between the TOMS and the Dobson/M83 measurements, source 1 should not be the cause of the differences seen in Figure 3. Systematic errors in the same direction may remain in both data sets. Source 2 is very difficult to judge and is closely tied to the poor spatial sampling of the Dobson and M83 networks (source 3). Spatial and temporal sampling errors (source 3) should not be a problem with the TOMS. The possibility of a real change in the ozone content of the atmosphere (source 4) can only be determined by analysis of the ground-based observations spanning the entire time period 1957–1982. In view of the known difficulties of intercalibration and spatial coverage with the Dobson and M83 networks, the TOMS instrument should provide a much better estimate of the global distribution of total ozone.
Fig. 5. (a) Amplitude $\Omega_1$ (Dobson units), (b) phase $\phi_1$ (months after January 1), and (c) fraction of the total variance explained by the annual harmonic (%).

Fig. 6. (a) Amplitude $\Omega_2$ (Dobson units), (b) phase $\phi_2$ (months after January 1), and (c) fraction of the total variance explained by the semiannual harmonic (%).
The TOMS analysis is more nearly zonally symmetric in middle latitudes than are the analyses of London and Oltmans [1978/1979] or Wilcox et al. [1977, Figure 1]. The ridges over the oceans and central Asia and the corresponding troughs over the continents are diminished in the TOMS map. The TOMS map shows distinct drops in total ozone over mountains, reflecting the decrease in the atmospheric column. The three analyses have a similar maximum over the Canadian Arctic. The distinct ozone maximum over Europe observed from the ground is not seen in the TOMS analyses. The Asian maximum is present in all three analyses but differs in position and strength.

The southern hemisphere ozone distribution is dominated by a large wave number 1 near 60°S, which is also the latitude of the maximum of the zonal mean. There is a minimum over the highest part of the Antarctic continent, not over the pole, but values south of ~70°S are unreliable because of the low solar zenith angles and the loss of data during the southern hemisphere winter. This will be discussed further below for the zonal mean values. Once again the large ridges over the southern hemisphere oceans seen in the London and Oltmans [1978/1979] map are not present in the TOMS map.

The rms deviation of the available daily measurements from the time mean is plotted in Figure 4. The variance is minimal just south of the equator and increases poleward in both hemispheres. The total variance is consistently larger in middle and high latitudes of the northern hemisphere than in the southern. Because the confidence intervals for the time mean and the harmonics are proportional to the variance, which is nearly zonally symmetric, they have not been plotted. The 99% confidence interval for the time mean increases from about ±0.4 DU (Dobson units) near the equator to ±2.3 DU at 70° latitude. Confidence intervals for the harmonic amplitudes are ±0.6 DU near the equator and ±4 DU at 70°. Confidence intervals for the phases of the harmonics are small (~10 days), except in a few regions where the amplitude of the harmonics nearly vanishes (see below).

The amplitude, phase, and fraction of the variance explained by the annual harmonic \( \Omega_a \) are plotted in Figure 5. In the northern hemisphere, \( \Omega_a \) increases nearly uniformly away from the equator. There are two regions with large annual variations over the Sea of Okhotsk and the Canadian Arctic. Both are located coincident with maxima in the time mean ozone. The minimum of \( \Omega_a \) is located at about 10°S. The maximum of \( \Omega_a \) in the southern hemisphere is also co-located with the maximum in \( \Omega_a \). There is a very low minimum in \( \Omega_a \) straddling the Antarctic peninsula.

The annual harmonic in the northern hemisphere reaches a maximum in late winter to early spring. The earliest maximum occurs where the amplitude is largest—over the Sea of Okhotsk. The phase of the annual harmonic increases southward across the equator, so that maxima in the southern hemisphere also occur in winter to early spring. Phase is difficult to determine near the poles, but there appear to be large differences between the annual harmonics in the Arctic and Antarctic regions. The annual harmonic explains a large fraction of the variance over much of the earth, especially in the northern hemisphere tropics.

The amplitude, phase, and fraction of the variance ex-
plained by the semiannual harmonic are shown in Figure 6. The amplitude $\Omega_2$ is flat throughout the tropics and generally increases toward the poles. At high latitudes the semiannual harmonic becomes very unreliable because of the large amount of missing data and is probably largely an artifact of the analysis method. Hopkins [1975] has suggested that the semiannual harmonic in the tropics results from the absorption of equatorward propagating planetary waves at the zero wind line. The total ozone shows no evidence for a maximum in the amplitude of the semiannual harmonic in the tropics, although such a feature could occur locally in the vertical. The maximum in the fraction of the variance explained over Asia appears to be associated with a real maximum in the amplitude of the semiannual harmonic, but the maxima over the Indian Ocean stretching toward the west and over the Weddel Sea appear to be caused by the absence of a strong annual harmonic (Figure 5).

Zonal Means

The annual evolution of the zonal mean ozone $\Omega$ is shown in Figure 7. The field has been smoothed slightly by computing 10-day means from the daily zonal means. This cross section is quite similar to that given in D"utsch [1974] and the BUV data from Nimbus 4 analyzed by Hilsenrath et al. [1979] and Tolson [1981].

At each latitude the daily, zonal mean values were expanded in temporal harmonics by using (2). The time mean $\Omega_0$ and the rms deviations of the daily values around the time mean are shown in Figure 8. The 99% confidence intervals are less than 1% of the time-mean zonal means at all latitudes. The confidence limits have been omitted from Figure 8 because the probable systematic uncertainties are larger. The hemispheric asymmetries notable in Figure 7 are also apparent in the time means. Both the means and the variances are larger in the northern hemisphere. The tropical minimum occurs several degrees south of the equator, and the minimum in the variance occurs slightly south of that.

Hemispheric differences, especially those in high latitudes, can be seen more clearly in Figure 9, in which the climatological daily ozone values are plotted for selected latitudes. Superimposed are the fits achieved at each latitude with two harmonics. Time means have been removed. In northern high latitudes the ozone peaks in late winter to early spring and then declines steadily through the sunlit portion of the year. Near the south pole the ozone remains low at the equinox and rises abruptly about 1.5 months later. It then falls through the last half of the sunlit period. This springtime rise was identified by Dobson [1966] in ground-based measurements from the Antarctic.

The few nighttime measurements available from the Antarctic indicate a slight secondary peak in May or June [Dobson, 1966; Chubachi, 1984]. However, the exaggerated peak in the fitted curves seen during the polar night in the southern hemisphere is caused by the large gap in the data and the abrupt springtime rise. The annual cycle in the northern hemisphere is much more easily fit by two harmonics.

The structures of the annual and semiannual harmonics of the zonal mean ozone and the 99% confidence intervals are shown in Figure 10. The percentage of the total variance explained by each harmonic is shown in Table 1 for the first four harmonics. Outside of the south polar region, two harmonics seem to capture the annual cycle of the zonal mean ozone very well. The spatial filtering of smaller scale features by zonal averaging has also removed much of the higher-frequency variability associated with planetary- and synoptic-scale waves. Therefore the annual and semiannual harmonics explain a larger fraction of the variance of the zonal means than of the two-dimensional gridded data.

The difference in the structure of the annual harmonic in the two hemispheres, especially poleward of 50°, is certainly
Fig. 10. (a) Amplitude of the annual and semiannual harmonics [Q]_1 and [Q]_2; (b) phase of the annual and semiannual harmonics [φ]_1 and [φ]_2; and (c) fraction of the total variance of the zonal means explained by the annual harmonic and the sum of the annual and semiannual harmonics.
real, as can be seen clearly in Figure 7. The harmonic amplitudes and phases from TOMS results agree quite well with the Nimbus 4 BUV results of Hilsenrath et al. [1979] and Tolson [1981]. Together the annual and semiannual harmonics explain between 50% and 95% of the variance of the zonal means. The third harmonic contributes substantially only in high southern latitudes, where the sudden springtime rise would produce a broad spectrum. The fourth harmonic is essentially negligible everywhere. The lowest explained variance is found in the tropics, where the total variance is small, the annual and semiannual cycles are weak, and a contribution to the variance from the quasiennial oscillation could be expected.

**Global Means**

Global means are biased by the absence of measurements in the polar night, where ozone values average about 10% higher than the global mean. Since the missing area comprises, at most, 10% of the globe, the estimates of the global mean values in Table 2 should be on the order of 1% low. Confidence intervals are not included because of the systematic nature of the missing data. The harmonics are dominated by the larger amplitude of the variations in the northern hemisphere. As a result the maximum of the global mean ozone occurs ~1 month after the vernal equinox, with a smaller maximum near the autumnal equinox.

**TABLE 2. Time-Mean and Annual and Semiannual Harmonics of the Global-Mean Total Ozone**

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Amplitude, Dobson units</th>
<th>Phase, months after January 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>288.1</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>4.7</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>3.9</td>
<td>--</td>
</tr>
</tbody>
</table>

**DISCUSSION**

The TOMS instrument has provided a valuable addition to our knowledge of the distribution of ozone in the atmosphere and its annual cycle. Observations continue to be collected at the present time, and further analysis should improve our understanding of the variability of ozone on both short (daily to weekly) and multiyear time scales. The TOMS instrument also resolves features at spatial scales much smaller than is possible with SBUV instruments, both the one on Nimbus 7 and those planned for the NOAA operational satellites. This should allow more detailed study of transport of ozone by eddies in the lower stratosphere and an evaluation of the errors in SBUV results caused by the poorer spatial and temporal sampling by the SBUV instrument. The latter question is certainly important for long-term trend monitoring with the SBUV.

Sufficient measurements have now been collected to reduce the sampling errors of the time mean and of the annual and semiannual harmonics caused by short time-scale variability to less than the accuracy of the instrument. Outside the polar regions the structure of the annual and semiannual harmonics is well determined. Because the large-scale and low-frequency features of the ozone are so well described by the annual and semiannual harmonics, the ability of numerical models to reproduce this behavior could be a good test of the models' accuracy.

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