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RECENT ADVANCES IN SATELLITE OBSERVATIONS OF SOLAR VARIABILITY AND GLOBAL ATMOSPHERIC OZONE

DONALD F. HEATH

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ABSTRACT

The sun has been under daily surveillance as an ultraviolet star since the launch of Nimbus 3 in April 1969. The launch of Nimbus 4 in April 1974 has made possible simultaneous measurements of the ultraviolet solar irradiance and the global distribution of atmospheric ozone by the Monitor of Ultraviolet Solar Energy (MUSE) and Backscatter Ultraviolet (BUV) experiments respectively. Two long lived ultraviolet active solar regions which are about 180° apart in solar longitude have been observed to be associated with central meridian passages of solar magnetic sector boundaries. The boundaries may be significant in the evaluation of reported correlations between solar magnetic sector structure and atmospheric circulation.

Daily zonal means of ozone data averaged in longitude within 10° bands of latitude have shown that daily variations in the zonal means are significantly larger in fall and winter than in spring and summer and in the southern hemisphere than in the northern hemisphere during their respective fall and winter periods. Monthly zonal means of total ozone have been calculated to give the monthly

mean latitudinal distributions of total ozone and the seasonal variability within the 10° bands of latitude for the period from April 1970 through April 1971. These in turn have been used to derive a hemispherical and global ozone budget for that period.

During the December 1970 and January 1971 period a major stratospheric warming was observed in the northern hemisphere. The warming was characterized by a very large increase in zonal mean of ozone at 70°N latitude. The ozone mass mixing ratio at 4 mb increased from a value of 8.5 to 23 μg/g. A corresponding maximum in the amount of ozone above 4 mb was observed to move south to 20°S latitude in about 10 days. The mass mixing ratios which were significantly greater than observed in the tropics are strongly suggestive of a non-photochemical source possibly originating within the auroral oval.

CONTENTS

RECENT ADVANCES IN SATELLITE OBSERVATIONS OF SOLAR VARIABILITY AND GLOBAL ATMOSPHERIC OZONE

INTRODUCTION

The launch of Nimbus 4 on April 8, 1970, began a data acquisition period for the inference total amounts and vertical distributions of atmospheric ozone on a global basis which now spans four years. One year earlier, an experiment which monitors the ultraviolet energy from 120 nm to 300 nm was launched aboard Nimbus 3 and subsequently again on Nimbus 4. These experiments have produced coverage for nearly five years of the temporal behavior of the solar ultraviolet irradiance. Simultaneously, the interplanetary solar magnetic field has been monitored from space. Combined, these data should provide an extremely valuable data base for the development of a climatology of atmospheric ozone. These satellite measurements should prove to be extremely valuable for investigating possible causal relationships between solar and terrestrial atmospheric phenomena.

This work describes the temporal behavior of the sun as an ultraviolet variable star in relation to daily zonal means of atmospheric ozone from the total amount to that above 10 mb and 4 mb pressure levels. A significant correlation has been observed between enhancements in the ultraviolet solar irradiances and terrestrial passages of the solar magnetic field sector boundary structure. Unfortunately, to date, it has not been possible to separate solar from the dynamical effects on the variability in the zonal means of ozone. Satellite acquisition of global atmospheric ozone data has made it possible to study the hemispheric behavior of total ozone from daily latitudinal zonal means from 80° N to 80° S which are averaged in longitude over one month intervals. This time averaging tends to minimize possible solar effects which might be associated with the 27 day solar rotational period. A principal goal of this work is to show some of the global changes in ozone which have been derived from the satellite observation in terms of season, solar variability and major stratospheric disturbances such as stratospheric warmings.

INSTRUMENTATION

Two principal experiments were used to provide the data for this paper. The Monitor of Ultraviolet Solar Energy (MUSE) experiment is a broad band photometer experiment which responds to solar radiation from 110 nm to 300 nm. The MUSE experiment which has been described by Heath (1973) was flown on board a rocket in August 1966, and subsequent versions were launched on board Nimbus 3 and 4 in April, 1969, and April 1970 respectively.

The Nimbus 4, Backscatter Ultraviolet (BUV) experiment which has been described briefly by Heath et al. (1973) measures the atmospheric radiance and incident solar irradiance from 255 nm to 340 nm with a double monochromator, every 32 seconds and the terrestrial albedo in an ozone absorption free region with a photometer at 380 nm at intervals of 400 ms. The instantaneous field of view corresponds to a ground resolution of about 210 km.

Collectively, the MUSE and BUV experiments have provided a unique data set on temporal behavior of the incident ultraviolet solar radiation and global distributions of atmospheric ozone.

ULTRAVIOLET SOLAR VARIABILITY

For discussion purposes, the types of solar variability observed in the solar flux are classified according to the time scale of the variability. The three dominant time scales which have been observed are those associated with the eleven year sunspot cycle, the 27 day solar rotational period and short period flare phenomena. Only the first two will be discussed in this paper.

Information on the changes with time of the ultraviolet solar spectral irradiance is shown in Figure 1. The quantity $\alpha = F_\lambda$ (obs)/F_λ (model) is a measure of the departure of specific measurements from some currently accepted distribution of solar spectral irradiance. The reference solar flux model used was that published by Detwiler et al. (1961) and Tousey (1963) of the U. S. Naval Research Laboratory. Early evidence of significantly lower ultraviolet solar fluxes (∇, 1964) in the atomic oxygen production region (210 nm) of the stratosphere was given by Brewer and Wilson (1965). The MUSE rocket observations in 1966 (Δ, 1966) also indicated that possibly the fluxes were significantly lower than the NRL model. These observations were close in time to the 1964 minimum in the sunspot cycle. On the other hand the Nimbus 3 MUSE observations (□, 1969) coincide with the period of maximum activity in the sunspot cycle. The symbols (○, +, 1970) represent the solar observation by the MUSE and BUV experiments on Nimbus 4 shortly after solar maximum. Recent rocket spectrometer measurements (●, 1972) by Ackerman and Simon (1973) round out a consistent set of measurements which indicate that there has been a significant change in the ultraviolet solar flux absorbed in the stratosphere between the maximum and minimum of the eleven year sunspot cycle number 20. The results shown in Figure 1 suggest the solar flux which produces atomic oxygen can change by a factor of two between solar maximum and minimum below 210 nm.

The MUSE experiments on Nimbus 3 and Nimbus 4, have observed the sun through more than 60 solar rotations since April 1969. From this extended observing period it is quite clear that the sun is an ultraviolet variable star. In the analysis of long term solar variability it has been assumed that the maximum in ultraviolet solar radiation is observed when an active region is on the central meridian. One then observes when plotting the solar longitude of the central meridian on the days of UV maxima in Figure 2 that there were two principal long lived UV active regions on the sun which were approximately 180° apart in solar longitude. Typically variations with solar rotation are 25% at H Lyman alpha, 5% at 175 nm and less than 1% at 290 nm.

The variability of the UV flux from these long lived regions is quite complex and beyond the scope of this paper. In general, the enhancement per solar rotation was significantly larger by about a factor of two in 1969, early 1970, late 1972 and early 1973 than in 1971, a period of low solar activity.

SOLAR MAGNETIC SECTOR BOUNDARIES AND UV VARIABILITY

Many investigations have concerned themselves with possible causal relationships between solar activity and meteorological phenomena. This area of research recently has been stimulated by a series of papers which report a significant correlation between passages of solar magnetic field sector boundaries past the earth and certain meteorological phenomena. A recent paper by Wilcox et al. (1974) provides an up to date representation of the current status of this research. Much work is being done to find a mechanism for coupling the two phenomena. It has been found from preliminary investigations by Heath and Wilcox (1974) that the UV long-lived active regions observed by the MUSE experiment correlate with certain well defined solar magnetic field sector boundaries. This correlation is illustrated in Figure 3 for the away-toward, toward-away boundaries and a composite of the two boundaries. The transit time of the solar wind from the sun to the earth is about 4.5 days which is very close to the mean of the composite case in Figure 3.

Typical enhancements which were observed above the minimum during a solar rotation in 1969 were: 1.6×10^{-3} w/m^2 at H, Lyman alpha, 1.0×10^{-3} w/m^2 at

175 nm and 2.30 x 10^{-1} w/m^2 at 295 nm. During this time period the UV enhancements per solar rotation were greater than the annual variation below 175 nm and less than it at longer wavelengths. Such an increase should be considered when investigating physical causes to explain the correlations observed between passages of solar magnetic sector boundaries past the earth and meteorological phenomena.

ANNUAL GLOBAL OZONE BUDGET (APRIL, 1970 - APRIL, 1971)

The global distribution of atmospheric ozone apart from its role as a shield for the biosphere against lethal ultraviolet solar radiation is important for the inference of transport and circulation in the stratosphere. The Nimbus 4, BUV experiment has provided the first satellite data for the inference of global atmospheric ozone distributions over a full year.

Total ozone is inferred from the atmospheric scattering of ultraviolet solar radiation by a technique developed by Dave and Mateer (1967). This technique as it applies to the BUV experiment has been discussed by Mateer et al. (1971). Vertical profiles of ozone can be inferred by a technique suggested by Singer and Wentworth (1957). The solution to the inversion equation has been treated by Mateer (1972) and the technique used for the inversion of the BUV data has been described by Krueger et al. (1973).

In the succeeding sections zonal means of ozone which were averaged in longitude over 10° latitude intervals were tabulated on a daily basis. Typically, a single day would consist of 400 to 700 ozone values, where the differences resulted mainly from "blind" orbits (i.e., no satellite interrogation possible), defective sensory data tapes or a low priority for satellite interrogation at the tracking stations. At mid and equatorial latitudes the standard deviation of a zonal mean was less than 5% and at latitudes greater than 70° the standard deviation was typically less than 10%.

The monthly zonal means of total ozone for 10° intervals of latitude are given in Figures 4-6. The ordinate on the left represents the number ozone molecules contained in the 10° latitude interval. The ordinate on the right gives the mean amount of ozone in the interval in m atm-cm. This representation of the temporal change of total ozone with latitude is somewhat distorted from that which one might expect for total ozone which has been averaged over several years since a major stratospheric warming occurred in the northern hemisphere in early January, 1971.

Global features of total ozone derived from 80 stations north and 17 stations south of the equator for the years from 1957 to 1966 have been described by Gebhart et al. (1970). While there is a general agreement with this work there are some significant differences. During early 1970 there apparently was a maximum in the northern hemisphere in the March-April period which is only partially mapped out since the BUV experiment was first operated on April 10, 1970. Moving towards the equator a maximum is observed at 30° N and 20° N in

May, at 10°N and the equator in late July. The minimum drifts in time from September at 70°N to February at 10°N. At the equator and 10°S, however, the minimum is shifted back into December. A strong northern hemisphere maximum is present in January at 70°N, in February at 60°N and in March-April from 50°N to 30°N. The strong asymmetric peak at 70°N and 60°N coincides with a major stratospheric warming.

As one moves southward into the southern hemisphere a minimum is observed at the beginning of the measurements in early April which appears to deepen as one moves southward to 60°S. The principal maximum of ozone in the southern hemisphere moves in time from August at 10°S to late September at 20°S, back to mid September at 30°S and 40°S, into October at 50°S, and into November for 60°S and 70°S. The minimum moves from December at 10°S into the March-April period down to 50°S then backward in time to February for 60°S and 70°S. An unusual second maximum is observed in June at 60°S and 70°S which may be associated with development of conditions which might precede a minor southern hemisphere stratospheric warming.

In this section, latitudinal distributions of the monthly zonal means of total ozone are shown in Figure 7 for a 13 month period from April 1970 through April 1971. The observed distribution for April 1971 has been plotted on the graph for April 1970 to illustrate the combined effects of the stability of the BUV experiment and global ozone distribution separated by one year. Similar ozone distributions have been given by Gebhart et al. (1970) for the months of January, April, July and October for data averaged over the period from 1957-1966 by Gebhart et al. (1970). These two sets of observations are qualitatively similar in that the seasonal variation of ozone is greatest in the polar regions of the northern hemisphere and least for tropical latitudes, however, significant differences are observed. These differences are shown graphically in Figure 8 where ratios of ozone are given for the two sets of data for the periods of 1970-1971 and 1957-1966 for the months, January, April, July and October. The upper left section of Figure 8 shows the ratio of the maximum ozone in the northern hemisphere to that in the southern hemisphere. The large enhancement in January 1971 over that for 1957-1966 can be attributed to the occurrence of major northern hemisphere stratospheric warming in late December 1970 and early 1971. Furthermore, one observes that the rate of decrease with season of the northern hemisphere peak is less for the BUV observations. The apparent consequence of the northern hemisphere stratospheric warming can also be seen in the lower left section of Figure 8 which gives the ratio of northern hemisphere maximum to the equatorial minimum. Again, the observed rate of change with season is the less for the BUV measurements. The ozone ratios in upper right section of Figure 8 indicate that the rate of increase of the ozone maximum from April to October in the southern hemisphere was greater during the period of 1957-1966 than it was for the year 1970-1971. The lower right section of Figure 8 indicates the BUV experiment detected 10-12% more ozone in the equatorial regions than ground based Dobson measurements of 1957-1966. Furthermore, the difference was less in April and July.

The change of the yearly mean of total ozone with latitude is given in Figure 9. The asymmetric nature of the yearly mean of the total ozone distribution is easily seen in this figure. The largest latitudinal gradients are between latitudes of 30°-50°. These gradients are 3.45 m atm-cm/° and 2.58 m atm-cm/° for the northern and southern hemispheres respectively. The northern hemisphere maximum, 415 m atm-cm, lies at latitudes above 70° whereas the southern hemisphere maximum, 363 m atm-cm, is observed at 60°. The minimum, 262 m atm-cm, appears to be shifted slightly south of the equator which is opposite to that reported by Gebhart et al. (1970). Not only are ozone values larger but so is the ratio of the northern to southern hemispheric peak if one compares the BUV observations from 1970-1971 with the Dobson measurements from 1957-1966.

The mean amounts of ozone from the BUV 1970-1971 data for the northern hemisphere maximum, the equatorial minimum, and the southern hemisphere maximum are 18%, 14%, and 13% higher respectively than the Dobson 1957-1966 mean data. From this it appears that even the yearly mean latitudinal ozone distribution is enhanced by a major stratospheric warming at high latitudes.

A global and hemispherical ozone budget has been derived from the monthly average of the daily zonal means. This budget in terms of the number of ozone molecules is presented in Figure 10 for a 13 month period which began in April 1970.

The temporal variation of the hemispherical ozone is determined by meridional transport, photochemical reactions and destruction mechanisms in the troposphere and at the surface of the earth.

The maximum hemispheric ozone gradients with time occur during the periods of May-June and November-December. In the May-June period ozone was being removed from the northern hemisphere at more than twice the rate at which it was increasing in the southern hemisphere. During the November-December period the rate of loss from the southern hemisphere essentially balanced the rate of increase in the northern hemisphere. These gradients are given in Table 1. A hemispheric ozone budget has also been published by Brewer and Wilson (1968) for the year 1964 which was a period of solar minimum in the sunspot cycle. They observed a loss rate of $1.6 \times 10^{29}\ s^{-1}$ in the northern hemisphere and a rate of increase of $2.3 \times 10^{29}\ s^{-1}$ in the southern hemisphere for the May-June period. During the November-December period they observed a rate of increase in the northern hemisphere of $5.4 \times 10^{29}\ s^{-1}$ and a loss rate of $2.1 \times 10^{29}\ s^{-1}$ from the southern hemisphere. It is not clear what the reason is for this discrepancy.

The global ozone budget for a period of one year, April 1970 to April 1971, is given at the top of Figure 10 and it is compared with that derived from the paper by Brewer and Wilson (1968) for 1964. Not only are the general shapes of the two curves quite different but the magnitudes are different. Compared on a yearly basis, the BUV observations give a yearly average of 4.24 x 10^{37} molecules of ozone which would be equivalent to a uniform distribution of 0.309 m atm-cm. The data for 1964 indicate a yearly average of 4.06 x 10^{37} molecules of ozone or 0.296 m atm-cm if distributed uniformly over the globe.

The daily zonal means of ozone are described on the basis of their changing nature throughout the one year period for the total, amounts above the 10 mb and 4 mb pressure levels, and the partial pressure at the 4 mb pressure level of the atmosphere. There are definite seasonal changes as well as geophysical changes which can be associated with a northern hemisphere stratospheric warming. Daily zonal means of total ozone are given in Figure 11 for the northern hemisphere and in Figure 12 for the southern hemisphere. The amount of ozone above the 10 mb level is given in Figure 13 for the northern hemisphere and in Figure 14 for the southern hemisphere. Similarly, the amount above the 4 mb level of the atmosphere is given in Figure 15 for the northern hemisphere and in Figure 16 for the southern hemisphere. The partial pressure of ozone in μmb at 4 mb level of the atmosphere is given in Figure 17 for the northern hemisphere and in Figure 18 for the southern hemisphere.

Seasonal changes in the total ozone can be seen in Figures 11 and 12 which are quite different from those which are evident in the monthly mean data. From 80°N to 30°N the day to day changes in the zonal mean of total ozone are significantly less in the spring and summer than they are in the fall and winter periods. The extent to which the fall-winter daily variations are related to the major northern hemisphere stratospheric warming of December, 1970 and January, 1971 is not known. This fall-winter seasonal effect in the daily variability of the zonal means of total ozone also appears to be present in the data for the southern hemisphere for latitudes south of 10°S which are given in Figure 12. This time period also appears to be characterized by quasi-periodic variation of 8-13 days for latitudes of 30°S to 60°S. In general, one can characterize total ozone in the southern hemisphere as being significantly more variable on a short term basis of days than it is in the northern hemisphere.

The significant increase in the magnitude of the short period variability of ozone in the fall-winter period for latitudes of 20°N to 80°N and 20°S to 80°S is also observed in the daily zonal means of the amount of ozone above the 10 mb and 4 mb pressure levels of the atmosphere which are presented in Figures 13 and 14 for the 10 mb level and Figures 15 and 16 for the 4 mb level for the northern and southern hemispheres respectively. As was observed for total ozone, the fall-winter variability is significantly greater in the southern hemisphere than in the northern hemisphere. The variability appears to be greatest for the amount of ozone above the 10 mb level. Some evidence of enhanced short period variability during the fall-winter also can be seen for the mid and high latitudes in Figures 17 and 18 which give zonal means of the partial pressure of ozone in μmb at the

4 mb level of the atmosphere. This is directly related to the mass mixing ratio in $\mu g/g$ which can be obtained by multiplying the value in μmb by 0.414.

The most dramatic temporal change in the ozone above the 10 mb and 4 mb levels and the partial pressure at the 4 mb level appears to be associated with the northern hemisphere stratospheric warming which according to the analysis by Quiroz (1973) began with the traveling wave retrogression on December 12, 1970 and ended with the reversal of polar circulation at the 10 mb level on January 18, 1971. The sudden phase of the warming lasted from December 30, 1970 to January 18, 1971. As remarked earlier this stratospheric warming appears to be associated with the total ozone at 60° N and 70° N reaching a maximum in January instead of during the normal March-April period. Ozone above 10 mb began a dramatic build up at latitudes north of 50° N in mid September. This build up reached a peak at 60° N-70° N about January 2, 1971. The peak can be followed southward to about 20° S. The peak at 20° S was observed 8-10 days after that at 60° N-70° N. Coincident with the steep rise in ozone at 60° N and northward but prior to the high latitude peak, two maxima are observed at 50° N on Nov. 6, 1970 and Nov. 26, 1970. From 40° N to 10° N a decrease in the zonal mean of ozone above 10 mb coincides with an increase at the high latitudes. During this same period ozone from the equator to 20° S increases to a maximum on about Jan. 10, 1971.

Ozone above 4 mb seems to follow the general trend just described for that above 10 mb. The peak in early January represents an increase by about a factor of four above the pre September level for both the 10 and 4 mb data. Some insight on possible explanations of the dramatic build up of ozone in the vicinity of the stratospheric warming may be obtained from the zonal means of the partial pressure (μ mb) of ozone at the 4 mb level which are given in Figures 17 and 18. This partial pressure, μ mb, can be converted into the ozone mass mixing ratio (μ g/g) by multiplying by 0.414. The 55 μ mb peak on January 2 at 70° N corresponds to a mass mixing ratio of 23 μ g/g. This is about 44% larger than the normal maximum of 16 μ g/g which is observed in the tropical stratosphere, and more than a factor of 2.7 larger than the pre-stratospheric warming value of 8.5 at 70° N. This large increase in the mixing ratio is not common to the other high latitudes at this time. At 60° N the mixing ratio increases from 11 to 15.7 μ g/g which represents only a 43% increase. Moving southward no other significant peaks are observed which can be associated with the stratospheric warming.

The abnormally high mass mixing ratios which are observed at 70° N are strongly suggestive of a non-photochemical source. An attractive high latitude source could be the creation and storage of ozone in the polar cap and the auroral regions during the polar night. A mechanism for the creation of a polar source of ozone by charged particles has been postulated by Maeda (1968). A stratospheric warming has been described by Hirota (1968) as the interaction of an eastward traveling thermal wave with a standing wave. Quiroz (1973) has used data from the SIRS and VTPR experiments on Nimbus satellites to track the high radiance systems which are associated with stratospheric warmings. His analysis indicates that a poleward migration of an amplified high radiance system began about December 30, 1970 and ended about January 18, 1971 when the center of the system reached the opposite hemisphere. It is suggested that the interaction of an easterly moving thermal wave with an east Siberian standing wave with the subsequent poleward migration on a high radiance system may be associated with the release of a store of ozone from the auroral and polar cap regions which had been created by incident charged particles during the polar night as described by Maeda (1968).

CONCLUSIONS

Simultaneous satellite observations of the sun, solar interplanetary magnetic sector boundaries and global distributions of atmospheric ozone have shown the system to be exceedingly complex but at the same time they should help define the boundary conditions and improve our knowledge of this system.

The sun has been observed to behave as an ultraviolet variable star in the 120 nm to 300 nm region. The principal periods are associated with the 27 day period of solar rotation and the eleven year sunspot cycle. The maximum change associated with the latter appears to originate in the region associated with the solar temperature minimum around 175 nm. The variability of radiation associated with the period of solar rotation increases with decreasing wavelength and for wavelengths less than 175 nm it exceeds the annual variation. Two principal UV active regions separated by about 180° in solar longitude have been observed for more than 60 solar rotations. These provide variable amplitude atmospheric forcing functions of 13-14 day periods. Furthermore, these ultraviolet active regions appear to correlate with central meridian passages of solar interplanetary magnetic field sector boundaries.

Monthly zonal means of total ozone have been used to derive a global ozone budget for the period of April 1970 to April 1971. An unexpected double maximum was observed in the southern hemisphere in the June - November period. In the northern hemisphere the normal spring seasonal peak at 60° N and 70° N appears to have been shifted back into January by a major northern hemisphere stratospheric warming. The distribution with latitude of the yearly mean of total ozone reached a peak value of 363 m atm-cm at 60° S whereas a peak of 415 m atm-cm was observed at 70° N-80° N. A yearly mean value of ozone averaged over the earth was 309 m atm-cm.

Daily zonal means of total ozone and amounts above 10 mb and 4 mb pressure levels exhibited largest day to day variations in the fall-winter period for both hemispheres. These variations were significantly larger in the southern hemisphere than in the northern hemisphere.

Ozone observations prior to the December 1970 - January 1971 stratospheric warming began increasing at high latitudes in September. The associated peak in the high latitude zonal means then moved rapidly southward to 20-30° S in 8-10 days. Abnormally high ozone mass mixing ratios at 70° N have been interpreted as indicating a nonphotochemical source which might have originated within the auroral oval during the polar night.

Table 1

Maximum Rate of Change in Hemispheric Ozone

	Northern	Southern
May - June	$-3.9 \times 10^{29} S^{-1}$	$+1.5 \times 10^{29} S^{-1}$
November - December	$+3.3 \times 10^{29} S^{-1}$	$-3.6 \times 10^{29} S^{-1}$

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Work on the Nimbus 4 BUV experiment has been carried out in collaboration with my colleagues A. J. Krueger of the Goddard Space Flight Center and C. L. Mateer of the Atmospheric Environment Service, Downsview, Ontario. I wish to thank I. Eberstein for computation of daily zonal means of ozone and A. Ghazi for some of the monthly zonal means.

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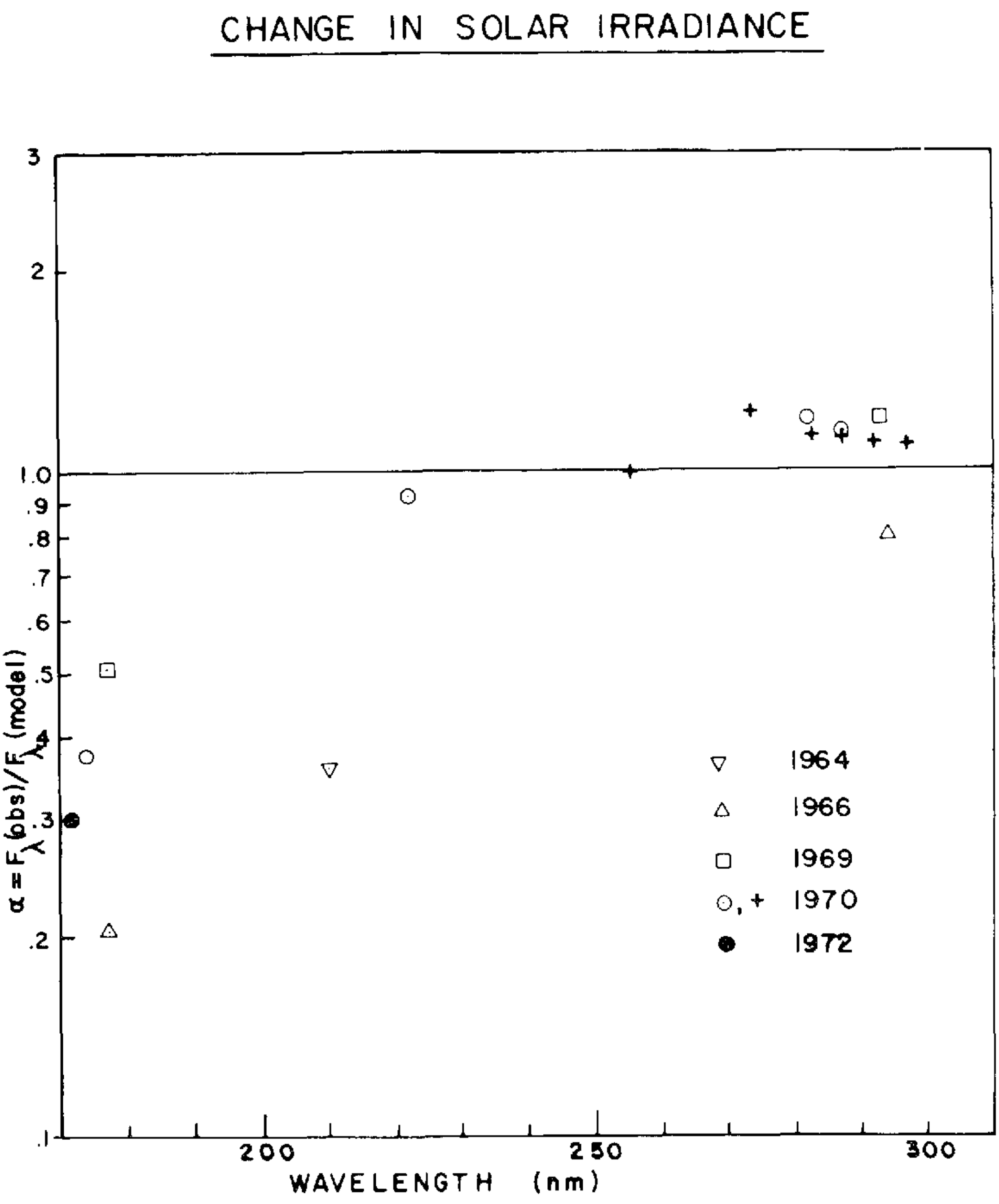

Figure 1. Changes required in NRL model of solar spectral irradiance in order to be compatible with some measurements from balloons, rockets and satellites for a period from minimum to after maximum for solar cycle 20. The quantity, α, when multiplied by the NRL model gives a solar spectral irradiance which is consistent with observations.

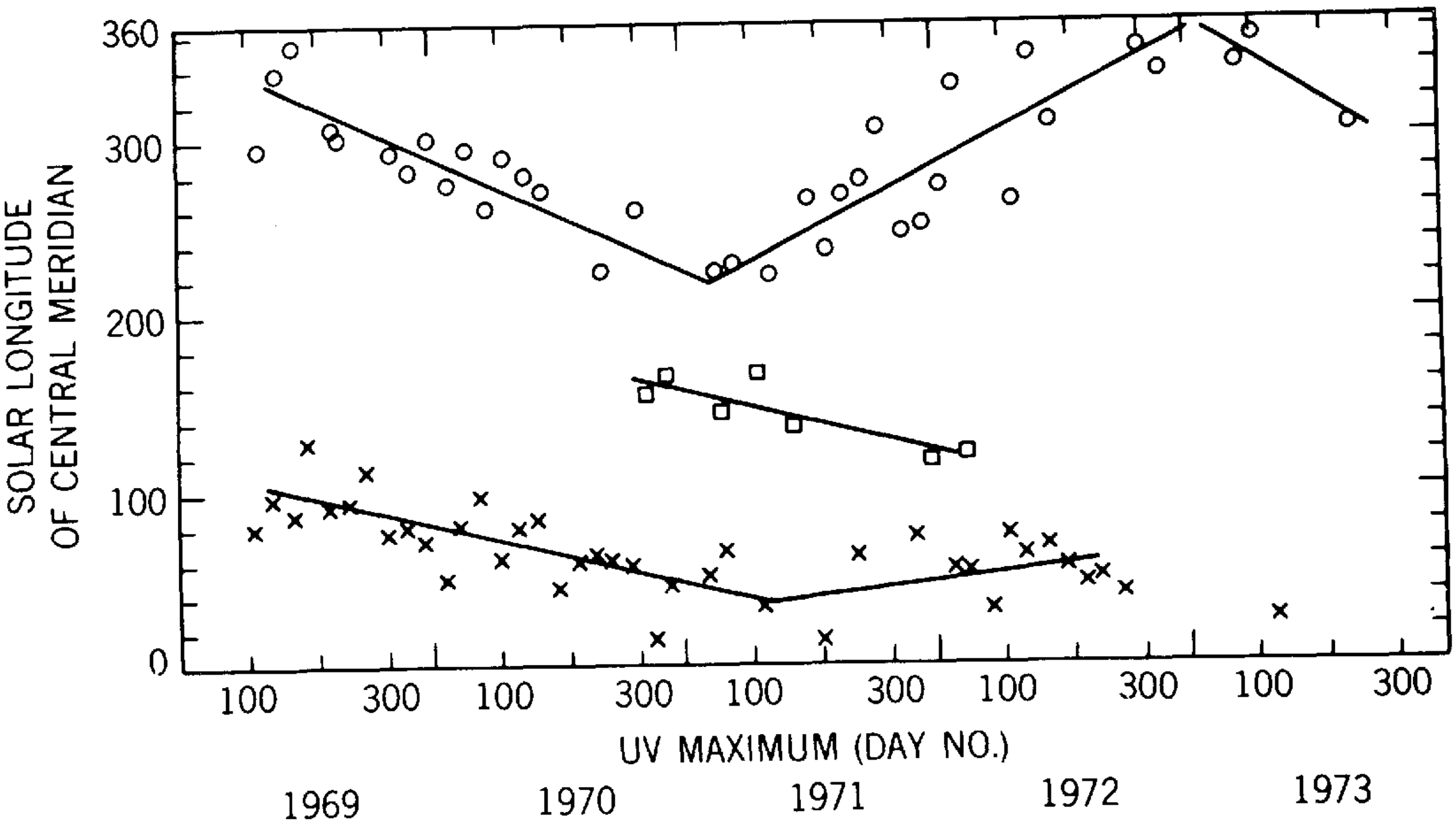

Figure 2. Carrington solar longitude of the central meridian on the day of observed enhancements of irradiance at 121.6 nm and 175 nm during a solar rotation.

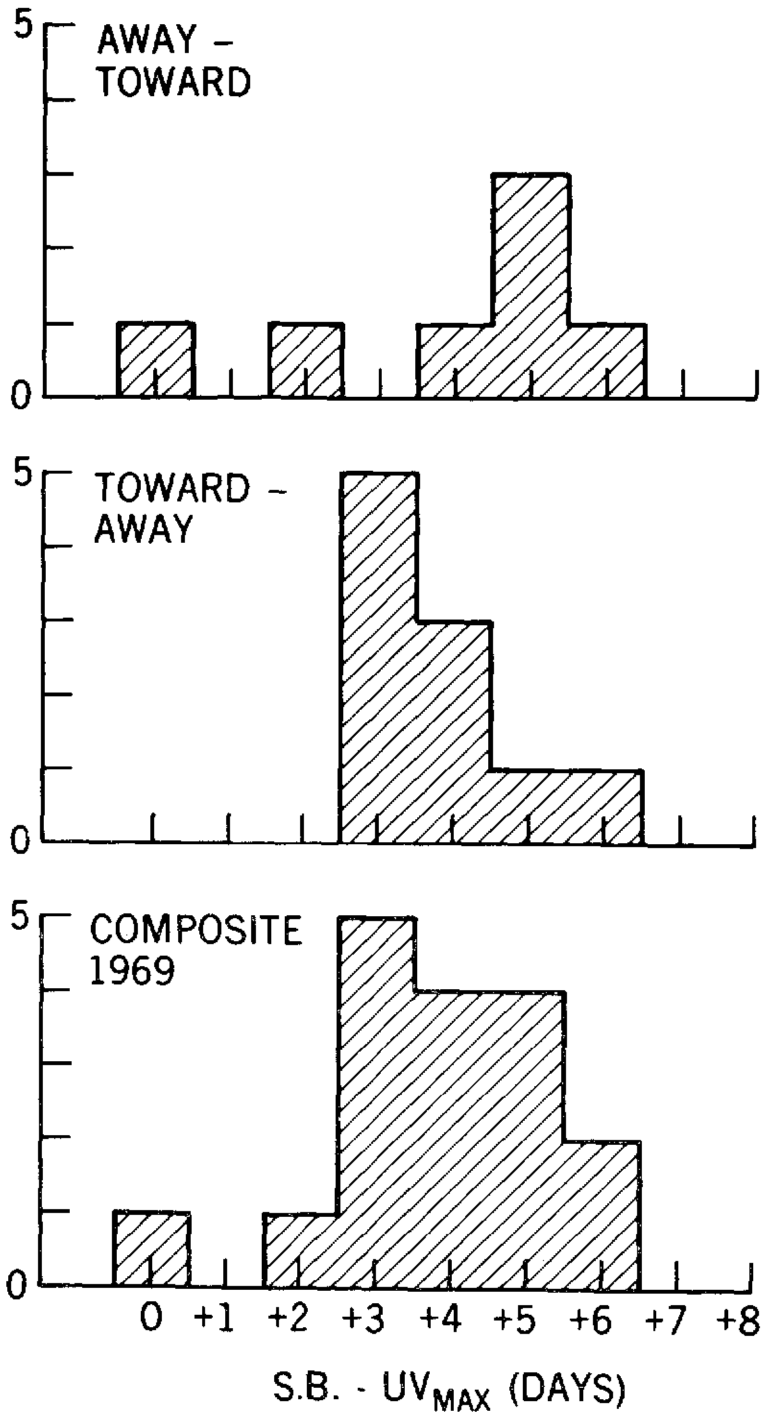

Figure 3. Number of cases of observed time delays between central meridian passages of a solar magnetic field sector boundary and an enhancement in ultraviolet solar irradiance.

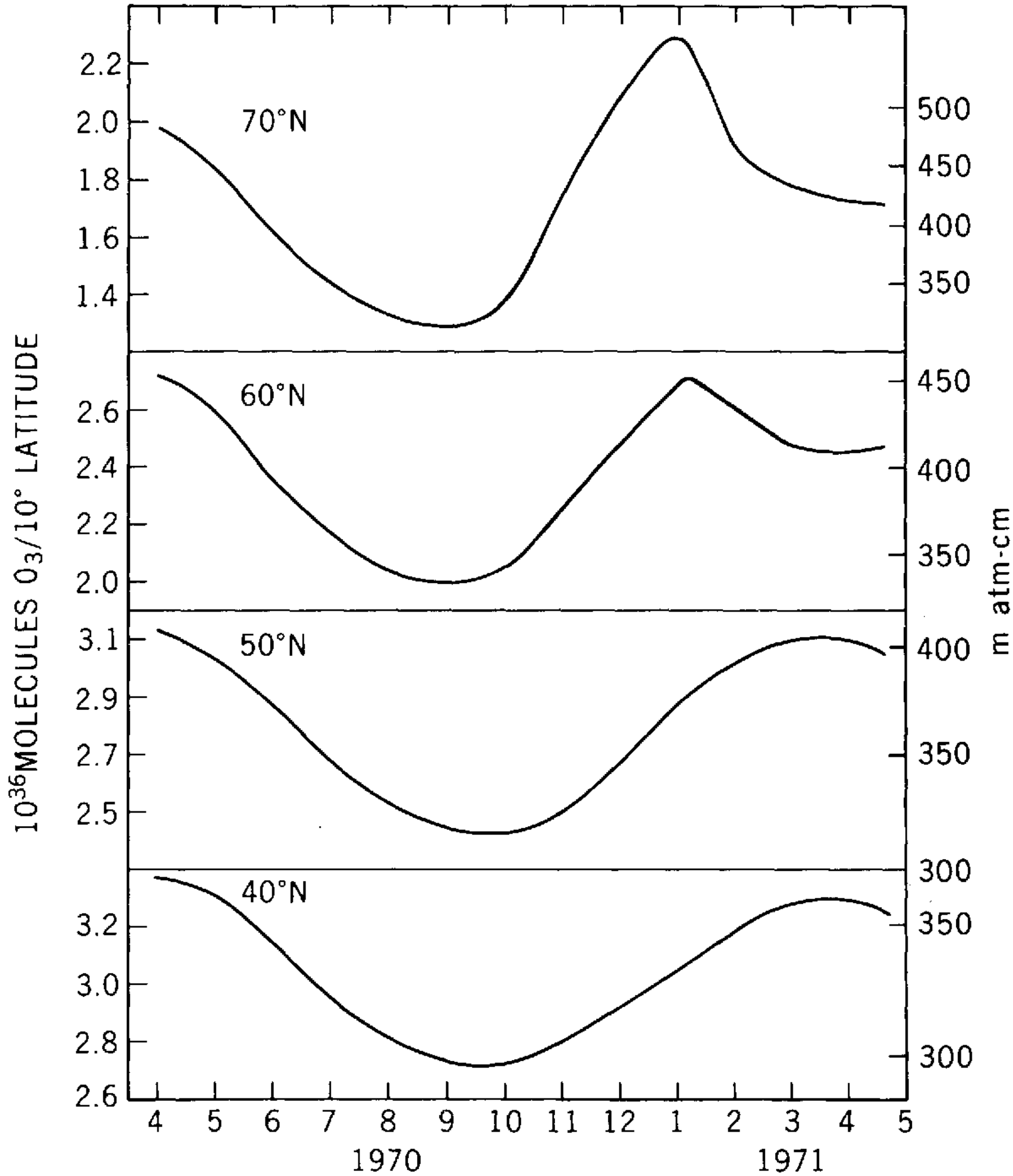

Figure 4. Monthly zonal mean of total ozone averaged in longitude over 10° intervals of latitude from 70° N to 40° N in terms of the total number of molecules within the interval and the corresponding amount in m atm-cm.

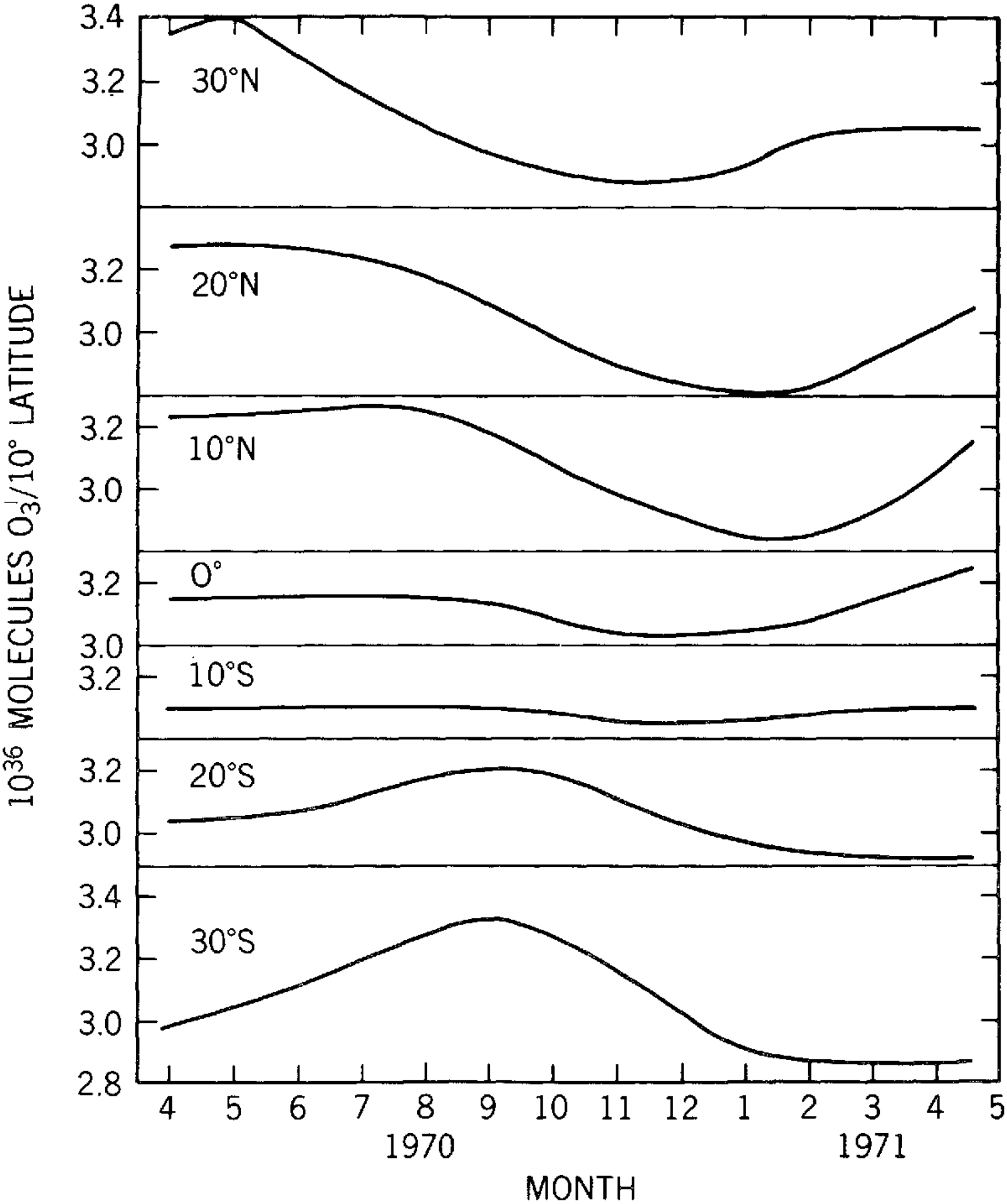

Figure 5. Monthly zonal of total ozone averaged in longitude over 10° latitude intervals from 30°N to 30°S in terms of the total number of molecules within the interval and the corresponding amount in m atm-cm.

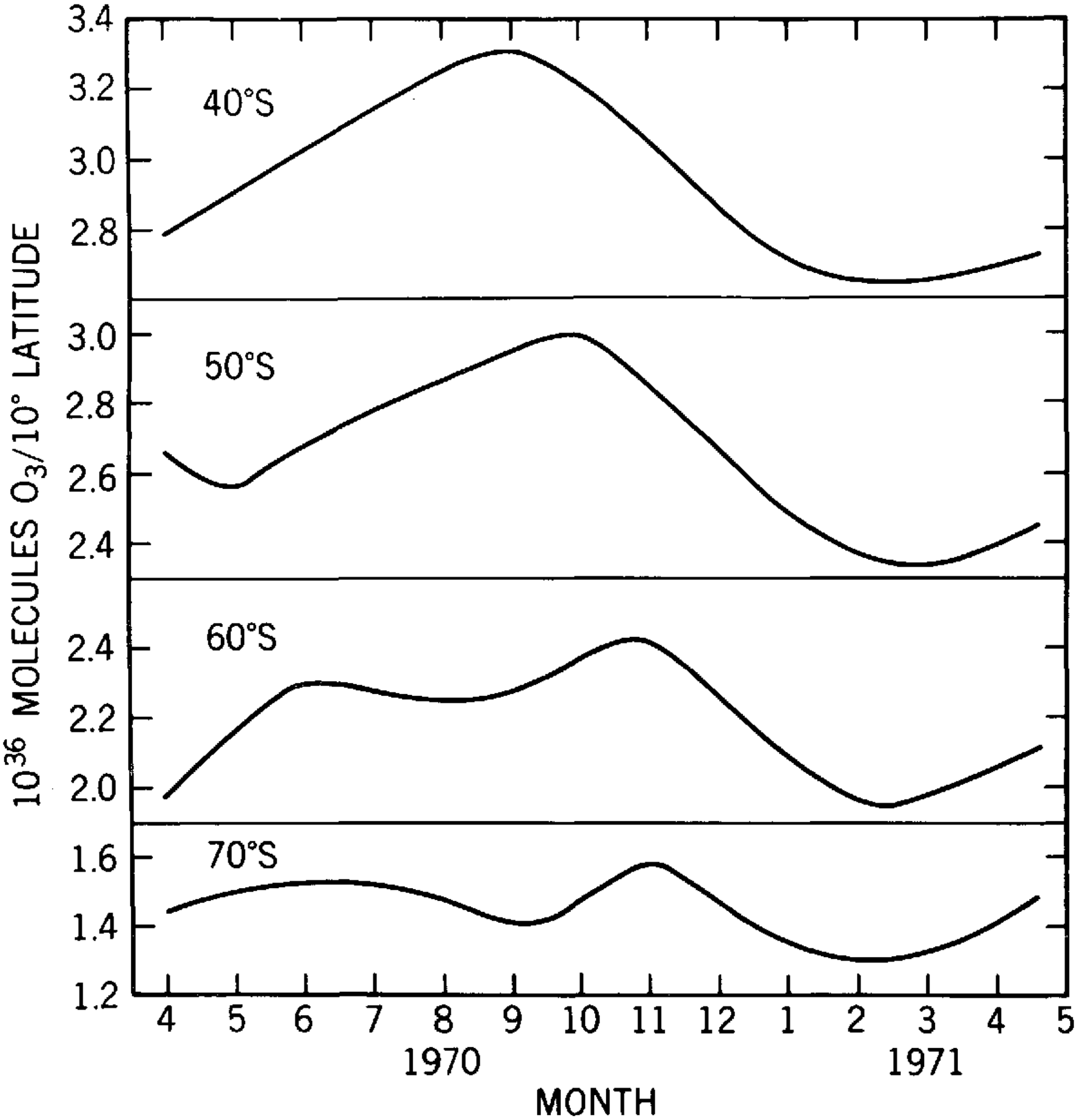

Figure 6. Monthly zonal mean of total ozone averaged in longitude over 10° latitude intervals from 40° S to 70° S in terms of the total number of molecules within the interval and the corresponding amount in m atm-cm.

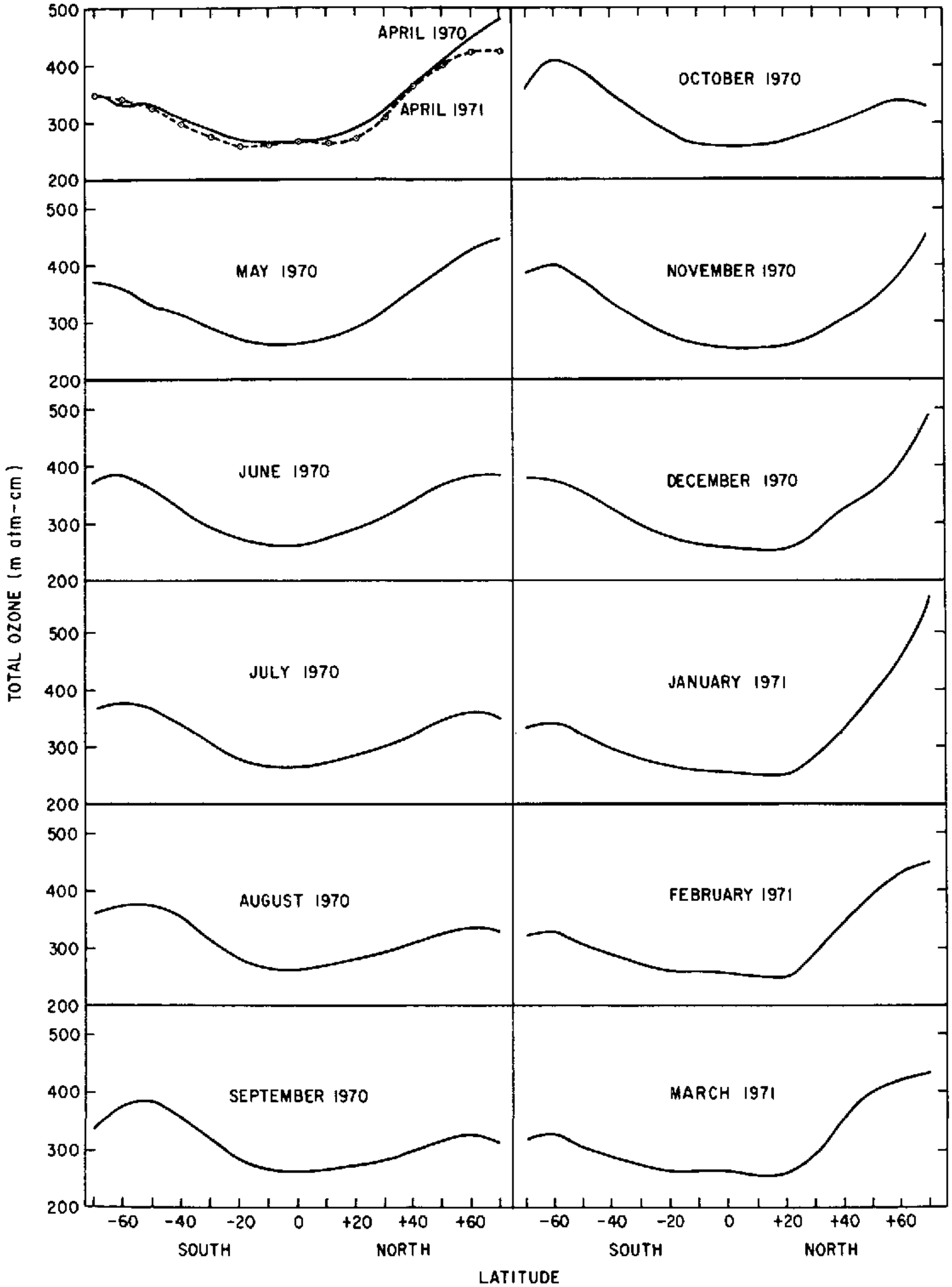

Figure 7. Latitudinal distributions of the monthly zonal means of total ozone for 13 months from April 1970 to April 1971.

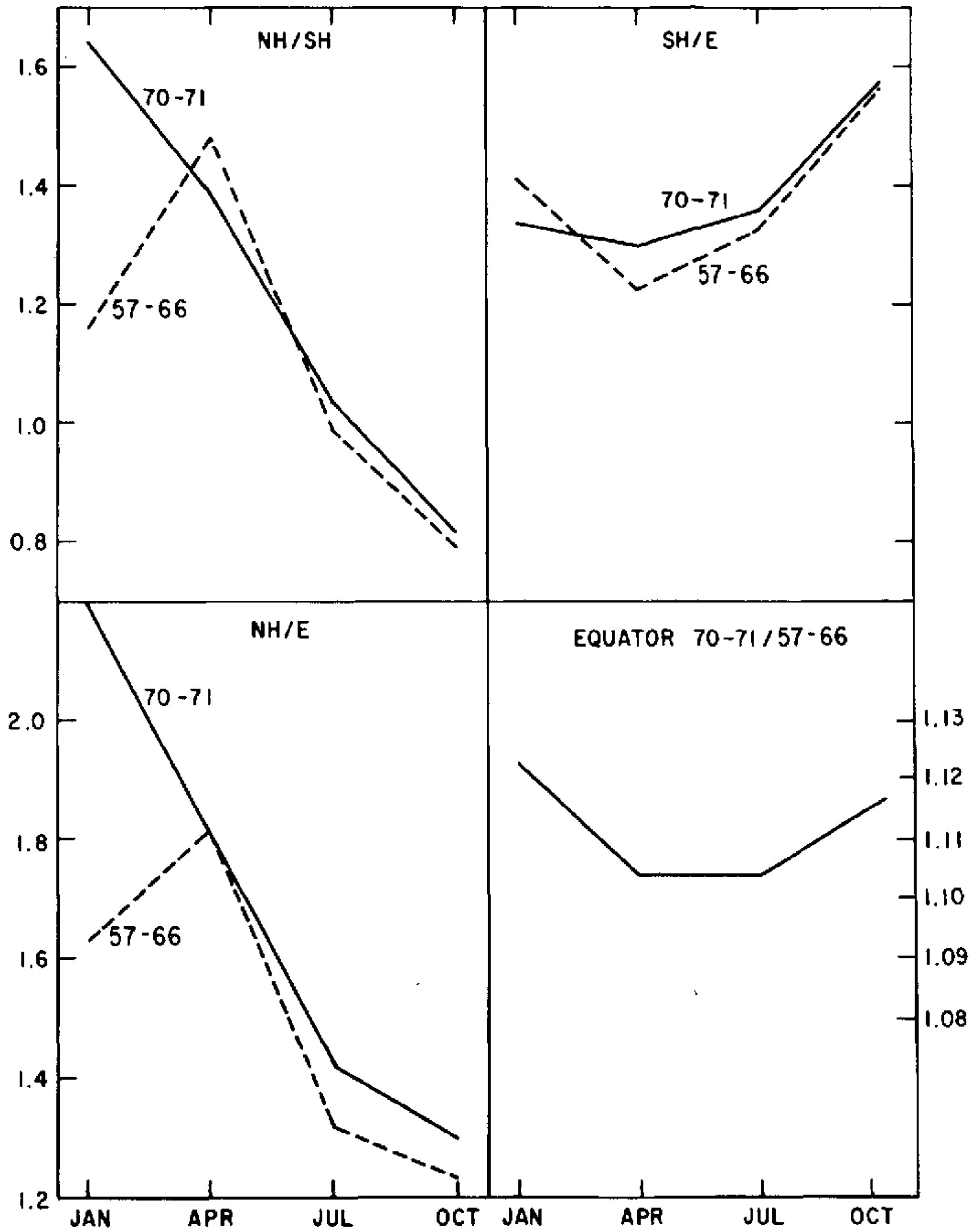

Figure 8. (Upper left.) Ratio of total ozone maximum in northern hemisphere to that in southern hemisphere. (Lower left.) Ratio of total ozone maximum in northern hemisphere to equatorial minimum. (Upper right.) Ratio of southern hemisphere total ozone maximum to equatorial minimum. (Lower right.) Ratio of equatorial total ozone minimum derived from BUV to that from Dobson measurements.

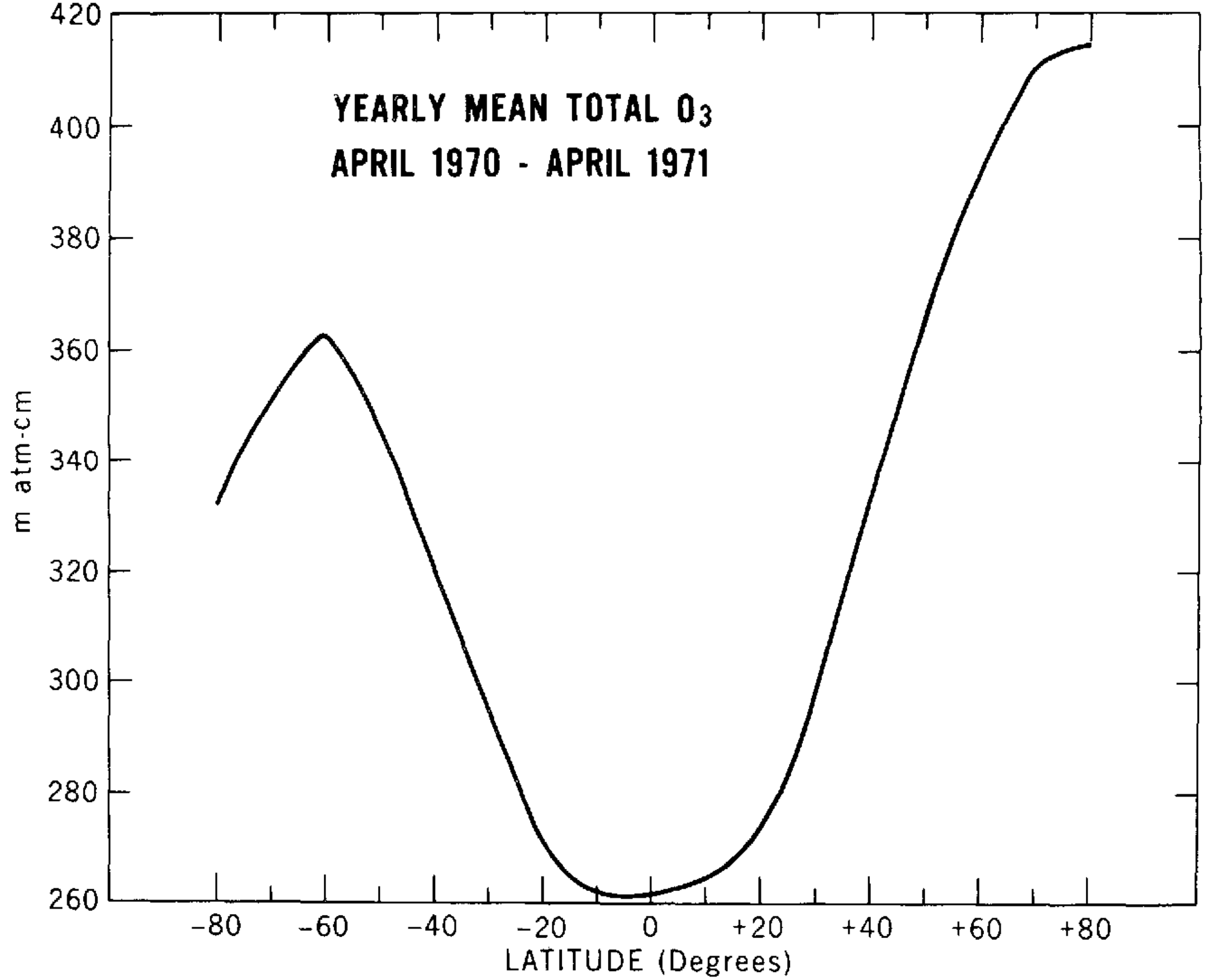

Figure 9. Yearly mean of the latitudinal distribution of total ozone averaged in longitude for the period from April 1970 - April 1971.

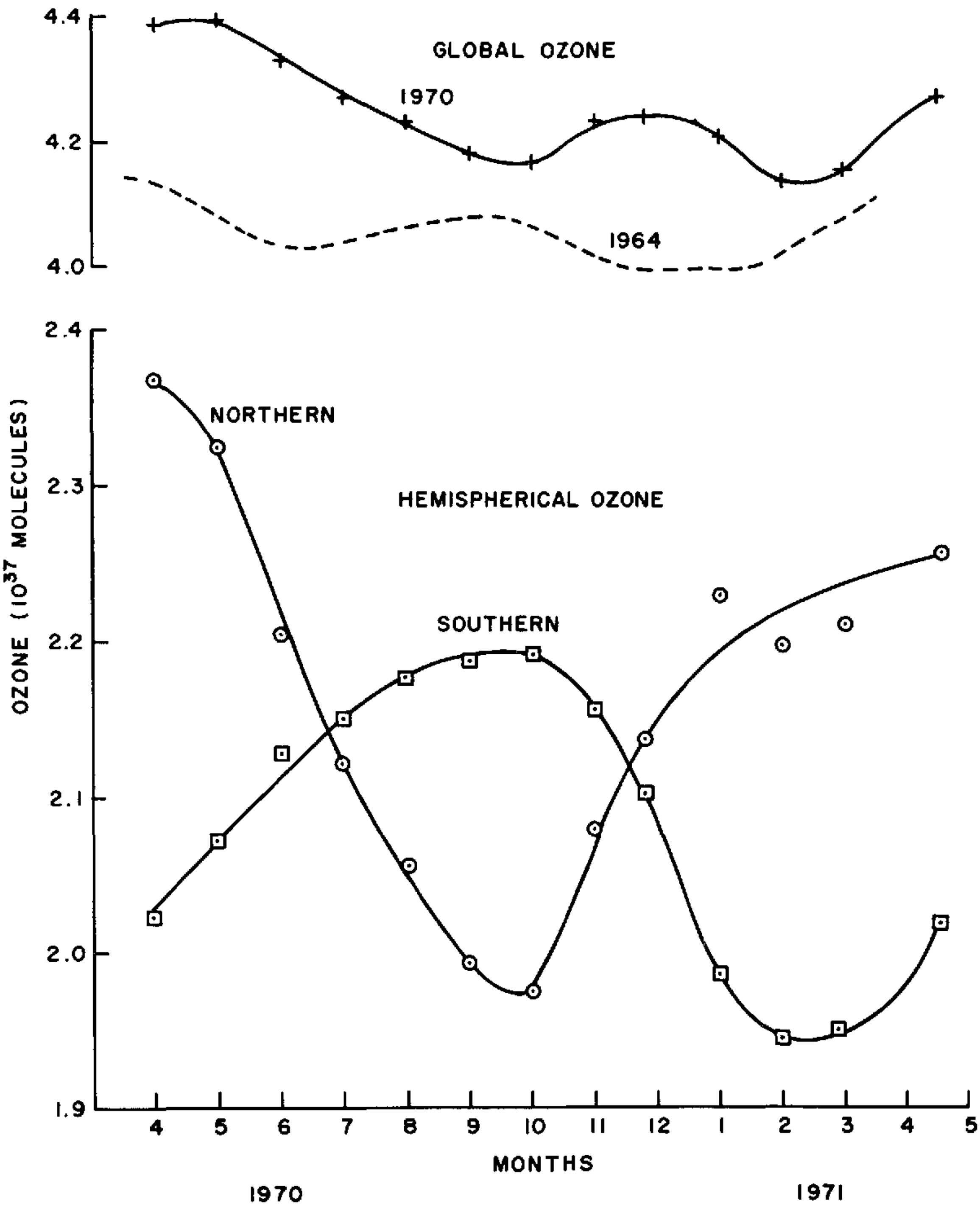

Figure 10. Hemispherical and global ozone budget as derived from monthly means of the zonal means of total ozone.

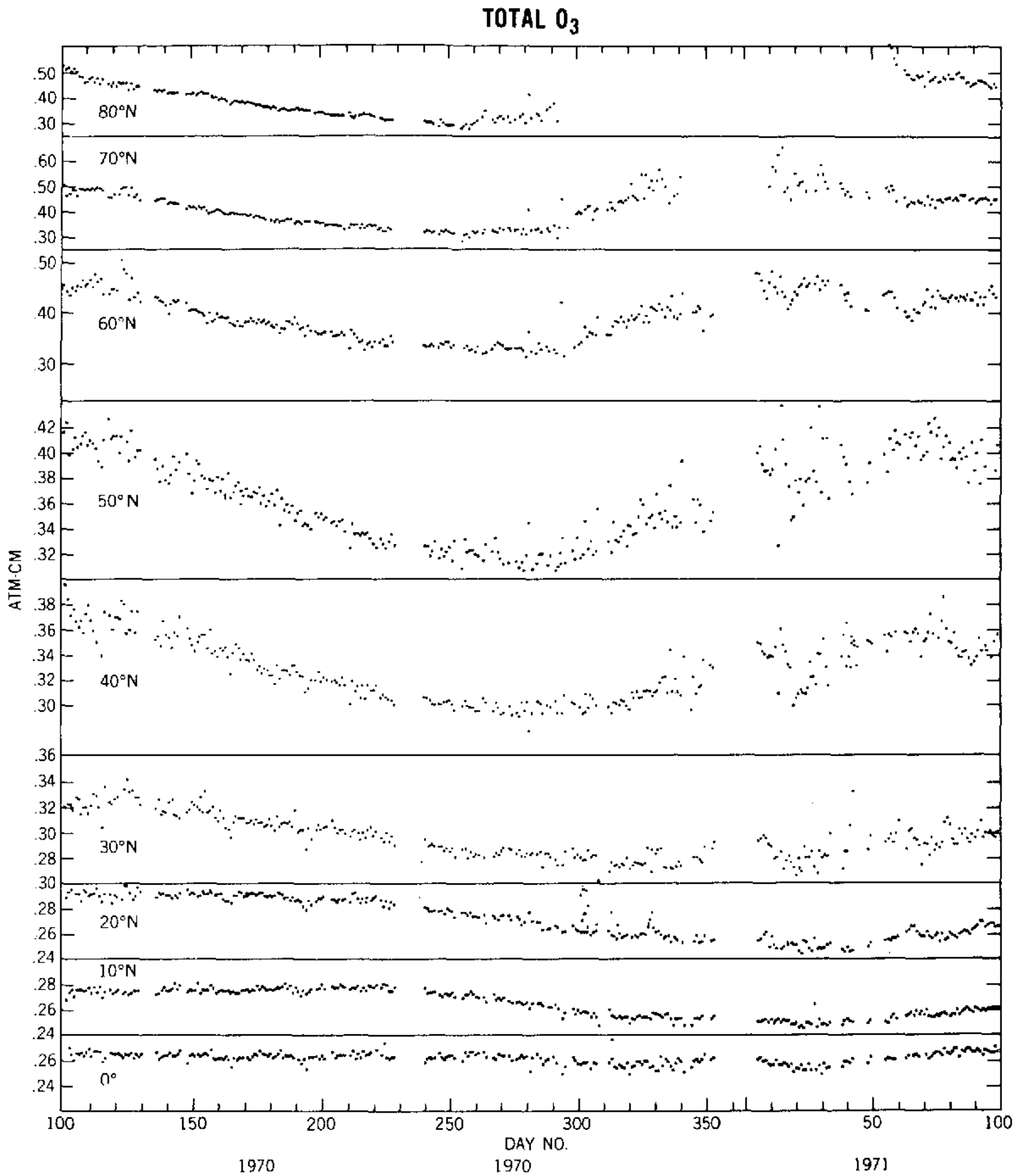

Figure 11. Daily zonal means of total ozone for 10° intervals of latitude in the northern hemisphere.

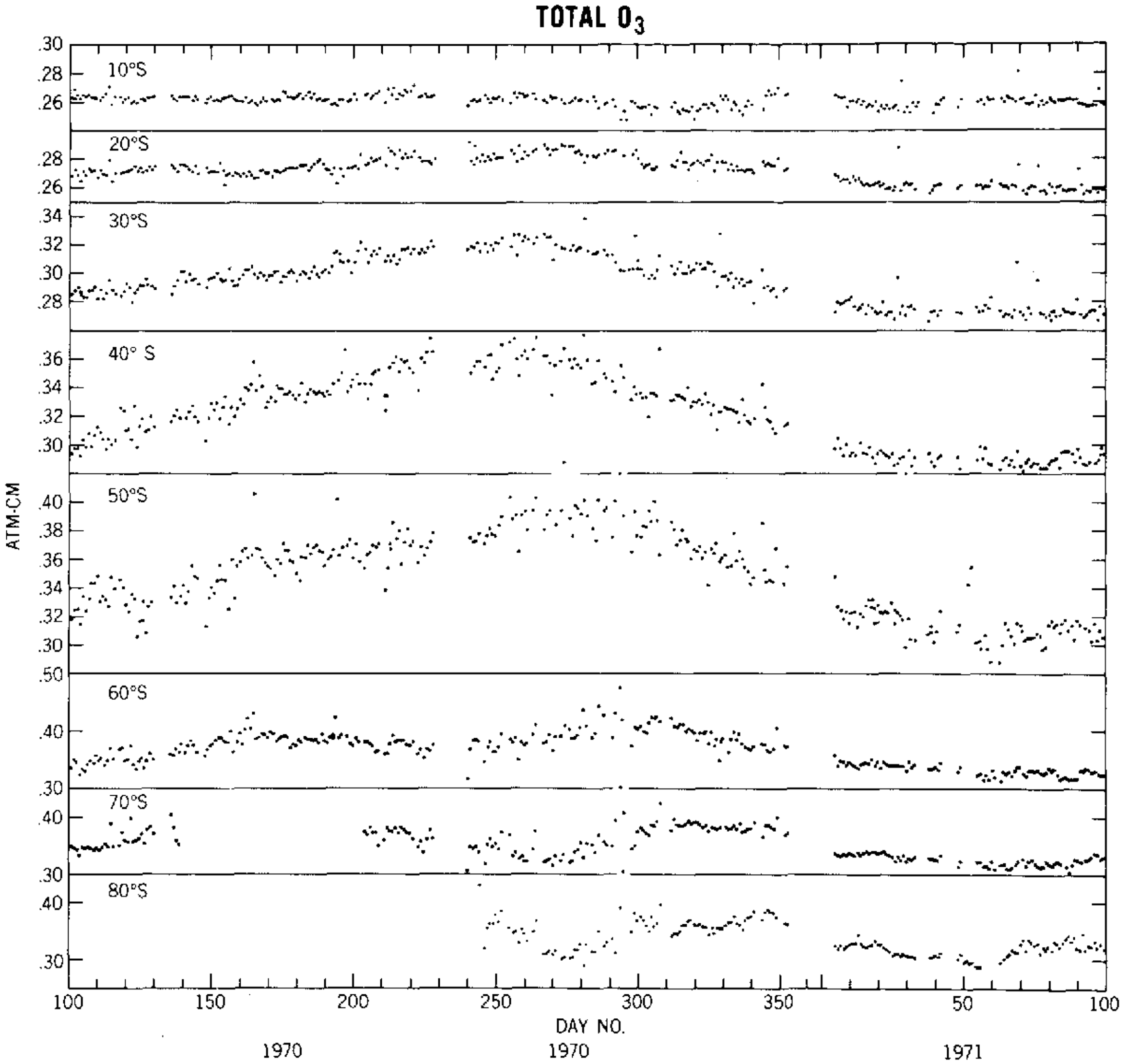

Figure 12. Daily zonal means of total ozone in atm-cm for 10° intervals of latitude in the southern hemisphere.

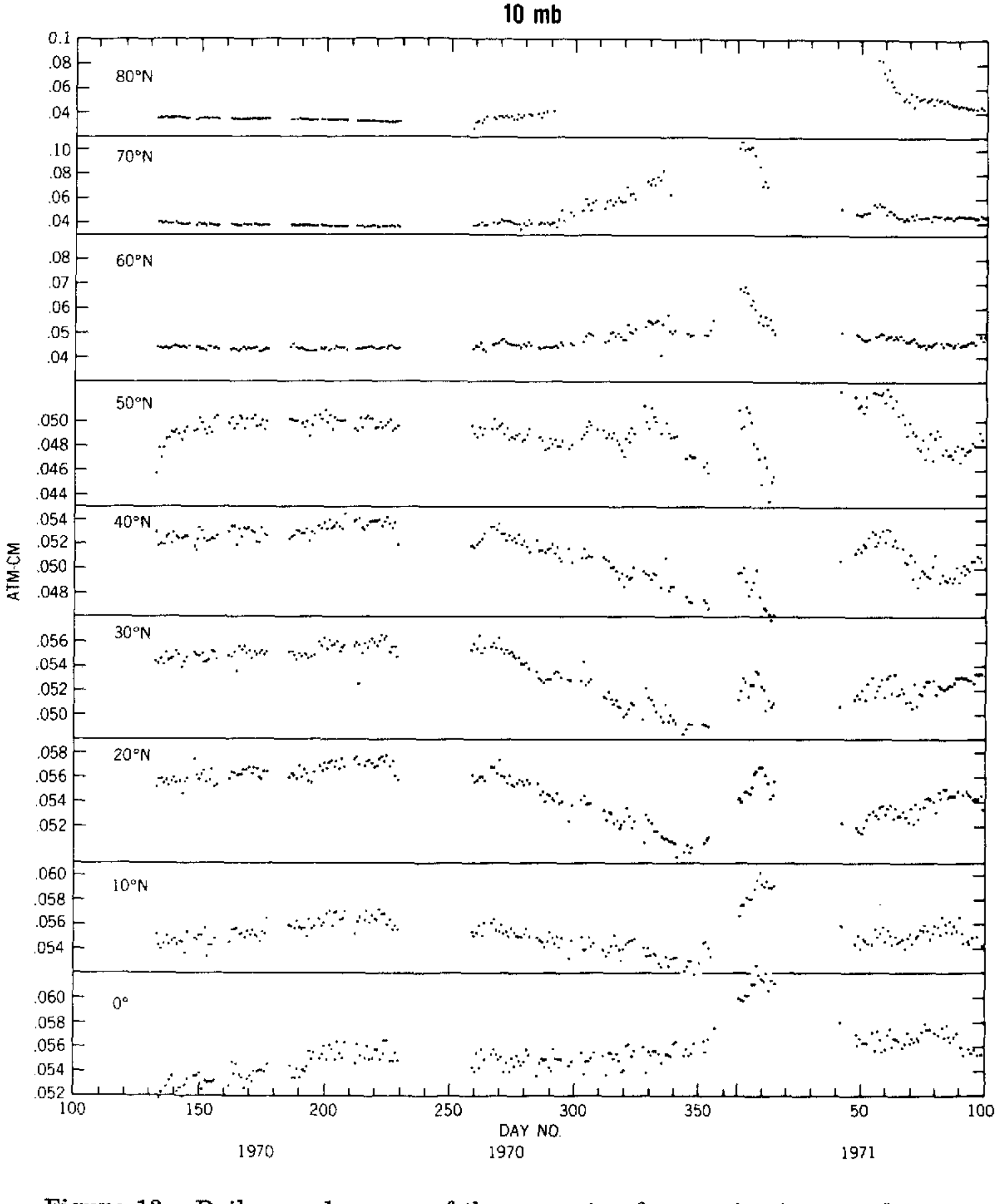

Figure 13. Daily zonal means of the amounts of ozone in atm-cm above 10 mb for 10° intervals of latitude in the northern hemisphere.

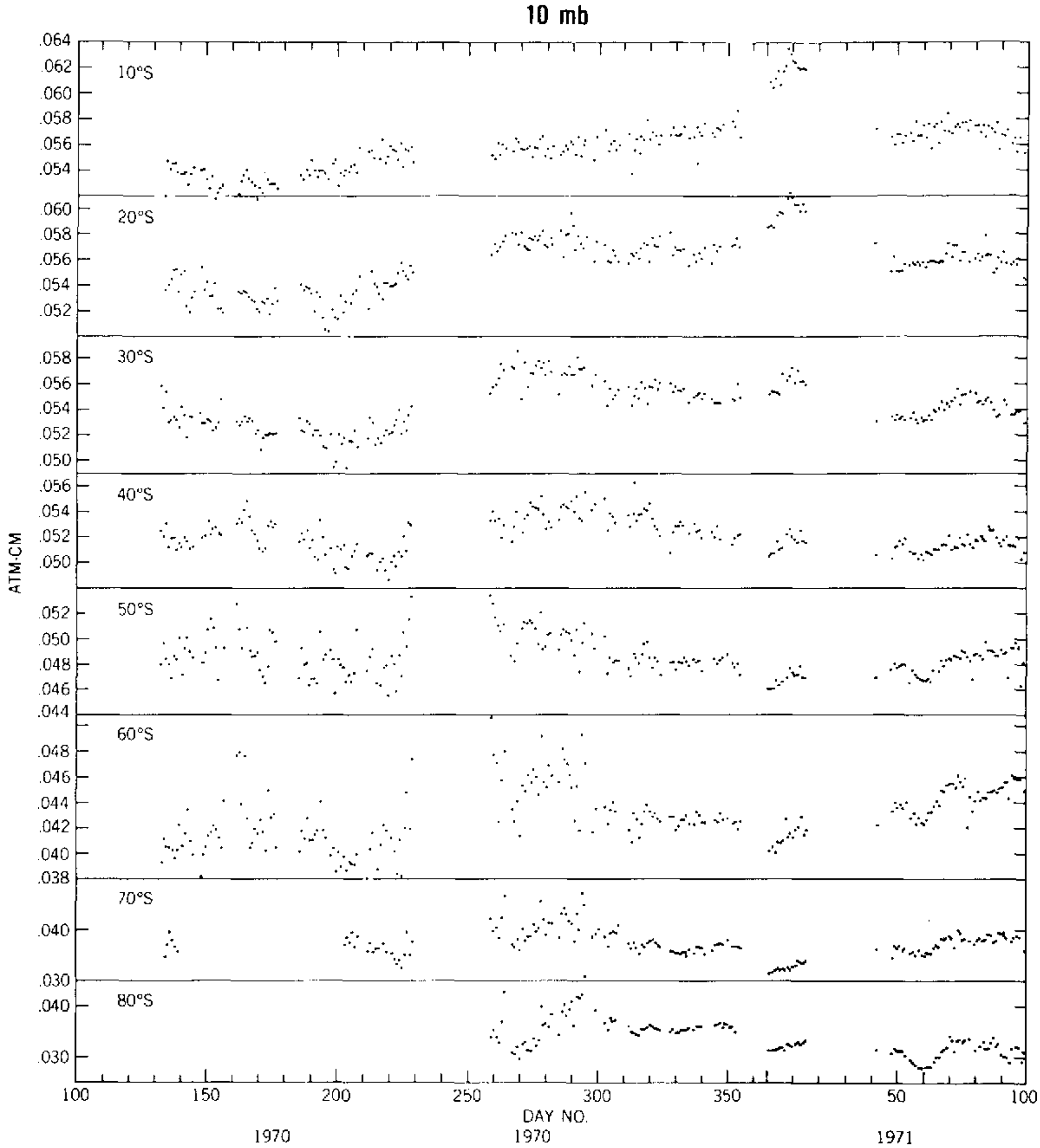

Figure 14. Daily zonal means of the amount of ozone in atm-cm above 10 mb for 10° intervals of latitude in the southern hemisphere.

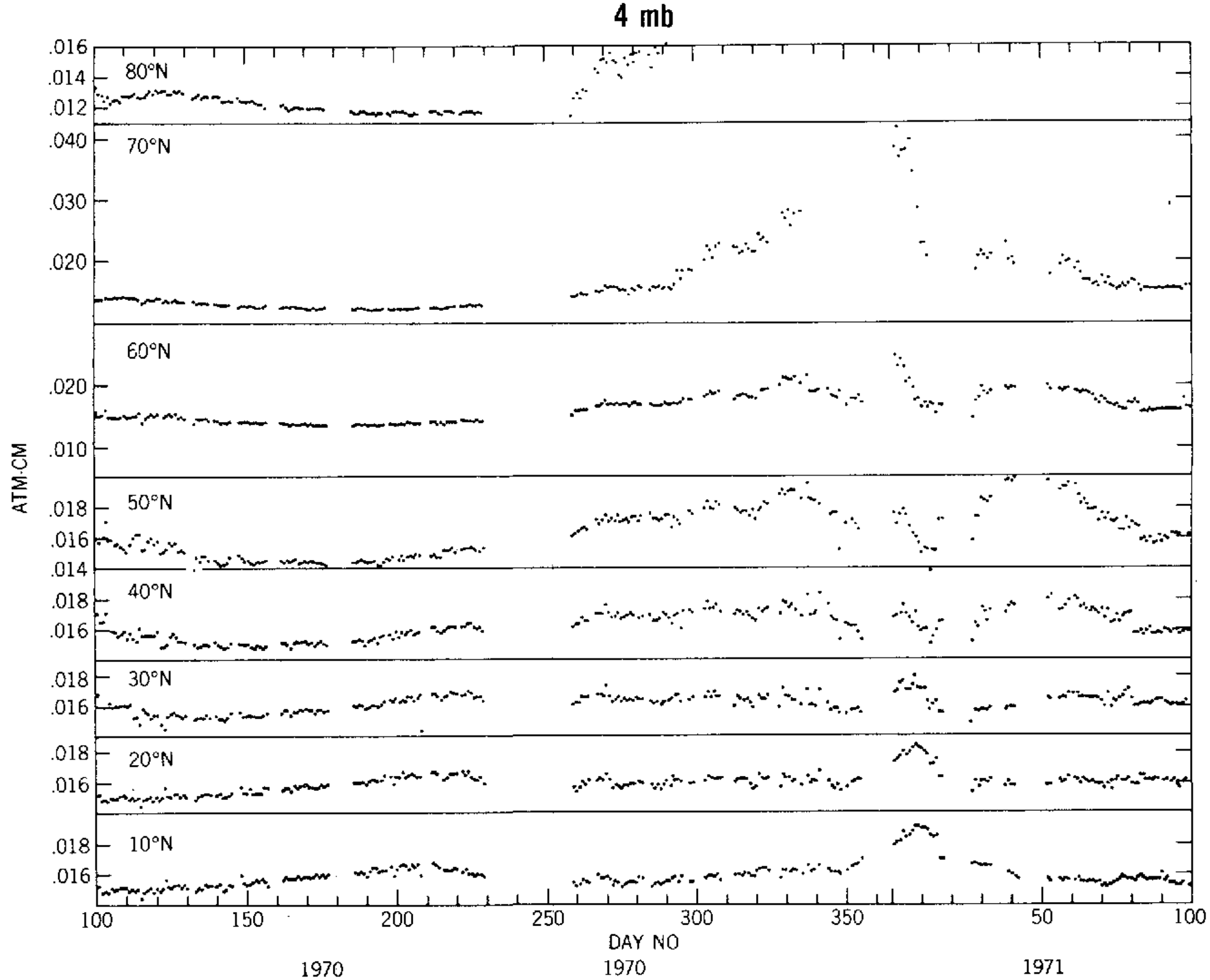

Figure 15. Daily zonal means of the amount of ozone in atm-cm above 4 mb for 10° intervals of latitude in the northern hemisphere.

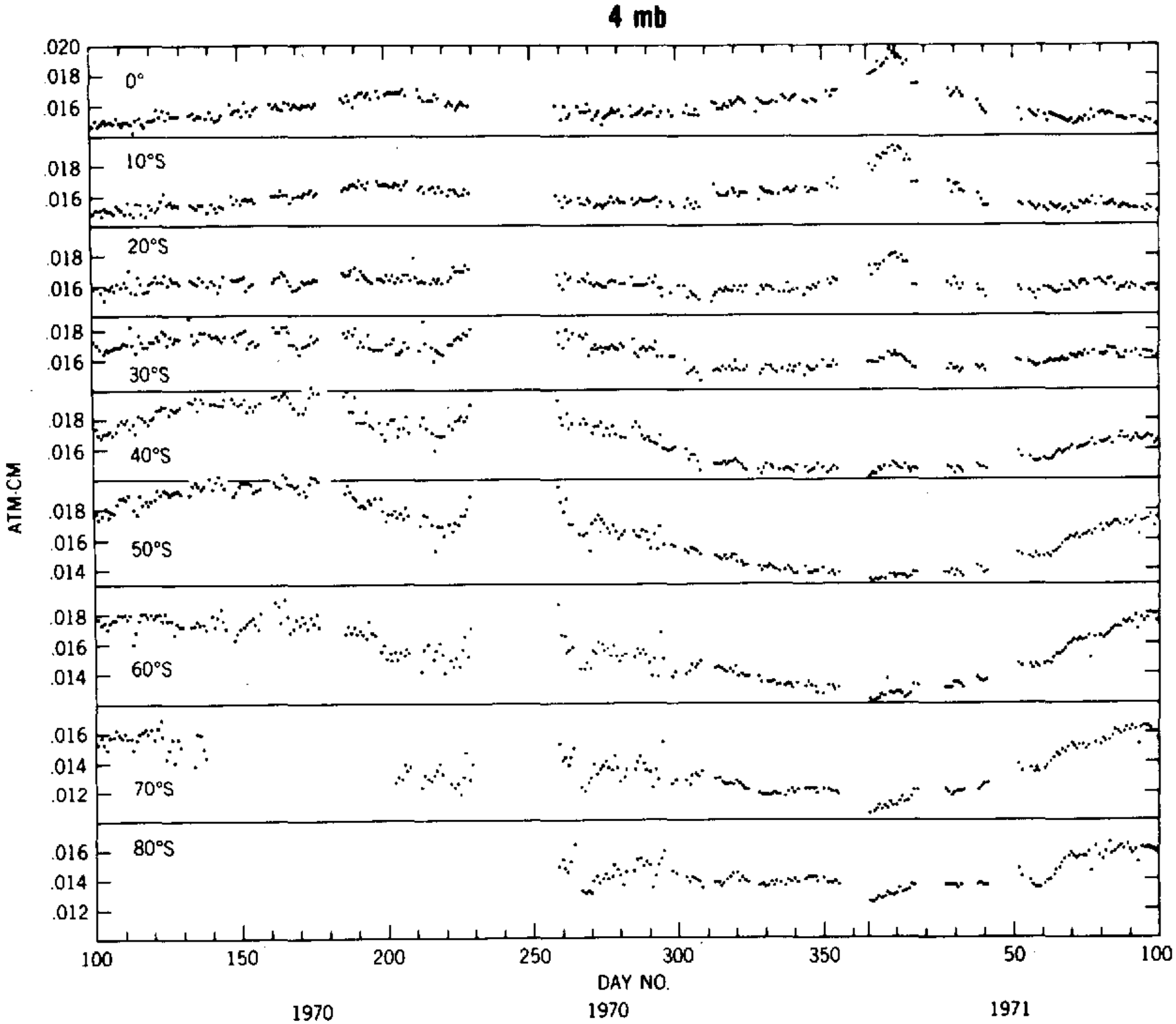

Figure 16. Daily zonal means of the amount of ozone in atm-cm above 4 mb for 10° intervals of latitude in the southern hemisphere.

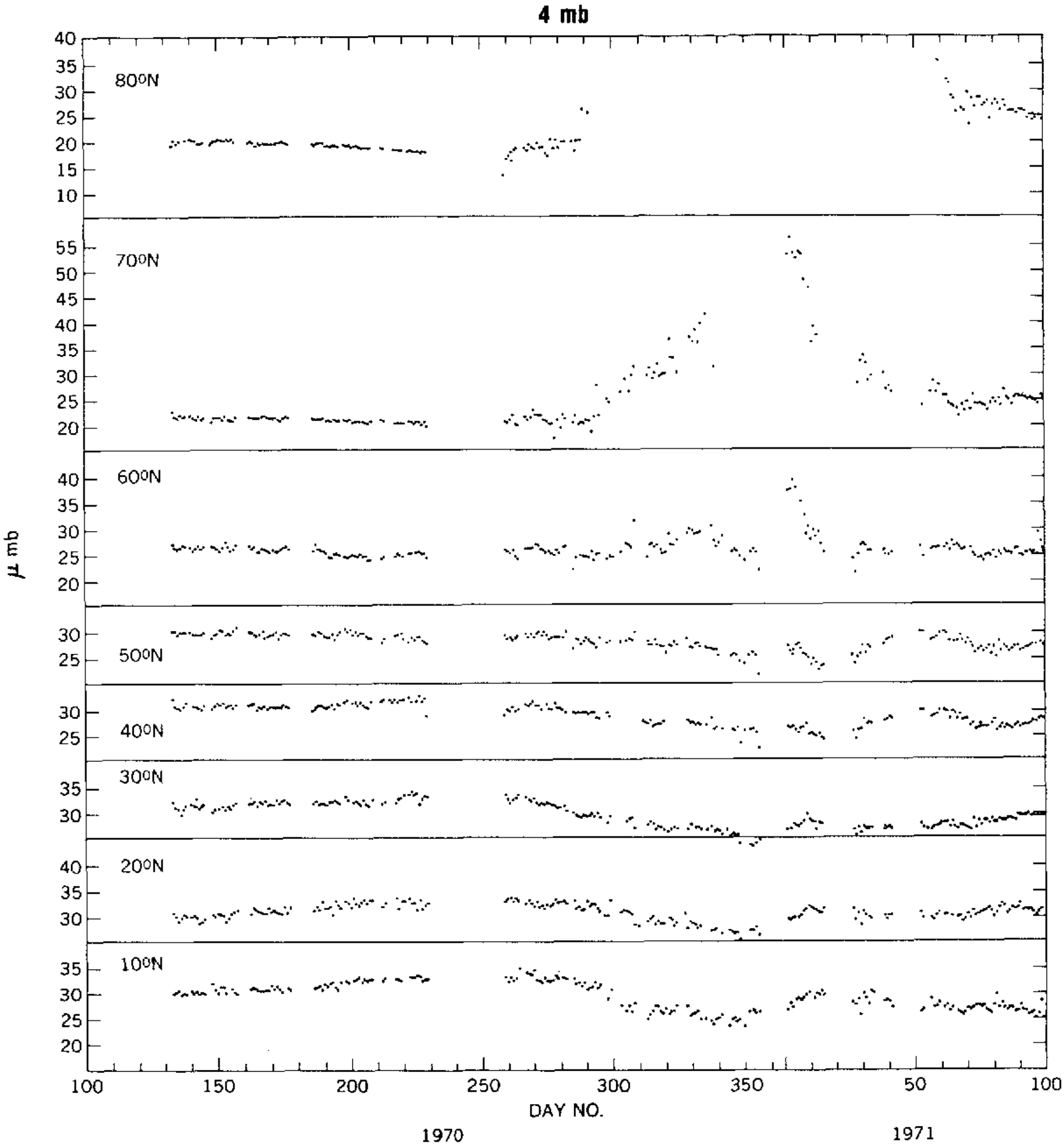

Figure 17. Daily zonal means of the partial pressure of ozone in μmb at 4 mb for 10° intervals of latitude in the northern hemisphere. Multiplication by 0.4.4 gives the mass mixing ratio in μg/g.

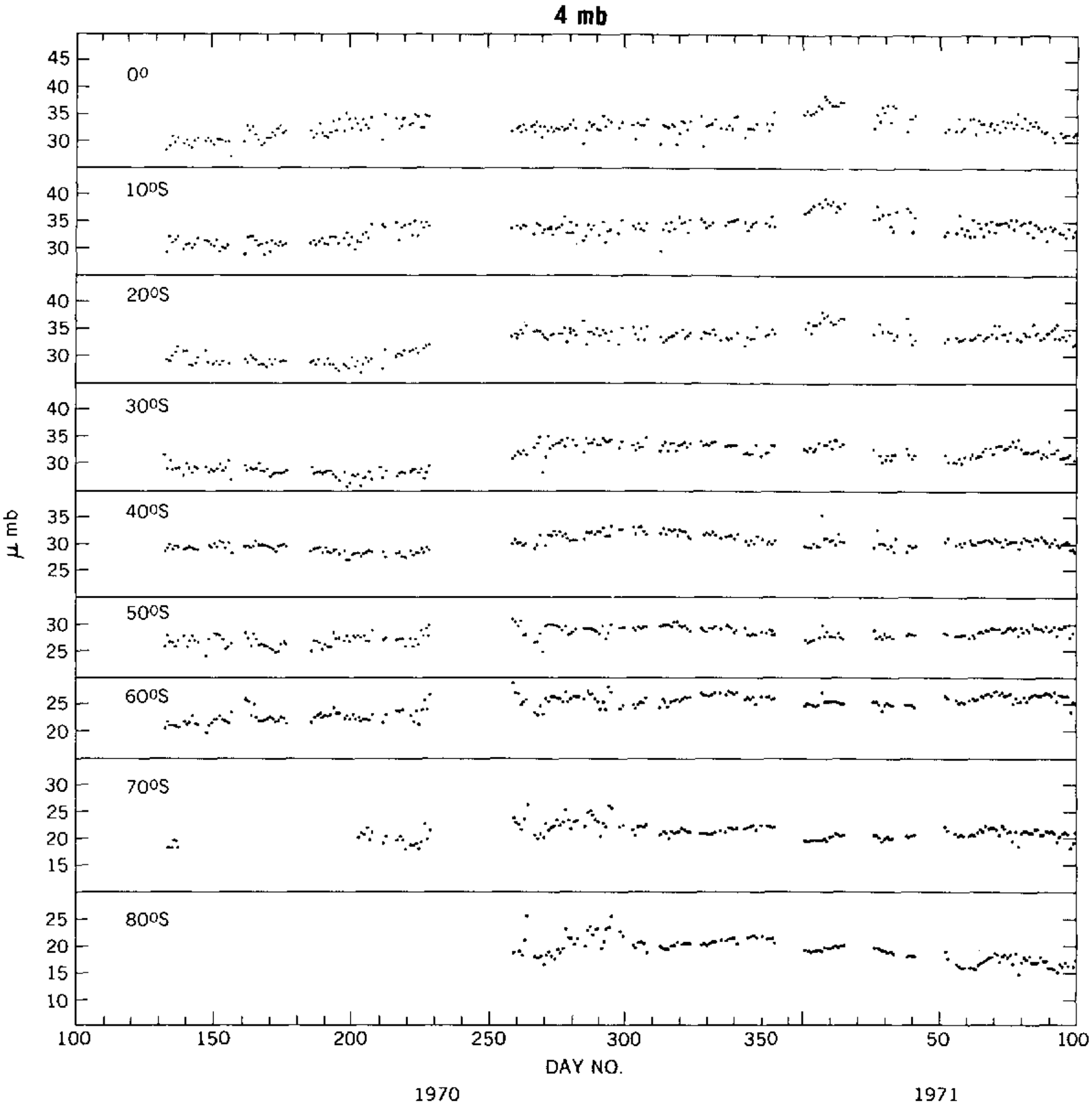

Figure 18. Daily zonal means of the partial pressure of ozone in μmb at 4 mb for 10° intervals of latitude in the southern hemisphere. Multiplication by 0.414 gives the ozone mass mixing ratio in μg/g.

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