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Seasonal and Interannual Variations in Total Ozone Revealed by the Nimbus-4 Backscattered Ultraviolet Experiment

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National Aeronautics and
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ABSTRACT

The first two years of Backscattered Ultraviolet (BUV) ozone data from the Nimbus-4 spacecraft have been reprocessed. The seasonal variations of total ozone for the period April 1970 to April 1972 are described using daily zonal means in 10° latitude zones and a time-latitude cross section. In addition the BUV data are compared with analyzed Dobson data and with IRIS data also obtained from the Nimbus-4 spacecraft. A harmonic analysis was performed on the daily zonal means. Amplitudes, days of peaks, and percentage of variance were computed for annual and semi-annual waves and for higher harmonics of an annual period for the two years. Asymmetries are found in the annual waves in the two hemispheres, with a subtle interannual difference which may be due to changes in the general circulation. A significant semi-annual component is detected in the tropics for the first year, which appears to result from influences of the annual waves in the two hemispheres.

SEASONAL AND INTERANNUAL VARIATIONS IN TOTAL OZONE REVEALED BY THE NIMBUS-4 BACKSCATTERED ULTRAVIOLET EXPERIMENT

INTRODUCTION

The Nimbus-4 spacecraft was launched April 8, 1970 carrying the Backscattered Ultraviolet (BUV) Spectrometer for measurements of the columnar amount of ozone and the vertical distribution above 30 km. The BUV continued to operate until October 17, 1977 when it was turned off because of insufficient spacecraft power. The initial data was analyzed and reported by Krueger (1974) and Ghazi (1976) as well as by others. These early analyses used existing instrument calibrations and orbital engineering data. In addition, the satellite-measured total ozone values were adjusted using a linear regression relationship developed from direct comparison of BUV measured values and Dobson values. Because of the recently recognized importance of the BUV data set, a task was initiated to reprocess the data and to continue processing the available data until the time the instrument was turned off. The general objectives of the reprocessing activity were the following: to establish a primary data base with screened, Earth located, and calibrated data for conversion to radiance values, to improve the algorithms for processing the primary data base of radiance values to ozone values; and finally, to validate the data to provide a consistent ozone data base. Details on satellite coverage, data quality checks, algorithm improvements, and validation methods will be published elsewhere.

Fleig et al., (in preparation) have extensively analyzed the comparability of BUV with the Dobson network. In a direct comparison of AD direct sun Dobson and BUV overflight values within 2° of the station, they obtained a correlation coefficient of 0.95 and an average difference of 12 Dobson units (D.U.) with Dobson higher for the first two years of operation. The change in the BUV-Dobson difference over the two years is about 3 D.U. or less than 1%, indicating a high degree of stability in the spaceborne instrument relative to the ground based network.

The first two years of total ozone data discussed here, covering the period April 1970 to April 1972, contain about 300,000 total ozone values per year. The Nimbus-4 orbital parameters and the BUV instrument description are detailed in the Nimbus-4 Users Guide (1970). There are about 13 orbits per day, with successive crossings of the equator occurring 27° in longitude apart. The total ozone measurement is limited to between 81° North and South and a maximum solar zenith angle of 85.7°. The orbit is sun-synchronized so that the northward equator crossing occurs near local noon. At high latitudes, the observations approach the morning terminator in the Northern Hemisphere, and the evening terminator in the Southern Hemisphere. Figure 1 is a typical coverage map, for one week of data in December, where the x's indicate a measurement.

The BUV measurement scheme has been previously described by Mateer et al. (1971) and is briefly summarized here. The instrument contains a monochromator, which sequentially scans 12 narrow wavelength bands in a region between 250.0 and 340.0 nm, and a photometer fixed at 380.0 nm. Both instruments measure the backscattered and reflected Earth radiances in the nadir, and have an instantaneous field of view of about 200 km on the earth's surface. Total ozone is derived from a measurement of the solar irradiance F_0, the backscattered radiance I, at 312.5 nm, 331.2 nm, 317.5 nm, and 339.8 nm and the effective surface reflectance determined from the photometer. Figure 2 shows the measurement geometry. The measured backscattered radiances are compared to those computed from 21 standard ozone profiles compiled from rocket and balloon soundings (Hilsenrath, 1977*). Any total ozone value can then be obtained from the table of pre-computed values containing the solar zenith angle dependence, θ, and reflectance, by interpolation.

This paper will emphasize the description of the seasonal and interannual variability of total ozone over a 2-year period as revealed by the spaceborne experiment. This approach to the

*["Standard Ozone Profiles for Satellite and Theoretical Model Input." Reported in the Collection of Extended Summaries of Contributions Presented at the Joint Assembly CMUA Sessions IAGA/IAMAP, Seattle, Washington, August 1977.]

interpretation of the data is important for 1) determining the relative role of photochemistry and transport in the global distribution of ozone, 2) recognizing transient phenomena in the stratosphere, such as stratospheric warmings and solar and geomagnetic events that may be important in sun/weather relationships and 3) a better understanding of long-term trends associated with solar cycles, other climate parameters, and man's activities that may effect the environment.

A time-varying, globally distributed geophysical variable can be conveniently described by zonal means as function of time and is particularly appropriate for total ozone since its variability is a strong function of season and latitude. The next section will describe the procedure for generating zonal means and a harmonic analysis for describing the seasonal trends. Following the next section, the BUV data will be compared to similar data from the Infrared Interferometer Spectrometer (IRIS), also flown on Nimbus-4 and the analysis of Dobson network data for the same period in the form of a time-latitude cross section. The last section will deal with the seasonal, interannual, and shorter variations detected by the BUV and derived from the harmonic analysis of the zonal mean data.

PROCEDURE

The latitude zones over which the averages are calculated are 10° wide, centered at the equator and at 10° intervals toward the pole. Because of the high-latitude limit of the satellite, the highest latitude zones are for 75° - 85° in each hemisphere. For each zone, a daily mean is calculated by averaging all ozone values given by the satellite for the given latitude range. Typical standard deviations of these means range from 10 D.U. near the equator to 50 D.U. at high latitudes. These standard deviations reflect primarily point-to-point variability at low latitudes and variations with longitude at high latitudes. Zonal means are based upon approximately 50 measurements per day.

For the two highest latitude zones in each hemisphere, covering 65°–85° in latitude, ozone values are not available during some days in winter, when the zone has a 24-hour night. Because a harmonic analysis cannot be carried out accurately when there are large gaps in the data, an estimate of the daily zonal means at the highest latitudes on these mid-winter days is derived by extrapolation from lower latitude zonal means. The extrapolation from lower latitude ozone values is based on the behavior of high-latitude ozone during those periods when measurements are available. The rule is as follows: When ozone values Ω_{j-1} and Ω_j are available for zones j–1 and j, respectively, but no value is available for zone j + 1, the estimated value for zone j+1 is given by

$$\Omega_{j+1} = \max \left\{ 0.96[\Omega_j + (\Omega_j - \Omega_{j-1})], 0.95\Omega_j \right\}$$

Further details on estimation of polar night ozone are given by Heath, et al., (in preparation). Because some ozone values are extrapolations, results for the zones centered at 70° and 80° must be regarded with caution.

The daily zonal means for each latitude zones have been converted into time series. A harmonic analysis has been carried out separately for each of these 17 time series. Amplitudes, days of peak ozone, and the percentage of variance have been computed for each harmonic. The first fifty harmonics of a one-year (365.242-day) period have been computed for the 365-day periods April 10, 1970–April 9, 1971 and April 10, 1971–April 8, 1972. Also, the first fifty harmonics of a two-year (730.484-day) period have been computed for the interval April 10, 1970–April 8, 1972. These are the first 730 days for which data are available from Nimbus-4 BUV.

In a harmonic analysis, the ozone $\Omega(t)$ is expressed in the following form:

$$\Omega(t) = \langle\Omega\rangle + \sum_m C_m \cos\left(\frac{2\pi m t}{T} + \phi_m\right) \tag{1}$$

where C_m is the amplitude for harmonic m, ϕ_m its phase, and T the period corresponding to the first (fundamental) harmonic.

If the ozone values are Ω_i for N consecutive days t_i, then average ozone $\langle\Omega\rangle$ is given by the following expression:

$$\langle\Omega\rangle = \frac{1}{N} \sum_i \Omega_i \tag{2}$$

The amplitude and phase are derived from the sine and cosine transforms:

$$A_m = \sum_i \Omega_i \cos \frac{2\pi m t_i}{T} \Delta t_i \tag{3}$$

$$B_m = \sum_i \Omega_i \sin \frac{2\pi m t_i}{T} \Delta t_i \tag{4}$$

Normally, $\Delta t_i = 1$.

$$C_m = (A_m{}^2 + B_m{}^2)^{½} \tag{5}$$

$$\phi_m = \tan^{-1} (-B_m/A_m) \tag{6}$$

The peak day t_p is that where $\frac{2\pi m t_p}{T} + \phi_m = 0$; or

$$t_p = \frac{\phi_m}{2\pi} \frac{T}{m} \tag{7}$$

with

$$|\phi_m| < \frac{\pi}{2} \text{ for } A_m > 0 \tag{8}$$

$$\frac{\pi}{2} < |\phi_m| \leq \pi \text{ for } A_m < 0. \tag{9}$$

The percent of the variance attributable to harmonic m is given by $C_m{}^2/2\sigma^2$, where σ^2 is the variance of the yearly average. Since occasional days are missing in the data, values are derived for these days by linear interpolation for calculating the average ozone, (Ω). For the sine and cosine transforms, Δt_i is set to $(t_k - t_j)/2$, where t_k is the first day following t_i with available data and t_j is the last day with data before t_i.

The uncertainties of the amplitudes and peak days have been estimated by shifting the data period and varying the treatment of missing days; they are approximately 10% of the amplitude and 3–4 days for the peak time and are not significant for this study.

RESULTS

A. Time–Latitude Cross Sections

A time latitude cross section, depicted in Figure 3, was generated from smoothed averaged daily means for the 10–degree wide latitude zones. Total ozone is shown as contours with 20 Dobson Unit increments for the 26–month period (contours are missing in the polar night). The seasonal march of total ozone is evident in the two hemispheres. Ozone has a spring high and fall low at mid to high latitudes in both years. However, there are distinct differences in the seasonal trends for each hemisphere. These differences are as follows:

1. In the Northern Hemisphere, the spring maximum occurs nearly simultaneously at mid and high latitudes in late March. The maximum values occur near the pole, with total ozone amounts of about 500 D.U. in the spring of 1970 decreasing to 480 D.U. and 460 D.U. in the spring of 1971 and 1972 respectively. This is consistent with the analysis of Angell and Korshover (1978) who show from Dobson data a comparable decrease in the North Temperate and polar regions for this same time period.

2. In the Southern Hemisphere, the spring maximum occurs first in September at 50°S with ozone values substantially lower than those in the Northern Hemisphere spring. The spring maximum values occur about one month later in the polar regions. The asymmetry in the winter build-up of the two hemispheres can be explained by the well-known differences in the circulation features in the two hemispheres, as described by Newell et al. (1974), Dütsch (1974) and others. In the Northern Hemisphere, eddy processes associated with the intense winter planetary waves transport

ozone poleward from mid latitudes. In the Southern Hemisphere, however, the circulation is generally more zonal and there is a northward component of eddy fluxes in the South Polar regions. Poleward transport may be further delayed because stratospheric warmings may be less intense or because of the resistance to breakdown of the Southern Hemisphere polar vortex. Also note that the decrease in the Southern Hemisphere spring maximum values is not as large as the decrease in the Northern Hemisphere.

3. In the tropical regions, the total ozone amount and the seasonal variations are considerably smaller than at higher latitudes. The average value is about 250 D.U. The ozone minimum is centered below the equator in April and moves northward as the year progresses. This cycle is repeated in the second year. Because of changes in the sun earth distances and/or the solar declination, this effect could be interpreted as a photochemical response, since the tropics represent the source region for ozone. However, the effect appears rather to be the result of high latitude influences and will be discussed in more detail below. Also note the ozone minimum in the northern tropics that appears rather suddenly just after the Southern Hemisphere spring maximum and at the beginning of the Northern Hemisphere winter buildup occurs in both years.

The global mean trend can be easily derived by summing the area weight of the zonal mean ozone values. This calculation shows a gradual decrease in the mean global ozone consistant with that shown by Angell and Korshover (1978). However, trends in global mean ozone as determined from satellite and compared with ground networks are being studied by Heath, et al. (in preparation) and are not pursued here.

B. Comparison with Dobson Analysis

The Dobson network of stations provides an alternate source of total ozone values. London et al. (1976) have derived monthly hemispheric ozone maps from the Dobson data for the period 1957-1967. London (private communcation) has kindly provided additional maps for the period 1968-1975.

These data are used to form a time–latitude cross section similar to that in Figure 3 for BUV data. In the Northern Hemisphere the seasonal features shown by Dobson and BUV are nearly the same. The general pattern of ozone values and the times of the spring maximum and fall minimum agree reasonably well although there are differences in detail. In the tropics both data sets show the ozone minimum moving from south of the equator in April to its most northern point in January. In the Southern Hemisphere there are significant differences. The spring buildup at mid to high latitudes does not appear at all in the analyzed Dobson cross section. This difference is not unexpected, since there are few ground observing stations in the Southern Hemisphere (eight stations south of 30 S reported in 1970 and only two reported in October).

In order to understand the discrepancy between the two cross sections, the BUV data can be examined in more detail in the form of latitude–longitude maps. Figure 5 is a map of contoured ozone values at 20 Dobson unit increments f. - October 1970. A very strong wave one type feature appears at about 60°S, with the highest ozone values southeast of Australia. This feature has been detected in the past from Dobson (London et al., 1976) although the ozone values were considerably lower than the 480 Dobson units measured by the BUV. It is concluded then, that the differences in the Southern Hemisphere illustrated in Figures 3 and 4 result mainly from the absence of Dobson stations and the large ozone high that was not detected in the Dobson analysis. The discrepancy recurs when comparing the BUV and Dobson analyses for the period March 1971 to March 1972. It should be noted, however, that the seasonal trends for the two years shown in Figure 3 agree fairly well with the ten year averaged cross section derived by London et al. (1976) This would imply that the BUV data more closely describes the mean global ozone, while the Dobson analysis suffers from insufficient coverage.

C. Comparison with IRIS

The Infrared Interferometer Spectrometer (IRIS) also flew on Nimbus-4 and measured total ozone. The results were reported in detail by Prabhakara et al. (1976). Prior and Oza (1978) performed a preliminary comparison of BUV, Dobson and IRIS data and showed the BUV and Dobson agree better in general with each other than with IRIS. However, Figure 5 can be directly compared with the October analysis, Figure 13 in the Prabhakara et al. paper, derived from IRIS. The ozone high over Manchuria and low over the North Atlantic, as well as the closed contour of 240 Dobson units in the vicinity of the Indonesian Islands also appear in their analysis. The ozone high in the Southern Hemisphere high latitudes centered at 170 E longitude also appears in the IRIS data, except this feature is about 20 Dobson units lower. With the consideration that the IRIS total ozone measurement underestimates and overestimates the ozone values in the spring and fall respectively, (Prabhakara, et al., 1976) the monthly analyses from the two instruments are nearly identical.

D. Harmonic Analysis

The seasonal trends and the year to year differences in the global total ozone were obtained from a harmonic analysis of the daily zonal means, using the procedures discussed in a previous section. Figure 6 illustrates daily zonal means for five latitude zones for the period April 10, 1970 to April 9, 1971. The daily zonal means were normalized and smoothed, in this example only, by setting the maximum and minimum values to plus and minus one respectively and smoothing with a binomial filter with a ten day half width. An annual wave is clearly present at all latitude zones except at the equator, with some periods of shorter variability. For some zones, for example 30 S, the variations are nearly sinusiodal, while at 60 S the curve differs significantly from a pure sinusoid. In addition there appear periodicities of the order of 3 weeks during the Southern Hemisphere winter buildup. The phase shift for the time of the maximum value in Southern Hemisphere zones discussed earlier, is clearly evident in this figure.

The annual wave or the first harmonic in the Fourier expansion is shown in Figure 7. The amplitude of and percent of variance in the first harmonic are plotted as function of latitude. Both years shown in the single figure permits a direct comparison. It should be clear that the data shown in this figure is a representation of information in Figure 3. The important features are the following:

1. In the Northern Hemisphere .he amplitude of the annual wave increases with latitude. In addition, the first harmonic contributes more than 90% of the variance from subtropical latitudes to the pole. These features are essentially the same for the two years.

2. The amplitude of the annual wave is a minimum in the tropics and is only a few Dobson units. The percent variance in the first harmonic is nearly zero at the equator, at least for the first year, and the location of the minimum amplitude shifts about 10° southward in the second year.

3. In the Southern Hemisphere the amplitude of the annual wave is greatest at mid-lattitudes and decreases towards the South Pole. The percent variance in the annual wave decreases near the pole, indicating that the total ozone annual wave is less pronounced in the South Polar region than in the North; however, one should recall that values in winter polar latitudes are derived by extrapolation. At mid-latitudes there is a 10° southward shift in the location of the maximum amplitude comparable to the shift detected in the tropics. This shift could be the result of year to year changes in the strength and location of the Hadley cell circulation in the Southern Hemisphere. Interannual changes in the strength of the Hadley cell determined from a study of 10 years of Northern Hemisphere wind data have been discussed by Rosen and Wu (1976). Moreover, Newell and Wu (1978) found a correlation of total ozone from long term monthly mean Dobson observations with geopotential thicknesses for the same period and concluded that circulation changes due to variations in the Hadley cell govern the year to year changes in ozone.

Information on the semi-annual component in the seasonal ozone trend is contained in the second harmonic of the Fourier expansion of the daily zonal means. A semi-annual component would be expected since the sun crosses the equator twice and a photochemical response may be detected in the tropics. On the other hand, there is possibly a correlation with the semi-annual oscillation in the temperature and winds detected in the tropics in the upper stratosphere, or a correlation with the winter high lattitude/tropical disturbances as discussed by Fritz and Soules (1972). These phenomena are of great interest and a more detailed analysis than that performed here, may well show correlations with ozone. However, the semi-annual component detected in the satellite measured total ozone for the two years studied here will be shown to result from none of the above.

Figure 8 depicts the semi-annual component in the same format as Figure 7, except that the ordinates for both the amplitude and the percent variance are half those of that figure. The important features are as follows:

1. At mid-latitudes for both years the semi-annual wave is small and of the order of its uncertainty.

2. In the tropics, this component becomes significant in the first year but less so in the second year. From 0 to 10 S the amplitude of the semi-annual component is comparable to that of the annual component and contains about 40% of the variance for the first year.

3. At high latitudes in the Southern Hemisphere the semi-annual oscillation becomes important again and the amplitude is comparable to that of the annual wave. However, the significance of this feature should again be regarded with some caution since nearly one-half of the values appearing in the highest latitude zone are the result of extrapolation from lower latitudes.

The harmonic analysis also provides the time of the maximum ozone value derived from Equation 7 in each latitude zone for each harmonic component. Figure 9 shows the time of the maximum ozone value as a function of latitude for both the annual and semi-annual waves for each year. The ordinate is given in month as well as day of the year. The significant aspects of the phase are summarized below and the results are consistent with the interpretation of the time-latitude cross section, Figure 3.

1. In the Northern Hemisphere the time of the maximum of the annual wave occurs nearly simultaneously from mid to high latitudes.

2. In the Southern Hemisphere, after passing through a 6 month phase shift at the equator, the spring maximum occurs first at the 40°S in September and then spreads poleward and equatorward, reaching maximum values in these regions in late November.

3. For the semi-annual wave, the time of the first maximum was plotted only at latitudes where the percent of the variance in the second harmonic is greater than 2%. At low latitudes, the first peak occurs about April, which is coincident with the Northern Hemisphere spring maximum of the annual wave. The second maximum of the semi-annual component occurs 6 months later in October which is coincident with the maximum of the annual wave in the Southern Hemisphere subtropics. Close inspection of Figure 6 supports this result. The maximum annual ozone value at 30 S occurs on day 265 while the maximum annual value at 40 N occurs about day 85, which very nearly correspond to peak days at 0 S. This result does not exclude a possible response to the solar equatorial crossing, but it seems more likely that the semi-annual wave detected at low latitudes in the first year is the result of the annual wave at higher latitudes in the two hemispheres where the phases are six months apart.

E. Shorter Periods

The results of the harmonic analysis were examined for shorter periodicities. For periods of one month or shorter, the noise level ranges from 2 Dobson units at low latitudes to 5 Dobson units at high latitudes. No periodicity with higher amplitude was found, although variations of two to three week periods are evident in Figure 6, particularly during the first six months at 60 S. Harmonic analysis is not a particularly sensitive method for determining shorter periods. Further work in this area is under way.

CONCLUSION AND SUMMARY

The Nimbus-4 data have been reprocessed after an extensive effort to retrieve the data and trace the instrument performance. The data have been analyzed here for the period April 1970 to May 1972. The coverage and overall sensitivity of the satellite measurement permit accurate determination of the seasonal march of total ozone in the two hemispheres and reveal some interannual differences.

A harmonic analysis of the daily zonal means has revealed asymmetries between the annual waves in the two hemispheres. In the Northern Hemisphere, the amplitude of the annual wave increases going toward the pole and the maximum value occurs nearly simultaneously at mid to high latitudes. In the Southern Hemisphere, the maximum amplitude of the annual wave occurs at about 50 S. The maximum occurs first also near this latitude, it then spreads equatorward and poleward. A semi-annual component was detected at the equator in the first year and at Southern Hemisphere high latitudes in both years. The high latitude semi-annual component should be regarded with caution since an appreciable portion of the data was derived by extrapolation because the satellite was in darkness. The semi-annual component detected at the equator results from the influences of the annual waves in the two hemispheres, whose phases are six months apart. A search for shorter periods (higher order harmonics) using a harmonic analysis with a one year period revealed no periodicity whose amplitude was significantly higher than the noise level.

A 10° southward shift in the location of the annual wave in the Southern Hemisphere was detected for 1971 when compared to 1970. This may be the result of interannual variations in the Hadley cell circulation which may have caused the decrease in global mean ozone values reported for this period.

Work is under way to analyze the remaining five years of BUV data as they become available. Of particular importance is the development and testing of analysis schemes which can handle missing data, because the BUV operation was considerably reduced after the second year.

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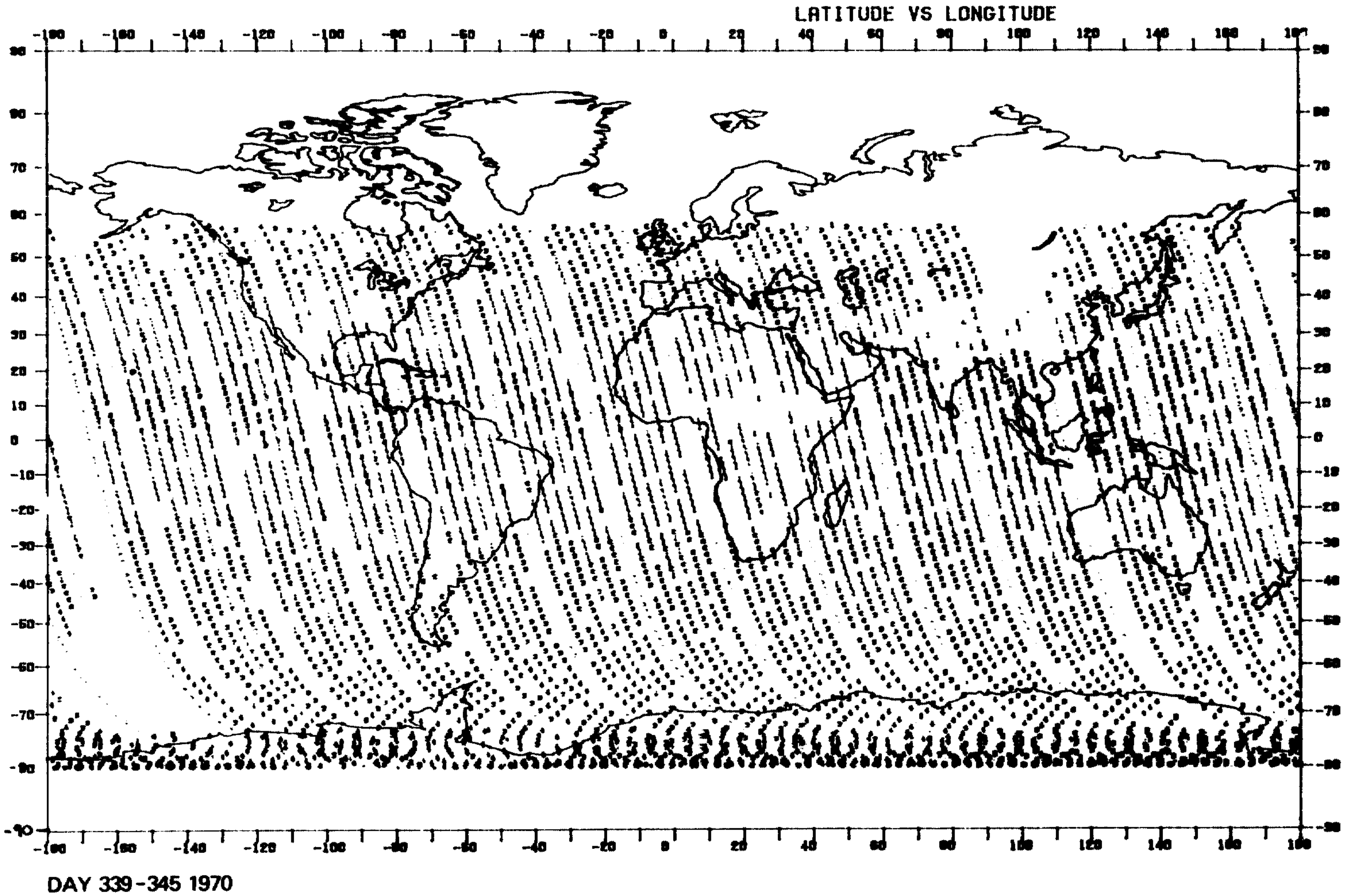

Figure 1. Coverage map for one week of Nimbus 4 BUV observations. X's indicate a square measurement sample approximately 200 km on a side.

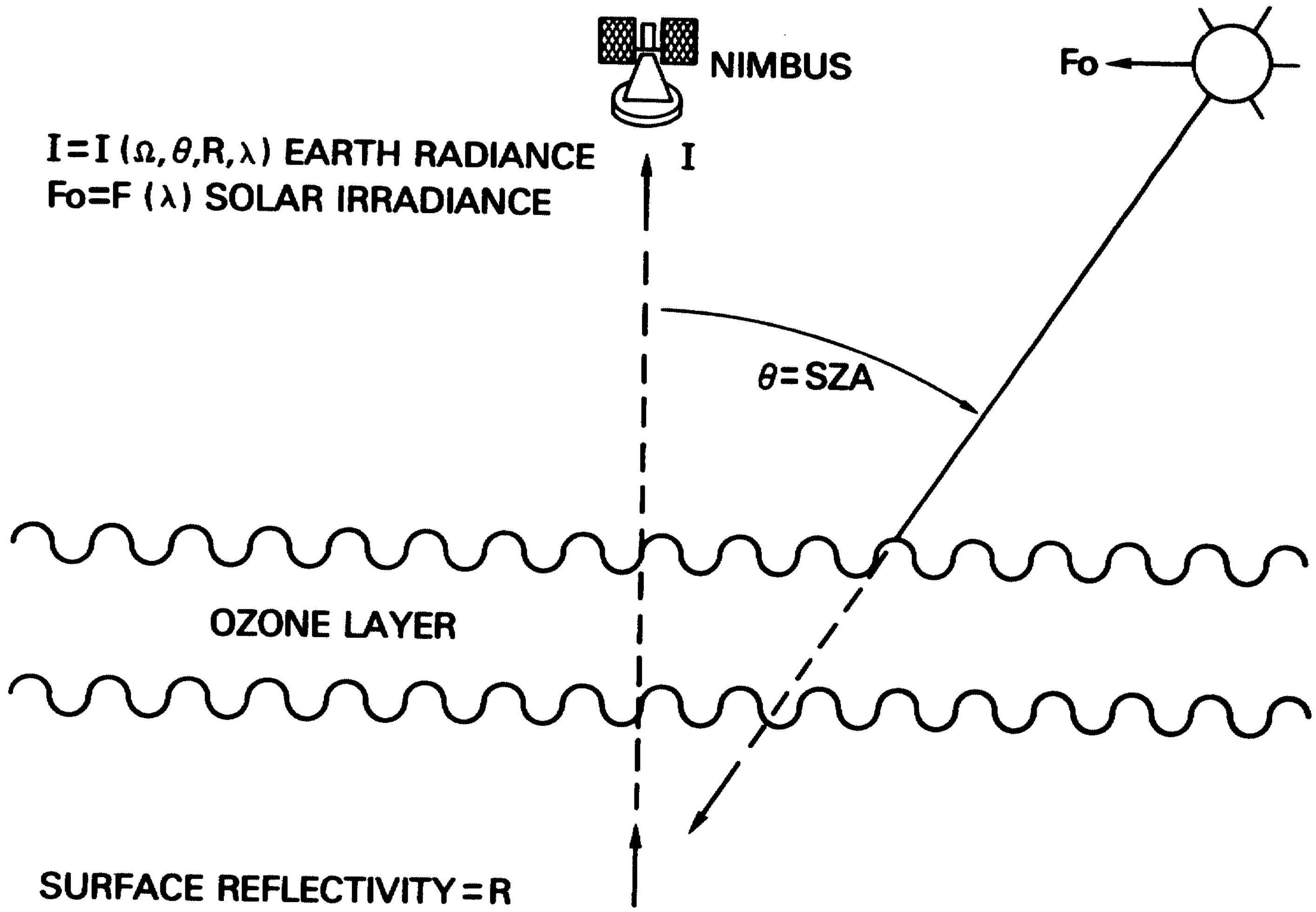

Figure 2. Geometry for total ozone measurements using backscattered ultraviolet observations.

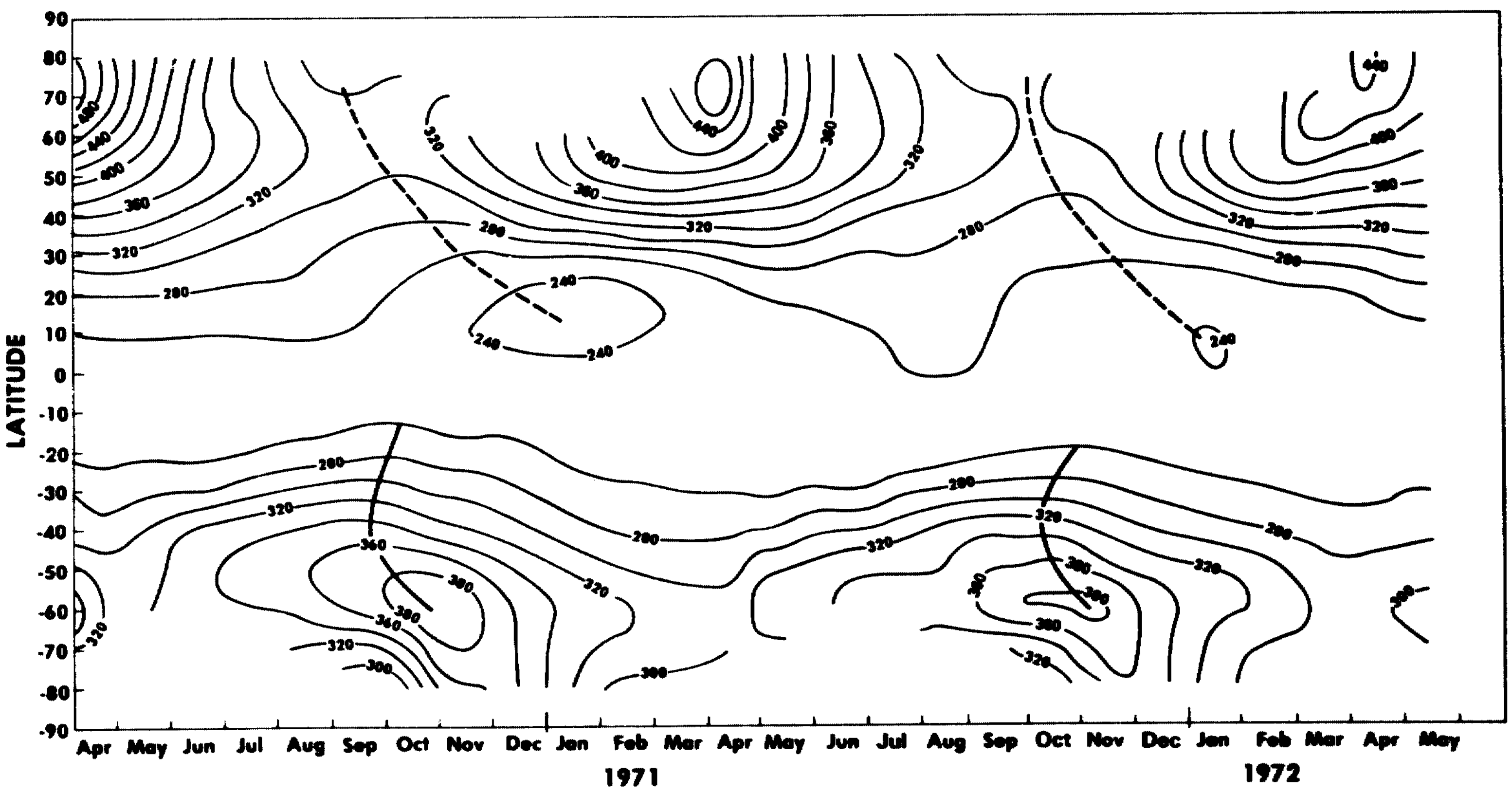

Figure 3. Time latitude cross of total ozone for period April 1970 to May 1972 derived from 10 degree wide daily zonal mean and smoothed with a binomial filter. Contours are 20 Dobson unit increments.

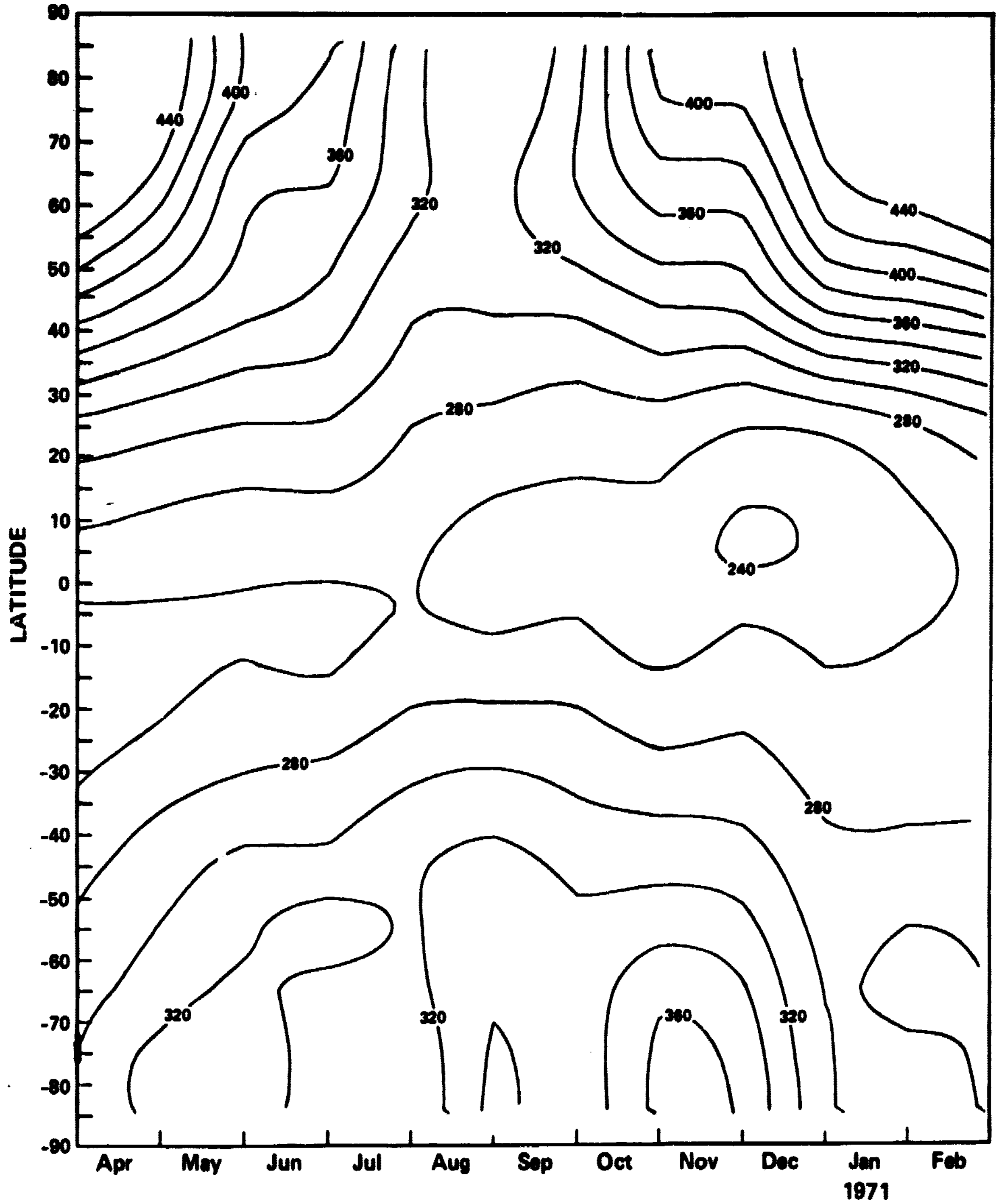

Figure 4. Time latitude cross section derived from analysis of Dobson data using monthly zonal averages (London, private communication).

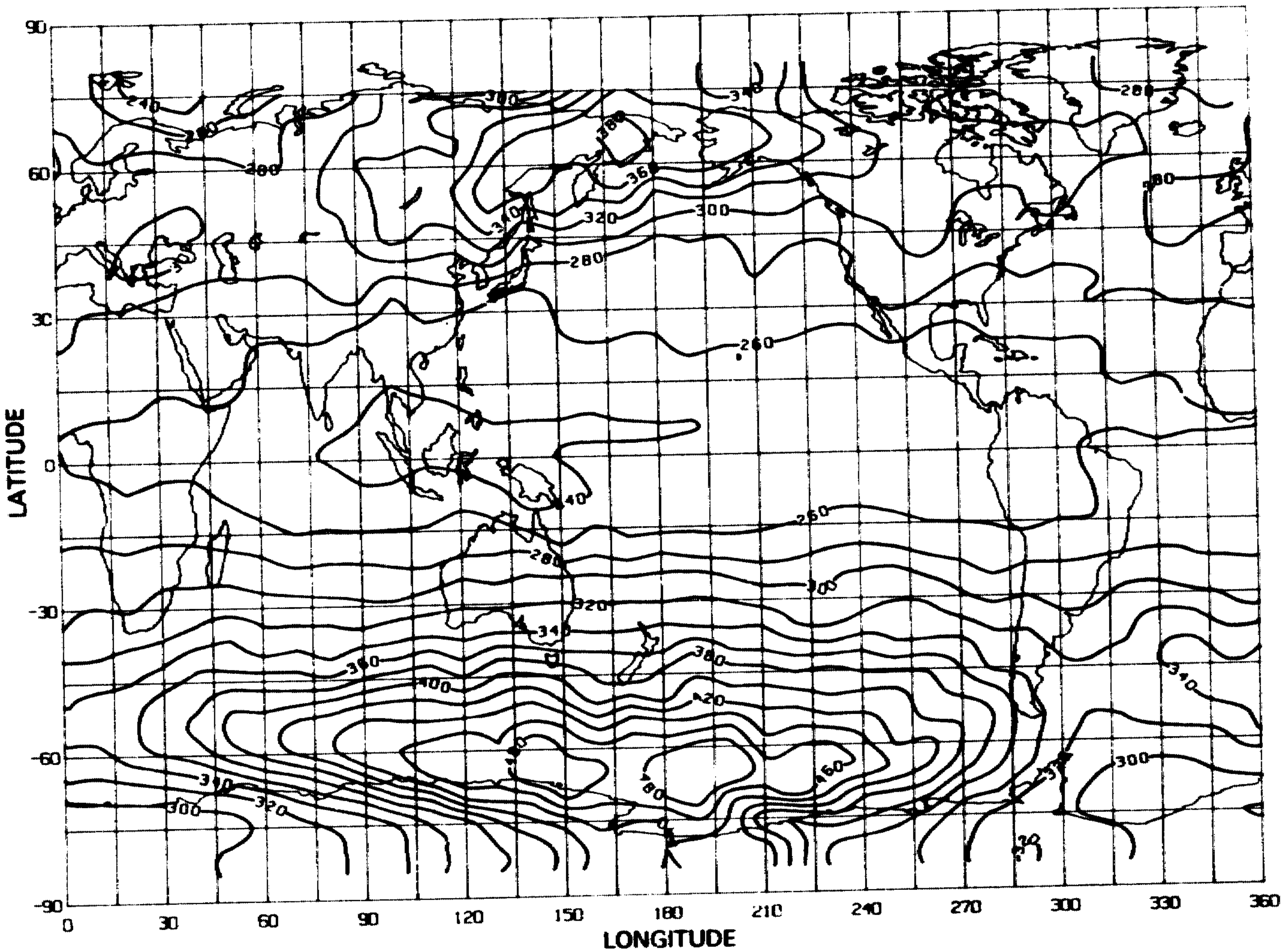

Figure 5. Average total ozone for October 1970 contoured ozone values are in 20 Dobson Unit increments.

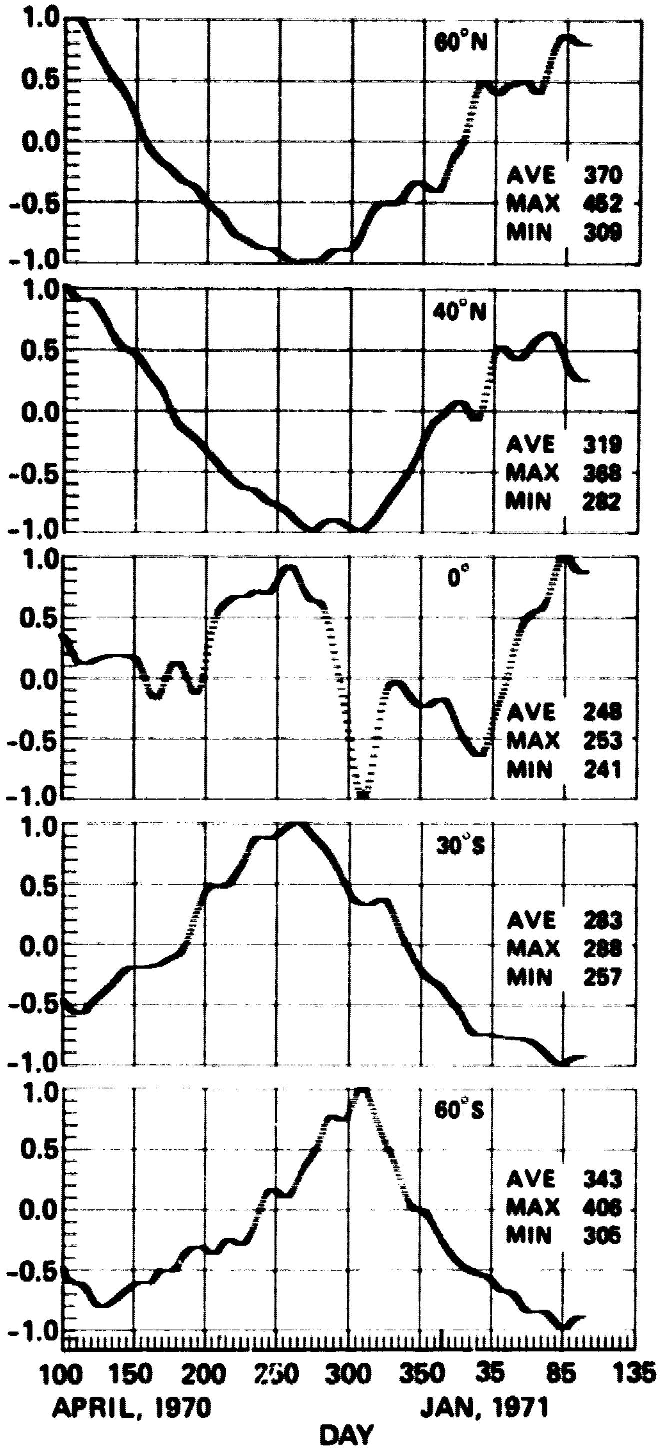

Figure 6. Normalized and smoothed (see text) daily zonal means illustrating periodic behavior for 5 latitude zones. The absicca is day number.

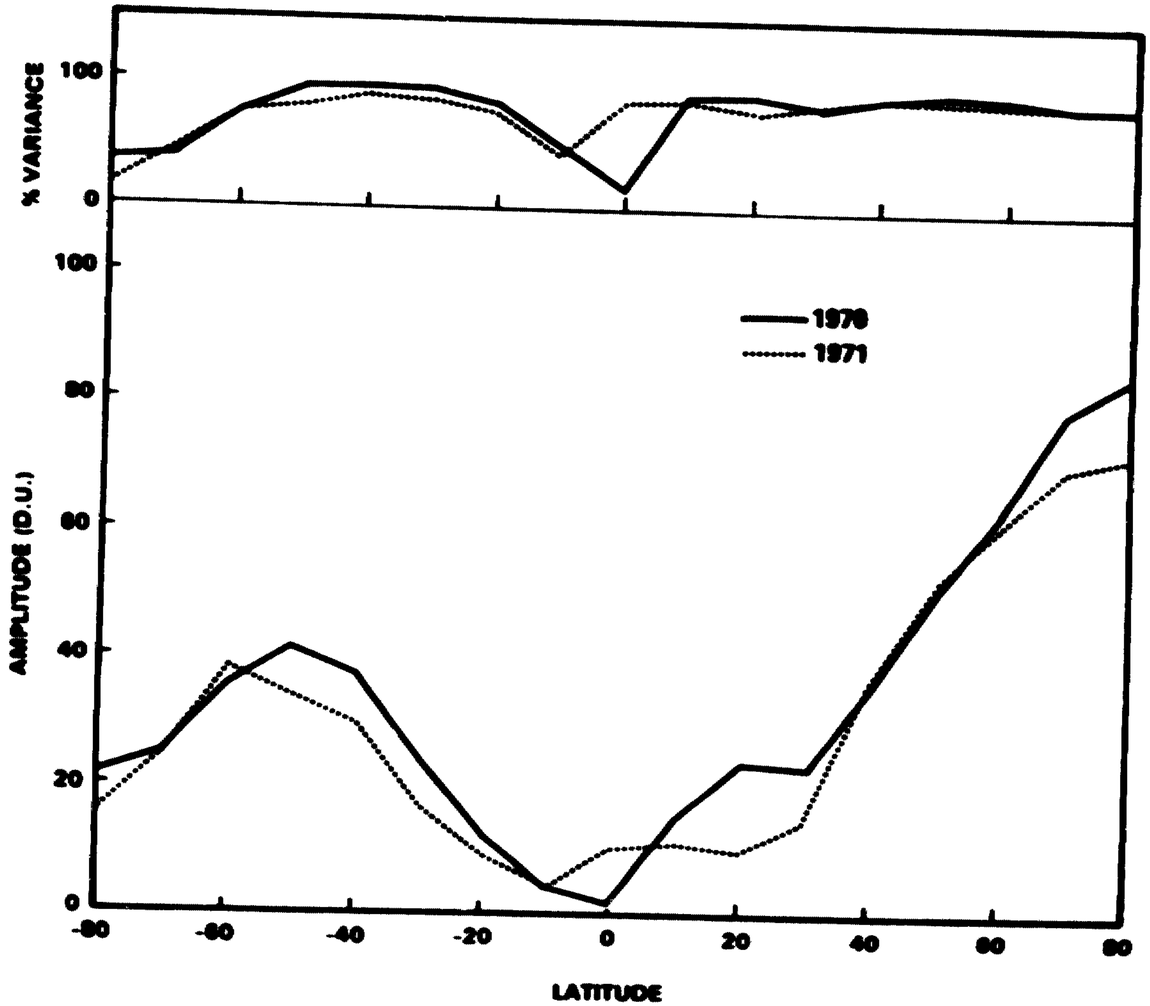

Figure 7. Below, amplitude of annual wave and above, variance of first harmonic total ozone from first and second year of BUV data.

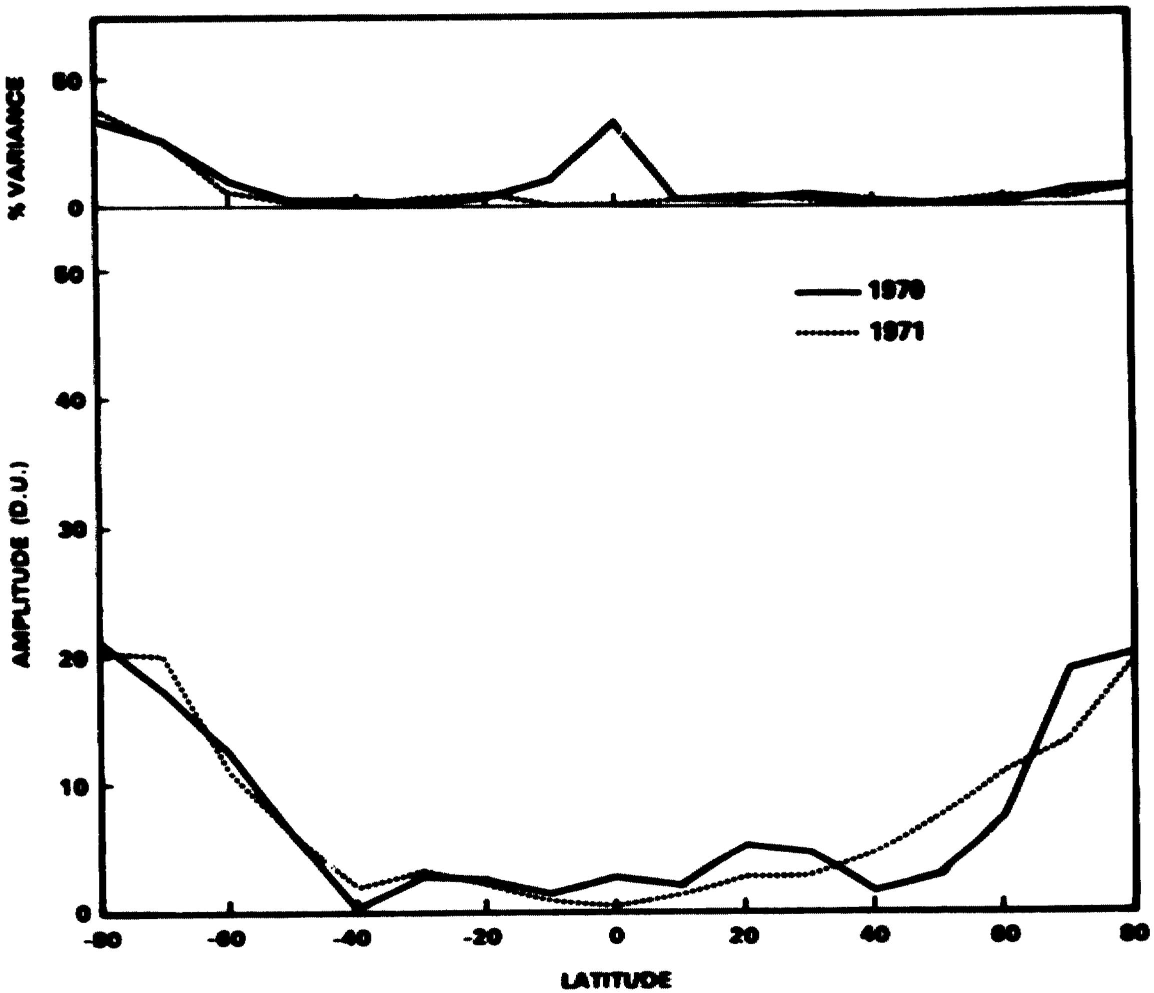

Figure 8. Below, amplitude of semi-annual wave and above, variance of second harmonic of total ozone from first and second year of BUV data.

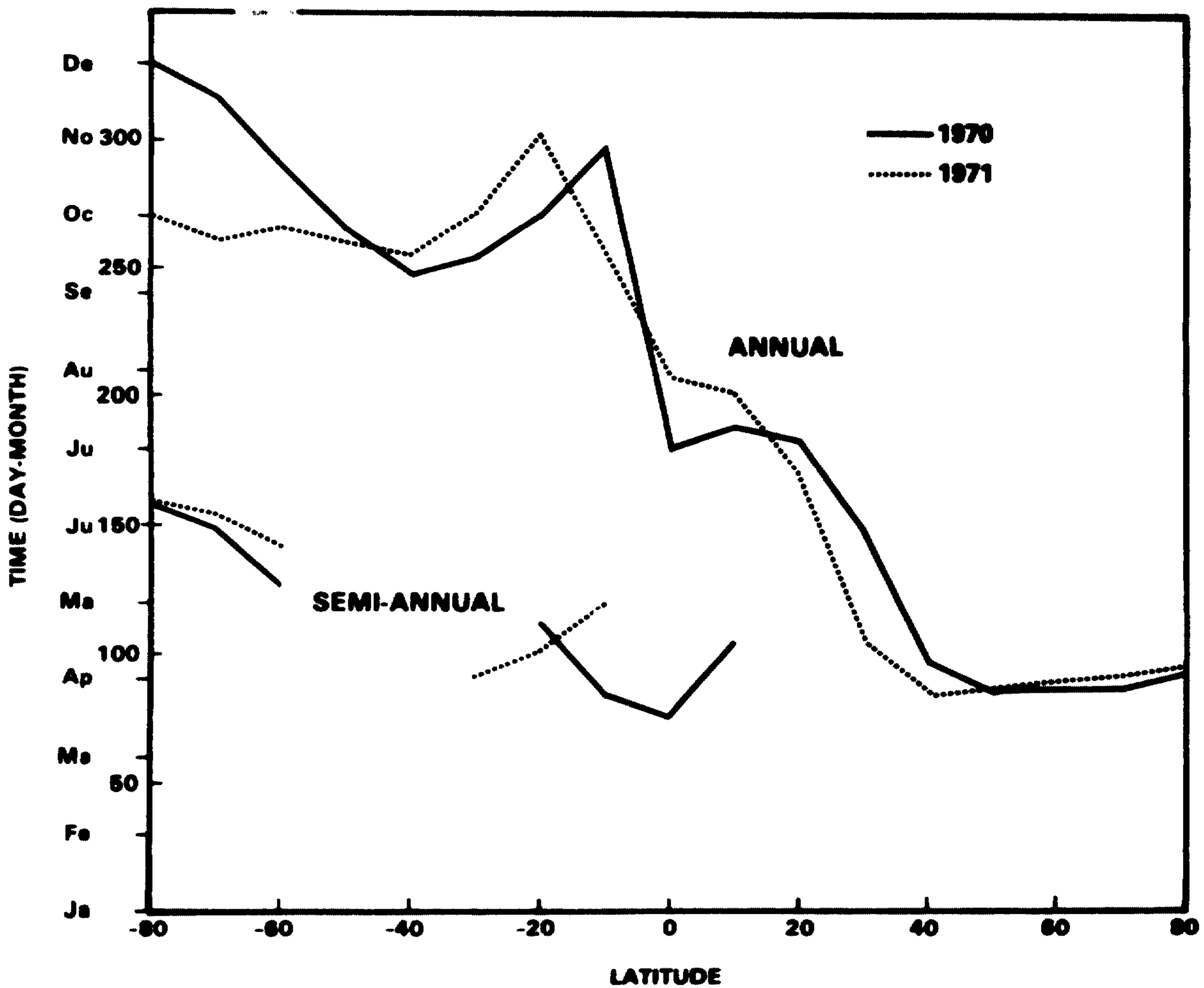

Figure 9. Time of maximum ozone value derived from phase in the harmonic analysis of daily zonal means.