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PERIODIC ANALYSIS OF TOTAL OZONE AND ITS VERTICAL DISTRIBUTION

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Abstract

Both total ozone and vertical distribution (below 33 km) ozone data from the period 1957-1972 are analyzed. For total ozone, improved monthly zonal means for both hemispheres are computed by weighting individual station monthly means by a factor which compensates for the close grouping of stations in certain regions of latitude bands. Longitudinal variability show maxima in summer in both hemispheres, but, in winter, only in the Northern Hemisphere. The geographical distributions of the long-term mean, and the annual, quasi-biennial and semiannual waves in total ozone over the Northern Hemisphere are presented. The extratropical amplitude of the annual wave is by far the largest of the three, as much as 120 m atm cm over northern Siberia. There is a tendency for all three waves to have maxima in high latitudes.

Monthly means of the vertical distribution of ozone determined from 3-8 years of ozonesonde data over North America are presented. Number density is highest (long term mean $> 80 \times 10^{11}$ molecules cm^{-3}) in the Arctic near 18 km. The region of maximum number density slopes upward toward 10^{o}N, where the long-term mean is 45×10^{11} molecules cm^{-3} near 26 km. Maximum deviations of individual observations from the seasonal means occur just above the tropopause. Periodic analysis of the vertical distribution data shows that the amplitude of the annual wave is as much as 18×10^{11} molecules cm^{-3} in the Arctic lower stratosphere. The annual maximum occurs in the spring throughout the extratropical lower stratosphere, but above 26 km in middle latitudes the maximum occurs in summer. The quasi-biennial (29 month) oscillation has a maximum amplitude of 9×10^{11} molecules cm^{-3} in the Arctic lower stratosphere, but is elsewhere generally much smaller than that. The semiannual wave has small maxima between 14 and 18 km in middle latitudes.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

I. INTRODUCTION

The natural temporal and spatial variability of ozone is of interest for several current stratospheric pollution studies, such as possible effects on stratospheric ozone of supersonic transports, space shuttles, chlorofluoromethanes, and volcanic disturbances. As a preliminary to studying the effects of these disturbances, mathematical models of the ozone distribution in the "undisturbed" stratosphere have been constructed. These models must be evaluated by comparison with the observed natural temporal and spatial variability of ozone. On the scale of decades, estimates of trends in total ozone have been made by, among others, Angell and Korshover (1973), Pittock (1974), London and Kelley (1974), Komhyr, et al. (1973), and Goldsmith, et al. (1973). Also, evaluation of the quasi-biennial variations in total ozone have been given by Angell and Korshover (1973) and of the annual variation by Wu (1973).

However, it is the natural horizontal variability at discrete stratospheric levels that is most needed to evaluate the significance of a model's results. Therefore, analyses of the quasi-biennial (29 month), annual, and semiannual waves in the vertical distribution of ozone as well as in total ozone are provided here. Zonal means of total ozone have been reevaluated using an improved weighting procedure. Results are presented graphically on hemispheric maps, height-latitude sections, and in tabulations.

II. DATA AND PROCESSING

A. DATA SOURCES

Total ozone data for the period 1957-72 were obtained from the World Data Center for Ozone, Toronto. Earlier data also were obtained (London, 1962) but have been processed separately because of the difficulty in assuring that the measurements at each station are uniformly calibrated among themselves and with the other stations, or that they are compatible with the more recent data edited at Toronto. The periodic analysis results of the two periods will be discussed in Section IV-A. The pre-1957 data were not included in the current periodic analysis in order to be more comparable with ozonesonde data period.

The total ozone stations used, their periods of record, and the number of months for which data were available are presented in Table 1 and Figure 1. Almost all of the western stations use the Dobson spectrophotometer for total ozone (a few French stations use the Vassy instrument), but the Soviet Union and East Germany use the filter ozonometer type M-83. The Dobson spectrophotometer is generally thought to be quite accurate while the filter ozonometer type M-83 is subject to serious errors under certain sun angles and restricted visibilities (Bojkov, 1969). An excellent discussion of problems in sensing, including instrument differences and geographical bias, is given by Angell and Korshover (1973).

Ozonesonde data were obtained from three sources. The first was Air Force Cambridge Research Laboratory, which conducted a program of quasi-weekly soundings at 14 stations in North America from January 1963 through December 1965 (Hering, 1964; Hering and Borden, 1965a, 1966, 1967). Following this program, several of these stations, plus two additional ones, continued to take data through 1969, while at Bedford sondes continued into 1971. These data were obtained from World Data Center-A (Meteorology), Asheville, N.C. The second source of data was the World Data Center for Ozone, Toronto, which supplied ozonesonde data from 26 stations in both hemispheres, measured with various sondes. "Toronto" and "AFCRL" stations, their locations, periods of record, type of sonde, and total number of observations are given in Table 2. It will be noticed that observations from Bedford, Fairbanks, Goose Bay, and La Paz are included in both Toronto and AFCRL data sets. In all processing these data have been merged, with care taken not to include the same observation twice.

In addition to the two data sets on magnetic tape, data from a three-year sounding program using the Brewer-Mast sonde at Boulder, CO (40.0N, 105.2W) were extracted from Dütsch (1966) and Dütsch, et al. (1970), and punched on cards. These data were merged with the AFCRL data from Fort Collins, about 75 km away.

Ozonesonde data are calibrated to obtain agreement of the integrated vertical ozone, plus an allowance for ozone above the balloon's maximum level, with nearby Dobson total ozone measurements. Craig (1965) describes the Dobson instrument, the various ozonesondes and their problems, and also the Umkehr method used for estimating vertical profiles from Dobson data. As the Umkehr technique is very sensitive to calibration problems and to particulates in the atmosphere (Holland and Thomas, 1975), and as accurate calibration of the Dobson instrument is almost impossible (Dütsch and Ling, 1973a), no Umkehr data are used in this study.

B. COMPUATION PROCEDURE

1. Total Ozone Monthly Zonal Means

The data were grouped into 10° latitude bands centered at 15, 25, 35°, etc. Along a latitude circle, each station is assumed to be representative of the arc which extends halfway to the next station in both eastward and westward directions. The long-term monthly mean at each station is then weighted by the length of this arc, W.

In addition, all monthly means were weighted by the square root of the number of months of data used, N. The zonal mean $\overline{X}$ is thus given by

$$\overline{X} = \frac{\sum_{i=1}^{M} X_i \, W_i \sqrt{N_i}}{\sum_{i=1}^{M} W_i \sqrt{N_i}} ,$$

where the X_i's are the long-term monthly means of total ozone at each of the M stations in the latitude band. However, this scheme might apply zero weight to one of two stations which happen to be at the same longitude. Therefore, when two or more stations are separated in longitude by 1/2 degree or less, a weight is computed as if there were only one station. The actual stations in the 1/2 degree interval each share equally the weight of the assumed single station.

The standard deviation of the station monthly means from the zonal monthly means was computed by weighting the squares of the station monthly means in the same manner--by the arc length and by the square root of the number of observations:

$$\sigma^2 = \frac{\sum_{i=1}^{M} X_i^2 W_i\sqrt{N_i}}{\sum_{i=1}^{M} W_i\sqrt{N_i}} - \bar{X}^2$$

2. Vertical Distribution

One objective of this study is to determine ozone number densities with 2½ km vertical resolution. As pressure was a vertical coordinate given in both AFCRL and Toronto data, it was convenient to use it as the working vertical coordinate. Each set of data used different pressure levels so it was necessary to interpolate (linearly in ln p) each observation to many standard pressure levels. The heights of the pressure levels were later determined as functions of season and latitude using the 10-20 year means given in Labitzke, et al. (1972) for the stratosphere, and U. S. Standard Atmosphere Supplements, 1966, for the troposphere.

Number density, n_3 (molecules cm^{-3}), was computed by:

$$n_3 = \frac{p_3 N_o}{R^* T}$$

where p_3 is ozone partial pressure, N_o is Avogadro's number, R* is the universal gas constant, and T is temperature. Temperature data were available for each sounding except at Aspendale and Boulder where climatological monthly mean temperatures had to be used.

In constructing monthly height-latitude sections, only North American stations, plus Grand Turk and the Canal Zone, were used. This was necessitated by the existence of only a very few non-North American ozonesonde stations with a respectable period of record. (Only Berlin and Hohenpeissenberg in Germany, and Tateno, Sapporo and Kagoshima in Japan, of the other Northern Hemisphere stations, each have more than 100 profiles.) As first pointed out by London (1962), eastern North America, eastern Asia, and central Europe show maxima in total ozone. This finding is supported by our analysis of total ozone, and by Wu (1973). Since our objective was to determine monthly mean profiles representative of the entire Northern Hemisphere, it would therefore only serve to bias the monthly means on the high side were the German and Japanese ozonesondes included. At the same time it should be noted that most of the North American stations are located in the eastern portion of the continent, but that the high bias so produced in partially offset by the inclusion of Boulder/Fort Collins, Seattle, Fairbanks, and Albuquerque.

III. MONTHLY VARIATIONS

A. TOTAL OZONE: ANNUAL MEAN MAP AND ZONAL MEANS

Figure 2 is a map of the annual mean of total ozone. Wavenumber three is dominant in the pattern, with maxima over eastern North America, central Europe, and eastern Asia. This is in agreement with London (1962), Wu (1973), and others. It should be noted that Figure 2 represents a good deal of smoothing. This is especially evident when comparing it with the annual mean total ozone map of Wu (1973), which retains much small-scale variability, especially over the Soviet Union. In view of the previously discussed errors associated with the filter ozonometer used in that country, the small-scale variability has been smoothed here. (Dash-dot lines in this and in all subsequent figures indicate those portions of the analysis which have large statistical uncertainty due to sparse data, short periods of record, or other reasons.)

Figure 3 shows the weighted zonal means of total ozone by month. The well-known spring maximum and fall minimum are clearly represented, as is the lesser amount of ozone in the Southern Hemisphere than in the Northern Hemisphere. The lowest values of total ozone occur from near the equator to 25N in December and January, and poleward of 80N in August. Also evident is the higher latitude of the Northern Hemisphere maximum (~75^{o}N) than the Southern Hemisphere maximum (~55^{o}S). This difference can be explained by the more zonal large-scale circulation of the Southern Hemisphere (van Loon, et al., 1972b). Presumably, ozone is transported to the lower middle latitudes by the Hadley cell but it cannot be readily transported to south polar regions due to the relatively small amplitude of standing waves in the Southern Hemisphere (Kao, et al., 1972).

Values in Figure 3 agree well with the literature (Wu, 1973; Dütsch, 1969; Sticksel, 1970) as the great majority of published values are within one standard deviation of the values given here. Part of the differences are due to our longer period of record. Other differences arise from our improved weighting scheme, i.e., the attachment of a large weight to longitudinally isolated stations whose means deviate significantly from the means of the remaining stations in the latitude band. Outstanding examples are Resolute and Tiksi in band 70-80^{o}N (values higher than others), Marcus Island in band 20-30^{o}N (values lower), Port au Francais in band 40-50^{o}S (values higher), and Dumont d'Urville in band 70-80^{o}S (values lower). Table 3 contains values from Figure 3 interpolated to each five degrees of latitude.

The (weighted) standard deviations of the means in Figure 3 are presented in Figure 4, serving as a measure of longitudinal variability. Of interest is the summertime maximum in both hemispheres. This feature reflects the small-scale variability of ozone in the summer which is also evident in the monthly and seasonal maps of Wu (1973). The physical reason for this variability has not yet been determined, but since the summer wind is usually a direct easterly in the middle and upper stratosphere it is probably not the result of variable horizontal advection. The vertical advection of water vapor may cause a destruction of ozone, as suggested by Rangarajan (1969), and Rao and Christie (1973). Possibly mid-latitude summertime thunderstorms account for such water vapor anomalies. Clearly this is an aspect of total ozone distribution which requires more study.

While the Northern Hemisphere standard deviations show seasonal maxima of longitudinal variability in winter as well as summer, the Southern Hemisphere standard deviations have only a summer maximum (except at very high latitudes). This is probably a reflection of the quite zonal mid-latitude circulation in the Southern Hemisphere winter, which is relatively ineffective in transporting ozone further poleward.

B. VERTICAL DISTRIBUTION OF OZONE BY LATITUDE

Figures 5 through 17 are height latitude sections of monthly means and the annual mean of ozone number density. Values of ozone concentration at 2½ km and 5° latitude intervals were interpolated from Figures 5-17 and tabulated in Appendix A. The stations used are indicated by letters; from high to low latitude they are Thule, Fairbanks, Churchill, Goose Bay, Seattle, Madison, Bedford, Fort Collins/Boulder, Sterling, Wallops Is., Albuquerque, Tallahassee, Kennedy Space Center, Grand Turk, and the Canal Zone. Analyses which faithfully fit the data were extremely ragged, a fact which was undoubtedly due more to longitudinal than to latitudinal variability. The data were therefore smoothed to be consistent with the scale of the section. (Note that in all height-latitude sections the height scale is the true vertical coordinate and the pressure scale is only approximate.)

The figures show the well-known lower stratospheric maximum ozone concentration, with the greatest concentration ($> 80 \times 10^{11}$ molecules cm^{-3}) in January poleward of $70^{\circ}N$. In January this belt of maximum ozone slopes upward from 15 km at high latitudes to 25 km at the equator, paralleling the mean height of the tropopause. Its intensity at high latitudes decreases to near 50 units in summer and the altitude of the maximum rises to 20 km. The poleward gradient of ozone below the level of maximum concentration is largest in the spring.

The rise in ozone concentration in the high-latitude region between 24 and 32 km from January to March is attributed by Hering and Borden (1965b) to an explosive stratospheric warming over North America in January and February, 1963. Dütsch, et al. (1970), and Dütsch and Ling (1973b) also link sudden stratosphere warmings to increases in ozone concentration, noting that the ozone rise lags the temperature rise. Also, since ozone mixing ratio is conservative in the wintertime middle stratosphere, the increased concentration is quite persistent, and is still evident after the temperatures have reverted to normal. However, one must always keep in mind the increasing statistical errors as the middle stratosphere is reached.

In the troposphere, there is least concentration of ozone in the tropics all year, and this minimum extends to mid-latitudes during winter. Also, there is almost always a tropospheric maximum concentration near 30 to 40°N below 4 km.

C. STANDARD DEVIATIONS

The standard deviation of individual observations from the seasonal mean are shown in Figures 18-21. All four seasons have the highest standard deviations just above the tropopause at middle and high latitudes. This is due to the fact that these particular levels are part of the time in the ozone-poor troposphere and part of the time in the ozone-rich stratosphere, (Dütsch, 1966, 1974a; Dütsch, et al., 1970). The maximum variability in the stratosphere, within a three-month season, occurs in January-March while the minimum is in July-September.

IV. PERIODIC ANALYSIS

A. PROCEDURE

1. Selection of Stations

In the periodic analysis of total ozone, all available stations were used. However only over the Northern Hemisphere did the total ozone station distribution warrant presentation in map form. Total ozone data taken prior to 1957 were also subjected to periodic analysis. Lower long-term means, consistent with the trend in total ozone shown by Angell and Korshover (1973), were detected at all stations. The differences in amplitude and phase of the annual and semiannual waves were generally within the error limits. Northern Hemisphere results given below are for the stations and periods of record in Table 1.

The distribution of ozonesonde stations is much more sparse than that of total ozone stations and therefore could not be mapped although it is expected that there is significant variation with longitude. Therefore, only eastern North American stations were used, approximating a meridional section. These stations are Thule, Churchill, Goose Bay, Madison, Bedford, Sterling, Wallops Is., Tallahassee, Kennedy Space Center, Grand Turk, and the Canal Zone. The observation series at Sterling and Wallops (220 km apart) were consecutive rather than concurrent, so they were combined to make a long period of record. The same was done with Tallahassee and Kennedy (430 km apart).

2. Analysis Method

A periodic analysis of both total ozone and vertical distribution data was made using the same periodic regression technique as previously applied to wind (Belmont, et al., 1974). This method accommodates unevenly spaced data and can fit any periodic function to the data. Further, it yields relative errors of estimate which help in assessing the reliability of amplitude and phase. Although periods down to three months were included in the basic analyses of both total and vertical distribution, the errors are relatively large for the three- and four-month waves, so little significance can be attached to them and they are not included here.

A sinusoidal waveform was employed because the annual variation of total ozone at Arosa, Switzerland over a 30 year period (Perl and Dütsch, 1959, reproduced by Craig, 1965) is almost sinusoidal. Since, to a first approximation, seasonal changes of total ozone are a result of variations in lower stratospheric ozone concentrations (Dütsch, 1974; Bojkov, 1969b), it seems likely that the annual variation of the vertical distribution of ozone is also largely sinusoidal. A sinusoid was also used for the QBO because time plots of twelve month running means of ozone concentration at several levels were reasonably sinusoidal. Also, Angell and Korshover (1973) determined the QBO in total ozone to be largely sinusoidal. A period of 29 months was used for the QBO to be consistent with the earlier analyses of stratospheric wind and temperature (Belmont, et al., 1974; Nastrom and Belmont, 1975).

B. ANNUAL OSCILLATION

1. Total Ozone

The amplitude and phase (time of the maximum) of the annual oscillation in total ozone are shown in Figures 22 and 23. The maximum, over 120 m atm cm, occurs in late winter over northeastern Siberia. The pattern of the annual wave amplitude tends to follow the pattern of the mean, i.e., maxima over North America, Europe, and Asia, although the apparent oceanic minima may be due to lack of observations. The location of the Siberian maximum amplitude coincides with that of autumn-through-spring northward winds at the level of maximum ozone near 50 and 30 mb. Further, the ridge of large amplitudes along the east coast of North America is associated with another major region of northward winds at 50 and 30 mb, as given in van Loon, et al., 1972. These flow patterns help explain the longitude of the maxima, but not the asymmetry of the pattern which must involve mean vertical motions as well. The maximum of the annual wave in total ozone (Fig. 23) occurs first in early February in the region of the amplitude maximum. The wave progresses radially from this location, reaching 30^{o}N in two or three months.

2. Vertical Distribution of Ozone

The annual wave over eastern North America (Figs. 24 and 25) has its maximum amplitude at high latitudes near 13 km with phase dates in the spring. This maximum rapidly becomes weaker from 50 to 30N, becoming quite small in the tropics at any altitude. In Figure 25 interesting features are the region of summer phase dates at middle latitudes, and winter dates in the tropics, both above 26 km. The annual maximum is earliest (February) at highest altitudes and latitudes and progresses southward and downward. The annual maximum in tropospheric ozone is quite small and occurs in late spring or summer.

3. Discussion

Dütsch (1974b), among others, suggests that the predominant cause of the high latitude winter-spring maximum in total ozone is advection from the middle and upper tropical stratosphere ozone source. This transport begins with the onset of the stratospheric westerlies in the fall, reaches a maximum in early winter, and gradually weakens in late winter and spring. It ceases with the reversal to easterlies in the spring. During the winter and spring months, when there is enhanced vertical mixing in the troposphere due to synoptic scale weather systems, ozone is transported downward into the troposphere where it reaches a maximum in early summer. [Recently Chameides and Walker (1973) said that photochemistry accounts for gross features of tropospheric ozone variability as reported by Hering and Borden (1964) for North American stations. Although this theory has not yet gained substantial acceptance (see for example Dütsch, 1974a; Fabian, 1974; Cunnold, et al., 1975), ozone photochemistry in the troposphere may be significant.]

The mid-latitude amplitude and phase in Figures 24 and 25 are quite similar to these at Arosa (47^{o}N) found by Dütsch and Ling (1973b), who analyzed six years of ozonesonde data. Both analyses show the summer tropospheric maximum (progressively earlier with increasing height), the late winter lower stratospheric maximum, and a rapid phase shift to a primarily summer maximum near 10 mb. In Dütsch and Ling's analysis, this middle stratospheric summer maximum, which they attribute to photochemical effects, is actually detectable down to just above 30 mb, but only above 20 mb is it larger than the winter maximum. The present analysis similarly shows a rapid phase change to early summer near 20 mb which supports the predominance of the photochemical maximum above 20 mb in middle latitudes.

The amplitude of the annual wave in the tropics at all altitudes is quite small, consistent with the small total ozone annual wave found there. The annual February maximum near 10 mb is possibly due to the minimum Sun-Earth distance which occurs during the Southern Hemisphere summer, producing maximum UV and hence ozone.

C. THE QUASI-BIENNIAL OSCILLATION (QBO)

1. Total Ozone

The amplitude of the QBO in total ozone is presented in Figure 26. Although the analysis has been smoothed within the limits of the statistical errors, some tight gradients and outstanding values cannot be ignored. For example, the amplitude at Dushanbe (39N, 69E) is included on Figure 26 because of its relatively small statistical error despite its apparent lack of agreement with the Indian stations or the two nearest Soviet stations (Alma Ata and Ashkabad). These irregularities may represent geographic variations in the physical QBO, or they may be statistical in nature. As it is well known that the QBO in total ozone varies in amplitude and period from cycle to cycle in a non-uniform manner (Angell and Korshover, 1973), differing amounts of interference could easily occur between stations because of differing periods of record, or because of differing periods and amplitudes of the QBO, or both.

The phase of the QBO is more sensitive than is the amplitude to inhomogenieties in the data so it is not surprising that the patterns of phase progression associated with Figure 26 are very erratic and inconclusive, and are not presented here.

2. Vertical Distribution of Ozone

Figures 27 and 28 show the QBO in the vertical distribution of ozone over eastern North America. The maximum amplitudes occur at high latitudes, consistent with the gradient of the amplitude of the QBO in total ozone (Figure 26) along 80°W. Similar to the annual wave, the QBO is largest in the lower polar stratosphere. The phase (Fig. 28) is earliest near 20 km at all latitudes and is latest in the mid-latitude troposphere.

3. Discussion

The existence of a quasi-biennial oscillation in total ozone has been shown by Angell and Korshover (1964, 1973), Dütsch (1974a), Pittock (1968) and others. Dütsch believes it arises from the strengthening of the tropical Hadley cell during the tropical QBO's easterly phase. At this time the downward leg is extended poleward, advecting greater amounts of ozone to lower middle latitudes at the level of maximum ozone, i.e., 20-25 km. This then permits an increased poleward transport by the quasi-horizontal eddies at this level. From the level of maximum ozone (Fig. 17) the QBO in ozone descends with a phase speed much slower than the phase speed of the tropical QBO (Dütsch and Ling, 1973b; Dütsch, 1974b). The patterns of the present analyses (Figs. 27 and 28) are not inconsistent with this theory. In view of the like phase at all latitudes near 20 km, it is clear that transport from the tropics takes place very quickly at this level. At extra-tropical latitudes the ozone is then transported slowly downward. It appears to accumulate most between 8 and 16 km, i.e., just above the tropopause. The large, lower stratosphere amplitude maximum at Thule and Churchill must be considered tentative due to the short (3-year) records at Thule and Churchill. However, this feature is supported by Fairbanks, also having a three year record, which likewise shows a lower stratospheric QBO amplitude maximum (8×10^{11} molecules cm^{-3} at 12 km).

Dütsch and Ling (1973b) have matched the phase of the QBO above 18-20 km over Arosa during a six-year period with that of the QBO in zonal wind in the tropics. However, this relationship broke down below 18 km, presumably due to the increased effects of regional circulation patterns. Züllig (1973), using estimated total ozone north of 40°N, computed from a transport model, has also found a high positive correlation between total ozone and the strength of the easterlies at 30 mb over Canton Island.

As discussed earlier, there is undoubtedly an influence of individual synoptic events, such as stratospheric warmings, on local ozone concentration. In this connection, Hering and Borden (1965b) tied the appearance of a high-latitude ozone increase in 1963 to increased northward and downward transport of ozone from lower latitudes by the large amplitude disturbances associated with an early 1963 stratospheric warming. This is reflected in the present analysis as the broad maximum above 22 km at high latitudes. However, this effect does not account for the main high-latitude maximum, which is just above the tropopause, far below the main level of sudden warmings. As warmings occur every winter to some degree, their occurrence cannot have a quasi-biennial period. Further, there has been no evidence to date that there is any QBO in the amplitude of warmings. It therefore seems unlikely that sudden warmings are related to the tropical QBO and to the polar QBO in ozone. This agrees with Dütsch and Ling's (1973b) view that the QBO in ozone is more closely tied to the tropical QBO than to sudden stratospheric warmings.

D. THE SEMIANNUAL WAVE

1. Total Ozone

The semiannual wave in total ozone is mapped in Figures 29 and 30. The maximum amplitude is in polar regions where it is about one-quarter the amplitude of the annual wave. The first maximum of the year in general occurs in February at low latitudes and rapidly progresses to almost everywhere else within one month.

2. Vertical Distribution of Ozone

The semiannual wave in ozone's vertical distribution is shown in Figures 31 and 32. A relatively large maximum in the semiannual wave, more than 6×10^{11} molecules cm^{-3}, is suggested by Thule at highest latitudes in the middle stratosphere. The early spring phase date is consistent with that of total ozone (Fig. 30) near 80°W. It should be noted that this high-latitude, high-altitude maximum is doubtful due to the few Thule observations which reached above 26 km and also since it is not supported by Churchill (or Fairbanks).

There are also maxima near 18 km at 55°N and 16 km at 35°N which first occur in late winter and early summer, respectively. Because of the few data and associated uncertainty, the northern of these two centers requires verification when more data become available. The amplitude center at 35°N appears well supported.

The "early" phase center near 40N at 10 km is quite definitely shown by the long records of both Bedford and Sterling/Wallops. The phase is up to five months later near the ground and latest in the arctic middle stratosphere.

3. Discussion

A semiannual wave in ozone in the lower stratosphere, as shown here, has not been reported previously, even though the amplitudes, which are 10 to 20% of the mean concentrations, are significant. The cause of this lower stratospheric semiannual wave is not known. Rao and Christie (1973) have found effects of water vapor and oxides of nitrogen on ozone, so it is possible that a periodicity in these trace substances could have a significant effect on the periodicity of ozone.

V. SUMMARY OF FINDINGS (Asterisk indicates new findings)

A. MONTHLY VARIATIONS

1) The annual mean of total ozone over the Northern Hemisphere shows major maxima over eastern North America and eastern Asia with a lesser maximum over central Europe.

2) Monthly zonal means of total ozone over the Northern Hemisphere show a larger abundance of ozone, and a higher latitude of the maximum, than the Southern Hemisphere. Total ozone is a maximum in the spring and a minimum in the fall.

3)* There is large longitudinal variability in total ozone in the summer in mid-latitudes of both hemispheres, and in the winter in the Northern Hemisphere mid-latitudes. Small total ozone longitudinal variability in the wintertime Southern Hemisphere mid-latitudes is a reflection of the predominantly zonal general circulation there.

4) Concerning ozone's vertical distribution over North America, the region or maximum concentration extends from between 16km (January) and 20km (August) in the arctic to around 26 km at 10^{o}N. Maximum variability of ozone concentration occurs just above the tropopause.

B. PERIODIC ANALYSIS

1)* The annual wave in total ozone over the Northern Hemisphere has greatest amplitude ($>$ 120 m atm cm) in polar regions, with the maximum occurring in late winter there.

2)* In ozone's vertical distribution, there is a large (amplitude $> 18 \times 10^{11}$ molecules cm^{-3}) lower stratospheric annual wave in the Arctic. The amplitude of the wave decreases slowly southward through higher mid-latitudes and then rapidly through lower mid-latitudes, becoming quite small south of $20^{o}N$. The maximum occurs in late winter or early spring at most latitudes and heights, indicative of the dominance of advective effects. Above 26 km in mid-latitudes, an abrupt phase shift to late spring/early summer signals the dominance of photochemical effects above that level.

3)* The quasi-biennial (29 month) oscillation (QBO) in both total ozone and its vertical distribution is generally quite a small percentage of the annual mean. The existence of the extratropical ozone QBO seems to be due to a rapid advection of ozone from low to high latitudes near 20 km. Ozone is then transferred downward much more slowly, and it appears to accumulate significantly (QBO amplitude $> 9 \times 10^{11}$ molecules cm^{-3}) near 13 km in the Arctic.

4)* The semiannual wave in both total ozone and its vertical distribution is also a small percentage of the annual mean. The wave appears first in April near the tropopause at middle latitudes and progresses both downward and upward, reaching the ground up to five months later, and is latest in the Arctic middle stratosphere.

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N11km = 7.5664 E18 , cm^{-3}

O3 (ppbv) @ 11km = (molec/cm3) / 7.5664 E09

APPENDIX

OZONE CONCENTRATIONS (10^{11} MOLECULES CM^{-3}) OVER NORTH AMERICA (1963-1971)

		LATITUDE (N)														
Month	Ht(km)	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
01	32.5	8	9	10	11	12	12	13	14	15	17	18	19	20	20	20
01	30.0	10	15	14	16	18	20	21	22	23	25	25	26	27	28	29
01	27.5	15	17	20	24	28	29	31	32	33	34	35	37	40	41	41
01	25.0	18	25	31	37	40	43	47	49	50	50	51	50	46	44	42
01	22.5	33	45	52	56	58	60	61	61	59	55	52	49	42	38	35
01	20.0	64	66	67	65	64	63	62	60	53	46	38	31	27	23	21
01	17.5	80	81	77	67	63	60	52	44	37	28	19	13	10	8	7
01	15.0	85	81	70	60	53	45	37	30	24	18	10	6	4	3	2
01	12.5	75	61	50	41	37	31	25	20	16	10	5	4	3	2	2
01	10.0	40	29	26	22	19	16	11	9	7	5	4	3	3	3	2
01	7.5	13	10	9	9	8	7	5	4	4	3	3	3	3	3	3
01	5.0	8	8	8	7	6	5	4	4	4	4	4	4	4	4	3
01	2.5	9	9	9	9	8	7	5	5	6	6	6	5	4	4	3
02	32.5	8	9	10	11	12	12	12	15	17	18	18	19	20	20	20
02	30.0	12	14	16	15	18	20	21	23	24	26	27	28	28	29	30
02	27.5	19	22	24	27	28	30	31	33	34	37	38	40	41	42	42
02	25.0	30	32	34	35	37	40	44	49	50	51	51	49	48	46	44
02	22.5	40	42	46	50	55	57	59	60	60	58	53	50	43	39	37
02	20.0	68	70	68	65	65	63	63	62	60	50	40	32	25	21	20
02	17.5	74	73	71	68	64	61	56	48	43	34	20	10	6	5	5
02	15.0	72	71	69	62	55	48	43	38	32	20	8	5	4	3	3
02	12.5	62	60	56	52	45	38	33	27	18	9	5	4	3	2	2
02	10.0	39	40	39	34	30	23	17	11	8	5	4	3	3	3	2
02	7.5	10	11	11	11	10	9	8	6	5	4	4	4	4	3	3
02	5.0	6	6	6	6	6	6	6	5	5	4	4	4	4	4	3
02	2.5	6	6	6	6	6	6	6	6	6	6	5	5	5	4	4
03	32.5	22	19	17	16	15	16	16	17	18	18	19	19	21	23	27
03	30.0	30	27	26	24	23	24	25	25	26	27	28	29	30	32	34
03	27.5	37	36	35	34	34	34	34	35	36	37	38	40	41	42	43
03	25.0	47	46	46	45	44	45	46	47	48	48	47	47	45	44	44
03	22.5	60	61	61	62	63	61	60	59	57	55	53	48	42	38	34
03	20.0	73	73	73	74	76	73	68	64	59	50	42	33	27	22	17
03	17.5	70	67	65	65	66	65	58	49	40	29	22	14	9	6	5
03	15.0	57	56	56	56	55	53	45	37	30	20	11	5	4	3	2
03	12.5	52	51	49	48	44	39	33	28	22	13	7	4	3	3	3
03	10.0	39	32	28	24	20	19	16	14	12	7	4	4	4	3	3
03	7.5	20	10	9	8	8	8	7	6	5	5	4	4	4	4	4
03	5.0	7	7	6	6	6	6	6	6	5	5	5	5	5	5	5
03	2.5	7	7	7	7	7	7	6	6	6	6	7	8	8	7	6
04	32.5	17	16	15	15	16	17	18	19	20	20	20	20	21	22	23
04	30.0	24	22	20	20	21	22	24	26	27	27	28	28	28	29	30
04	27.5	30	28	27	27	27	28	30	33	36	37	38	39	40	41	41
04	25.0	50	42	40	39	40	41	45	47	47	48	47	47	48	46	43
04	22.5	62	59	57	56	56	58	58	57	55	53	51	45	42	39	35
04	20.0	73	73	71	67	65	65	63	61	53	45	39	32	28	23	20
04	17.5	78	77	72	68	70	69	60	48	36	23	16	11	9	7	6
04	15.0	72	70	67	64	65	54	47	40	26	16	9	6	5	4	3
04	12.5	57	56	54	52	48	42	40	33	23	13	7	5	4	3	3
04	10.0	40	37	33	29	23	20	19	16	12	8	5	4	4	3	3
04	7.5	15	12	10	10	9	9	9	8	8	7	6	5	5	4	4
04	5.0	6	6	6	6	6	6	7	7	7	7	7	7	6	5	5
04	2.5	6	6	6	6	6	6	8	10	10	10	9	8	7	7	7

APPENDIX (CONT'D)

		LATITUDE (N)														
Month	Ht(km)	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
05	32.5	13	13	14	15	16	17	17	18	19	20	21	22	23	23	24
05	30.0	18	18	19	20	22	23	25	27	27	28	28	29	30	31	32
05	27.5	25	25	26	27	28	30	33	36	38	40	41	41	42	43	44
05	25.0	34	35	36	38	40	42	44	46	47	47	47	47	47	47	46
05	22.5	46	47	48	50	51	52	53	53	53	52	51	46	43	40	37
05	20.0	60	60	62	63	63	59	56	53	50	42	36	33	29	26	23
05	17.5	61	61	61	62	61	57	50	43	33	24	19	18	14	10	8
05	15.0	56	55	54	53	51	47	42	34	24	16	12	8	7	5	3
05	12.5	51	49	46	44	42	39	35	30	19	13	9	7	5	4	3
05	10.0	37	30	28	28	27	26	23	19	12	8	6	6	5	4	3
05	7.5	19	15	14	13	12	10	9	8	8	6	6	6	6	5	4
05	5.0	7	7	7	7	7	7	7	8	8	8	7	7	6	5	4
05	2.5	7	7	7	7	7	7	7	8	10	10	9	7	6	5	4
06	32.5	18	18	17	14	14	16	17	20	22	22	21	20	19	19	20
06	30.0	21	21	21	21	22	23	25	27	28	28	28	28	28	29	30
06	27.5	27	27	27	28	29	31	34	36	38	39	40	40	41	41	42
06	25.0	34	35	35	36	37	40	42	45	47	49	49	47	46	45	44
06	22.5	46	46	46	46	48	50	50	51	51	50	46	43	40	39	38
06	20.0	55	55	56	58	58	56	53	50	46	41	36	33	30	28	25
06	17.5	51	52	53	54	52	48	44	40	33	27	24	20	17	14	12
06	15.0	42	42	43	43	41	38	34	28	22	17	14	11	9	7	4
06	12.5	34	34	35	34	33	30	25	20	14	19	8	7	5	4	2
06	10.0	20	20	19	18	17	15	12	9	8	7	7	7	5	4	2
06	7.5	8	7	7	6	6	6	6	7	7	7	7	7	6	5	3
06	5.0	6	6	5	4	5	6	7	7	7	7	7	7	6	5	4
06	2.5	6	5	4	5	6	6	6	7	10	10	8	8	6	5	4
07	32.5	11	11	12	13	14	16	17	20	21	21	20	19	19	19	19
07	30.0	17	17	18	19	20	23	26	27	28	29	29	30	30	30	30
07	27.5	23	24	25	27	28	30	33	36	37	39	40	41	41	41	41
07	25.0	30	31	33	34	36	38	40	43	45	47	48	48	45	43	42
07	22.5	39	40	42	43	44	45	47	48	47	45	43	42	41	39	37
07	20.0	50	51	53	56	55	49	47	43	40	35	33	32	30	29	27
07	17.5	50	50	50	50	50	47	41	33	24	19	17	15	13	10	10
07	15.0	42	42	42	41	39	35	30	21	12	9	8	7	6	5	4
07	12.5	35	35	35	34	33	28	23	15	8	7	6	6	5	4	3
07	10.0	27	26	23	21	18	14	10	8	8	7	6	6	5	4	3
07	7.5	10	8	8	8	8	8	7	7	8	7	6	6	6	5	4
07	5.0	6	6	6	6	8	8	7	7	8	8	7	7	7	5	4
07	2.5	5	5	5	6	8	8	8	8	9	8	7	7	7	5	4
08	32.5	11	11	12	14	15	17	19	20	20	20	20	20	20	20	20
08	30.0	16	17	18	20	22	24	26	27	28	29	30	30	30	30	31
08	27.5	23	25	26	27	28	31	34	37	40	40	41	42	42	42	42
08	25.0	32	33	34	36	37	40	42	44	45	46	46	46	46	45	45
08	22.5	45	45	46	46	46	47	48	47	46	44	42	41	40	39	37
08	20.0	54	54	53	53	52	49	46	42	37	34	32	30	28	25	22
08	17.5	51	50	49	47	44	40	34	29	24	20	17	14	13	10	8
08	15.0	37	35	33	31	28	26	22	17	13	9	7	6	5	4	3
08	12.5	27	25	24	23	20	17	14	11	7	5	5	4	4	3	2
08	10.0	15	13	11	10	9	8	7	6	6	6	5	4	4	4	3
08	7.5	6	6	6	6	6	6	6	6	6	6	6	6	5	4	3
08	5.0	6	6	6	6	6	6	6	7	8	8	8	8	7	5	3
08	2.5	5	5	5	5	5	6	6	7	10	11	10	7	6	5	3

APPENDIX (CONT'D)

Month	Ht(km)	LATITUDE (N) 80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
09	32.5	8	8	9	10	15	16	16	17	18	18	19	19	19	20	21
09	30.0		15	16	18	21	23	24	26	26	27	27	28	28	29	30
09	27.5	18	21	24	26	27	30	33	34	36	37	39	40	41	41	42
09	25.0	25	28	33	34	36	38	41	43	45	46	46	46	46	45	44
09	22.5	33	38	41	43	44	46	47	47	45	44	42	41	40	38	36
09	20.0	46	48	51	52	52	49	46	41	36	33	31	29	26	24	23
09	17.5	55	54	51	50	48	40	33	27	23	18	15	14	12	10	8
09	15.0	42	39	37	34	32	27	22	16	10	7	6	5	4	3	3
09	12.5	27	25	23	21	19	16	13	8	6	4	4	4	4	3	3
09	10.0	16	13	12	10	10	8	8	7	5	4	4	4	4	3	3
09	7.5	7	7	7	6	6	5	5	5	5	5	5	5	4	4	3
09	5.0	7	7	6	5	5	5	5	5	5	6	7	7	6	5	4
09	2.5	8	7	6	5	5	5	7	8	9	8	7	7	6	5	4
10	32.5	9	10	12	13	14	14	14	15	17	20	20	20	20	20	21
10	30.0	18	18	19	20	20	21	23	25	27	28	28	29	30	31	32
10	27.5	28	28	28	29	30	30	32	34	36	37	40	41	41	42	42
10	25.0	37	37	37	37	38	40	41	43	44	46	46	45	44	44	44
10	22.5	45	45	45	44	44	46	47	47	45	44	42	40	38	36	35
10	20.0	56	56	51	48	49	49	46	42	38	34	31	27	24	22	20
10	17.5	52	52	49	48	50	44	36	32	27	21	16	12	9	7	6
10	15.0	38	39	40	40	37	33	25	18	13	8	5	4	4	4	4
10	12.5	26	27	27	27	24	17	12	9	7	4	4	3	2	2	2
10	10.0	15	15	15	14	11	8	8	5	4	4	3	3	3	3	3
10	7.5	5	7	7	7	7	6	5	4	4	4	3	3	3	3	3
10	5.0	4	4	6	7	7	6	5	4	4	4	4	4	4	4	4
10	2.5	4	4	5	6	6	6	6	7	7	7	7	5	4	4	4
11	32.5	8	9	10	12	16	16	17	17	18	19	20	21	21	21	22
11	30.0	16	17	17	18	19	21	23	25	26	26	27	29	30	32	34
11	27.5	20	22	25	27	31	34	36	36	35	35	37	41	42	44	49
11	25.0	29	32	36	38	41	45	47	47	47	47	48	47	47	47	47
11	22.5	42	43	44	46	47	50	52	50	48	46	45	43	41	38	34
11	20.0	56	54	50	48	47	47	47	45	42	37	33	30	26	23	20
11	17.5	60	57	53	47	45	43	40	34	27	21	17	13	10	7	5
11	15.0	50	46	43	40	36	33	26	20	14	8	7	4	3	3	2
11	12.5	27	27	26	25	24	23	17	10	8	5	4	4	3	2	2
11	10.0	17	16	15	14	13	12	9	8	5	4	4	4	3	2	2
11	7.5	10	8	7	6	6	6	6	5	4	4	4	4	3	3	2
11	5.0	6	6	6	6	5	5	5	5	5	4	4	5	5	4	3
11	2.5	6	6	6	6	5	5	5	6	7	7	7	7	6	4	3
12	32.5	15	16	16	17	17	17	17	17	17	18	18	19	20	21	22
12	30.0	20	22	23	24	24	23	23	23	25	26	27	28	29	29	30
12	27.5	28	29	31	33	33	33	34	35	36	37	38	40	41	42	43
12	25.0	39	41	43	44	45	46	47	48	48	48	48	47	46	46	45
12	22.5	50	51	53	55	56	57	58	58	56	52	48	45	42	39	36
12	20.0	58	58	58	59	65	60	57	52	48	42	37	33	27	23	18
12	17.5	58	58	58	58	57	50	44	39	32	26	19	13	9	6	5
12	15.0	50	51	51	50	45	35	28	24	18	13	8	5	4	3	2
12	12.5	39	40	40	38	27	22	17	14	10	7	4	4	3	2	2
12	10.0	27	25	21	17	14	11	8	7	5	4	4	3	2	2	2
12	7.5	7	7	7	7	6	6	6	5	4	4	4	4	3	3	3
12	5.0	7	7	7	7	6	6	6	5	5	5	5	4	4	4	3
12	2.5	6	6	6	6	6	6	6	6	7	7	7	6	5	4	3

APPENDIX (CONT'D)

	Ht (km)		E	LATITUDE (N) 80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
ANN	32.5	2.0057	23	12	12	13	13	15	16	16	17	19	19	20	20	20	21	22
ANN	30.0	3.8250	23	17	19	19	20	21	22	24	25	26	27	28	29	29	30	31
ANN	27.5	3.6355	23	24	25	27	28	29	31	33	35	36	37	39	40	41	42	43
ANN	25.0	8.3346	23	34	35	37	38	39	42	44	46	47	48	48	47	46	45	44
ANN	22.5	1.2285	24	45	47	48	50	51	52	53	53	52	50	47	44	41	39	36
ANN	20.0	1.8487	24	59	60	59	59	59	57	55	51	47	41	36	31	27	24	21
ANN	17.5	2.1357	24	62	61	59	57	56	52	46	39	32	24	18	14	11	8	7
ANN	15.0	4.0495	24	54	52	50	48	45	40	33	27	20	13	9	6	5	4	3
ANN	12.5	[illegible]	24	43	41	39	37	33	29	24	19	13	9	6	5	4	3	2
ANN	10.0	3.4981	[illegible]	28	25	23	20	18	15	12	10	8	6	5	4	4	3	3
ANN	7.5	1.1586	23	11	9	9	8	8	7	7	6	6	5	5	5	4	4	3
ANN	5.0	1.5315	[illegible]	6	6	6	6	6	6	6	6	6	6	6	6	5	5	4
ANN	2.5	1.1896	[illegible]	6	6	6	6	6	6	6	7	8	8	7	7	6	5	4

TABLE 1.

TOTAL OZONE STATIONS

A. NORTHERN HEMISPHERE STATIONS

NUMBER	NAME	LATITUDE	LONGITUDE	PERIOD OF RECORD	NUMBER OF MONTHLY MEANS
1	LERWICK	60	1W	7/57-12/72	171
2	ESKDALEMUIR	55	3W	7/57-8/63	73
3	OXFORD	52	1W	7/57-12/72	184
4	BRACKNELL	51	1E	3/67-12/72	56
5	PARIS	49	2E	1/62-12/72	128
6	CAMBORNE	50	5W	7/57-4/67	116
7	MONT-LOUIS	43	2E	3/62-12/72	130
8	LISBON	39	9W	9/60-12/72	109
9	VIGNA DI VALLE	42	12E	7/57-12/72	186
10	AROSA	47	9E	7/57-12/72	184
11	CAGLIARI	39	9E	7/57-12/72	185
12	NAPLES	41	14E	7/58-10/71	147
13	AARHUS	56	10E	7/57-12/72	186
14	MESSINA	38	16E	7/57-12/72	184
15	LONGYEAR	78	16E	7/57-7/66	60
16	TROMSO	70	19E	7/57-6/69	124
17	MURMANSK	69	33E	10/61-10/72	126
18	LENINGRAD	60	30E	7/57-12/72	172
19	RIGA	57	24E	8/61-11/72	131
20	HRADEC KRALOVE	50	16E	8/61-12/72	137
21	BELSK	51	21E	3/63-12/72	118
22	POTSDAM	52	11E	7/57-12/72	125
23	BUDAPEST	47	19E	1/67-12/72	68
24	KIEV	50	30E	6/60-12/72	139
25	ODESSA	46	31E	7/62-12/72	124
26	KARADAG	45	35E	6/60-12/67	91
27	MOSCOW	56	38E	10/61-12/72	125
28	KUIBYSHEV	53	50E	7/62-11/72	123
29	ABASTUMANI	42	43E	7/57-12/67	120
30	HEISS IS.	80	58E	3/63-9/72	47
31	PECHORA	65	57E	7/63-11/67	48
32	SVERDLOVSK	57	61E	7/62-12/72	126
33	OMSK	55	73E	12/61-12/72	132
34	ASHKHABAD	38	58E	11/61-12/72	127
35	DUSHANBE	39	69E	7/63-12/72	108
36	ALMA-ATA	43	76E	6/60-12/72	149
37	QUETTA	30	67E	1/60-10/72	101
38	SRINAGAR	34	75E	1/60-12/72	120
39	MOUNT ABU	25	73E	9/69-12/72	40
40	AHMEDABAD	23	73E	1/60-10/69	118
41	NEW DELHI	29	77E	1/60-12/72	156
42	VARANASI	26	83E	12/63-12/72	109
43	DUM DUM	23	88E	2/63-12/72	119
44	KODAIKANAL	10	77E	1/60-12/72	155
45	GAN	0	73E	1/64-12/72	76
46	KARAGANDA	50	73E	11/63-12/67	38
47	SEMIPALATINSK	50	80E	11/65-11/67	24
48	IGARKA	67	87E	8/64-10/67	28
49	DIKSON IS.	74	80E	6/60-7/72	119
50	MARKOVO	65	170E	2/65-11/67	30
51	PETROPAVLOVSK	53	159E	10/63-12/67	51
52	VLADIVOSTOK	43	132E	10/61-12/72	122
53	BOLSHAYA ELAN	47	143E	9/63-11/72	115
54	KRASNOYARSK	56	93E	7/65-12/67	27

TABLE 1 (CONT'D)

NUMBER	NAME	LATITUDE	LONGITUDE	PERIOD OF RECORD	NUMBER OF MONTHLY MEANS
55	IRKUTSK	52	104E	7/60-12/72	145
56	YAKUTSK	62	130E	9/61-12/72	123
57	NAGAEVO	60	151E	4/62-12/71	109
58	SAPPORO	43	141E	1/60-12/72	156
59	TATENO	36	140E	1/60-12/72	156
60	TORISHIMA	30	140E	12/63-11/65	24
61	MARCUS IS.	24	154E	1/58-6/63	66
62	KAGOSHIMA	32	131E	1/60-12/72	156
63	TAIPEI	25	122E	7/65-12/69	54
64	FAIRBANKS	65	148W	12/64-6/72	61
65	MAUNA LOA	20	155W	11/57-12/72	132
66	RESOLUTE	75	95W	7/57-10/72	172
67	CHURCHILL	59	94W	12/64-12/72	95
68	EDMONTON	54	114W	1/60-12/72	156
69	BISMARK	47	101W	1/63-12/72	118
70	BOULDER	40	105W	1/64-12/72	106
71	ALBUQUERQUE	35	107W	11/63-9/68	58
72	GREEN BAY	44	88W	1/63-12/72	120
73	MOOSONEE	51	81W	2/59-6/61	29
74	TORONTO	43	79W	1/60-12/72	152
75	STERLING	39	77W	1/62-6/67	66
76	WALLOPS	38	75W	6/67-12/72	50
77	NASHVILLE	36	87W	1/63-12/72	117
78	TALLAHASSEE	30	84W	5/64-4/70	68
79	BEDFORD	42	71W	10/63-1/71	89
80	CARIBOU	47	68W	1/63-12/72	116
81	GOOSE	53	60W	1/62-11/70	131
82	REYKJAVIK	64	22W	7/57-12/71	158
83	CERRILLO	19	99W	1/69-6/70	18
84	CASABLANCA	34	8W	4/69-12/72	45
	B. SOUTHERN HEMISPHERE STATIONS				
85	ARGENTINE IS.	-62	64W	6/60-12/67	77
86	ASPENDALE	-38	145E	7/57-12/72	186
87	BRISBANE	-27	153E	7/57-12/72	186
88	DUMONT D'URVILLE	-67	140E	1/58-12/62	39
89	MACQUARIE IS.	-54	159E	7/57-12/72	136
90	WELLINGTON	-41	175E	7/57-6/70	105
91	HALLEY	-76	27W	5/57-12/67	97
92	LITTLE AMERICA	-78	162W	1/57-12/58	24
93	KERGUELEN	-42	70E	7/59-12/68	106
94	PRETORIA	-26	28E	4/64-2/72	93
95	BYRD	-80	119W	8/62-10/68	62
96	KING BAUDOUIN	-70	24E	2/65-12/66	24
97	MIRNY	-67	93E	2/60-12/66	43
98	BUENOS AIRES	-35	58W	10/65-12/72	86
99	HOBART	-43	147E	7/67-12/72	66
100	SYOWA	-69	40E	2/66-12/72	52
101	INVERCARGILL	-46	168E	5/70-12/72	26
102	HUANCAYO	-12	75W	2/64-12/72	107
103	SOUTH POLE	-90.	---	11/61-11/71	81
104	PUERTO MONTT	-41	73W	11/64-11/65	13
105	PERTH	-32	116E	3/69-12/72	46
106	DARWIN	-12	131E	5/66-12/72	80
107	SALISBURY	-35	139E	3/61-10/68	13
108	HALLETT	-72	170E	1/61-10/63	27

TABLE 2.

OZONESONDE STATIONS

STATIONS	LAT.	LONG.	PERIOD OF RECORD	TOTAL ASCENTS	INSTRUMENT TYPE*
FAIRBANKS	64.8	147.9W	11/64-12/65	51	R,CI
GOOSE BAY	53.3N	60.4W	1/63-12/63	49	R
BERLIN	52.5N	13.4E	11/66-12/72	355	B
UCCLE	50.8N	4.3E	12/65-8/67	99	B,R
PARIS	48.8N	2.3E	1/64-5/67	62	V
HOHENPEISSENBERG	47.8N	11.0E	3/65-12/72	372	M,B
SAPPORO	43.0N	141.3E	12/68-12/72	162	CI
BEDFORD	42.5N	71.3W	6/69-3/71	77	M
ELMAS	39.2N	9.0E	7/68-7/70	55	B
TOPEKA	39.1N	95.6W	4/63-5/63	10	R
STERLING	39.0N	77.5W	8/62-6/66	179	R,CI,M
TATENO	36.0N	140.1E	3/68-12/72	159	CI
KAGOSHIMA	31.6N	130.6E	12/68-12/72	143	CI
HILO	19.7N	155.1W	12/64-12/65	17	R
CANTON ISLAND	2.8S	171.7W	2/65-12/65	32	R,CI
LA PAZ	16.5S	58.0W	3/65-9/65	10	R
ASPENDALE	38.0S	145.1E	6/65-12/72	502	M
PUERTO MONTT	41.4S	72.8W	12/64-1/66	22	R
CHRISTCHURCH	43.5S	172.5E	3/65-12/65	25	M
WILKES	66.2S	110.5E	2/63-11/63	7	R
SYOWA	69.0S	39.6E	11/67-12/70	66	CI
KING BAUDOUIN	70.4S	24.3E	3/65-12/66	27	B
HALLETT	72.3S	170.3E	2/62-11/63	26	R
BYRD	80.0S	119.5W	11/63-12/66	111	R
AMUNDSEN-SCOTT	90.0S	----	3/62-12/66	111	R
USNS ELTANIN	VARIABLE		3/65-4/66	21	M
AFCRL OZONESONDE NETWORK					
THULE	76.5N	68.8W	1/63-1/66	92	R
FAIRBANKS	64.8N	147.9W	1/63-9/64	56	R
FT. CHURCHILL	58.8N	94.1W	1/63-12/65	100	R
GOOSE BAY	53.3N	60.4W	1/63-5/69	207	R,M
SEATTLE	47.4N	122.3W	1/63-12/65	148	R
MADISON	43.1N	89.4W	1/63-12/65	83	R
BEDFORD	42.5N	71.3W	12/62-5/69	509	M,R
FORT COLLINS	40.6N	105.1W	1/63-6/67	209	R
WALLOPS IS.	37.8N	75.5W	2/67-5/69	94	M
ALBUQUERQUE	35.0N	106.6W	1/63-12/65	208	R
POINT MUGU	34.1N	119.1W	6/65-12/65	18	R
TALLAHASSEE	30.4N	84.3W	1/63-12/65	138	R
CAPE KENNEDY	28.4N	80.5W	2/66-5/69	135	M
GRAND TURK	21.5N	71.1W	12/63-5/69	129	M,R
CANAL ZONE	9.0N	79.6W	1/63-5/69	126	R,M
LA PAZ	16.5S	58.0W	9/63-10/63	12	R

* Instrument types are in decreasing order of number of ascents; only instruments used for more than 10% of the ascents are included. B = Brewer; M = Brewer-Mast, R = Regener; CI = Carbon-Iodide; V = Vassy.

TABLE 3.

TOTAL OZONE (m atm cm)

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
90	320	350	330	350	350	308	281	250	220	273	306	310
85	331	377	341	382	375	312	288	267	226	281	325	319
80	381	403	417	421	396	350	305	279	269	296	333	350
75	408	452	465	465	416	354	317	293	288	306	347	353
70	392	430	450	437	403	347	312	296	289	305	326	350
65	373	411	429	423	388	335	309	297	296	304	310	331
60	379	417	430	420	387	349	320	305	297	303	318	338
55	396	426	432	418	386	350	324	306	298	304	324	346
50	390	420	422	401	375	345	320	300	293	300	320	344
45	374	398	402	384	359	333	305	290	288	294	309	344
40	346	365	375	359	340	323	302	290	285	285	290	312
35	314	331	339	334	329	314	298	289	283	277	279	295
30	275	299	310	313	309	301	288	278	275	268	263	264
25	244	253	266	283	292	285	277	271	267	262	249	243
20	244	249	263	279	282	279	271	270	270	263	249	246
15	244	251	260	276	275	269	266	270	272	265	253	250
10	245	253	261	270	270	266	264	270	270	264	253	250
5	247	254	262	264	265	263	263	270	268	262	252	244
0	250	255	262	263	264	262	262	268	268	265	256	245
-5	255	258	262	262	262	261	261	265	268	268	261	252
-10	258	260	262	261	260	260	260	264	268	270	265	263
-15	262	263	262	260	259	259	258	263	268	272	267	265
-20	267	264	264	263	262	264	268	275	281	285	281	273
-25	272	264	265	264	264	270	277	286	297	302	292	282
-30	280	273	270	271	275	287	297	306	319	315	304	290
-35	283	280	274	276	280	301	316	326	331	328	310	298
-40	308	297	290	288	301	320	331	342	353	349	335	322
-45	331	319	310	301	325	333	354	351	372	377	352	354
-50	328	310	310	310	328	343	359	361	390	401	369	350
-55	312	297	300	318	326	342	349	360	398	407	372	336
-60	313	301	298	299	299	321	325	324	340	395	370	340
-65	318	302	297	277	273	301	310	294	313	351	369	348
-70	319	300	291	280	279	295	310	306	310	335	364	350
-75	320	297	288	287	295	291	310	315	305	320	359	352
-80	318	292	279	288	282	283	300	300	296	318	355	354
-85	312	289	269	289	288	278	283	285	292	306	353	356
-90	312	288	266	288	287	277	280	281	288	306	354	356

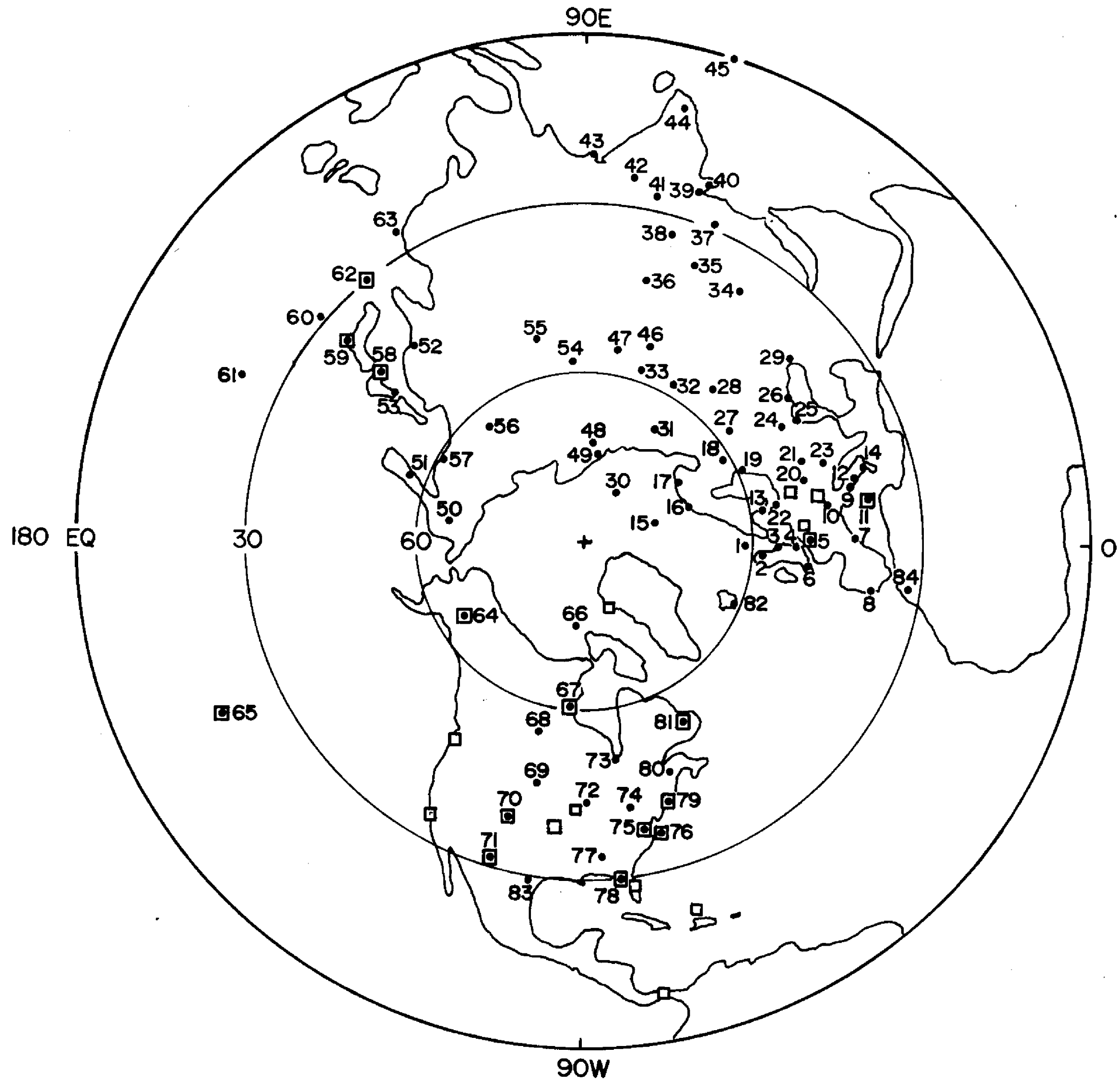

Figure 1. The distribution of total ozone (dots) and ozonesonde (squares) stations in the Northern Hemisphere. The total ozone stations are numbered according to Table 1.

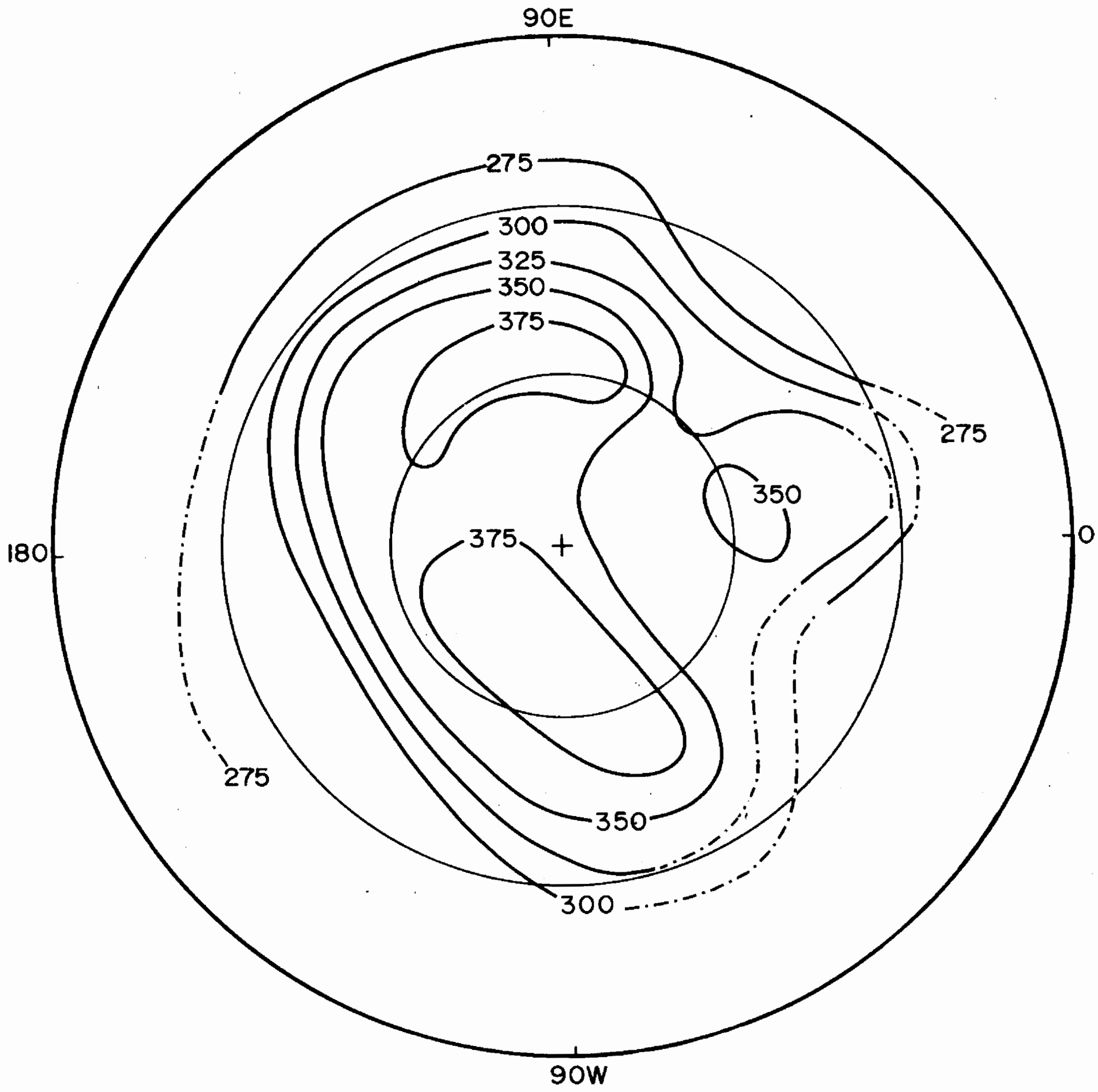

Figure 2. Annual mean total ozone from data for the years 1957-1972. Units: m atm cm.

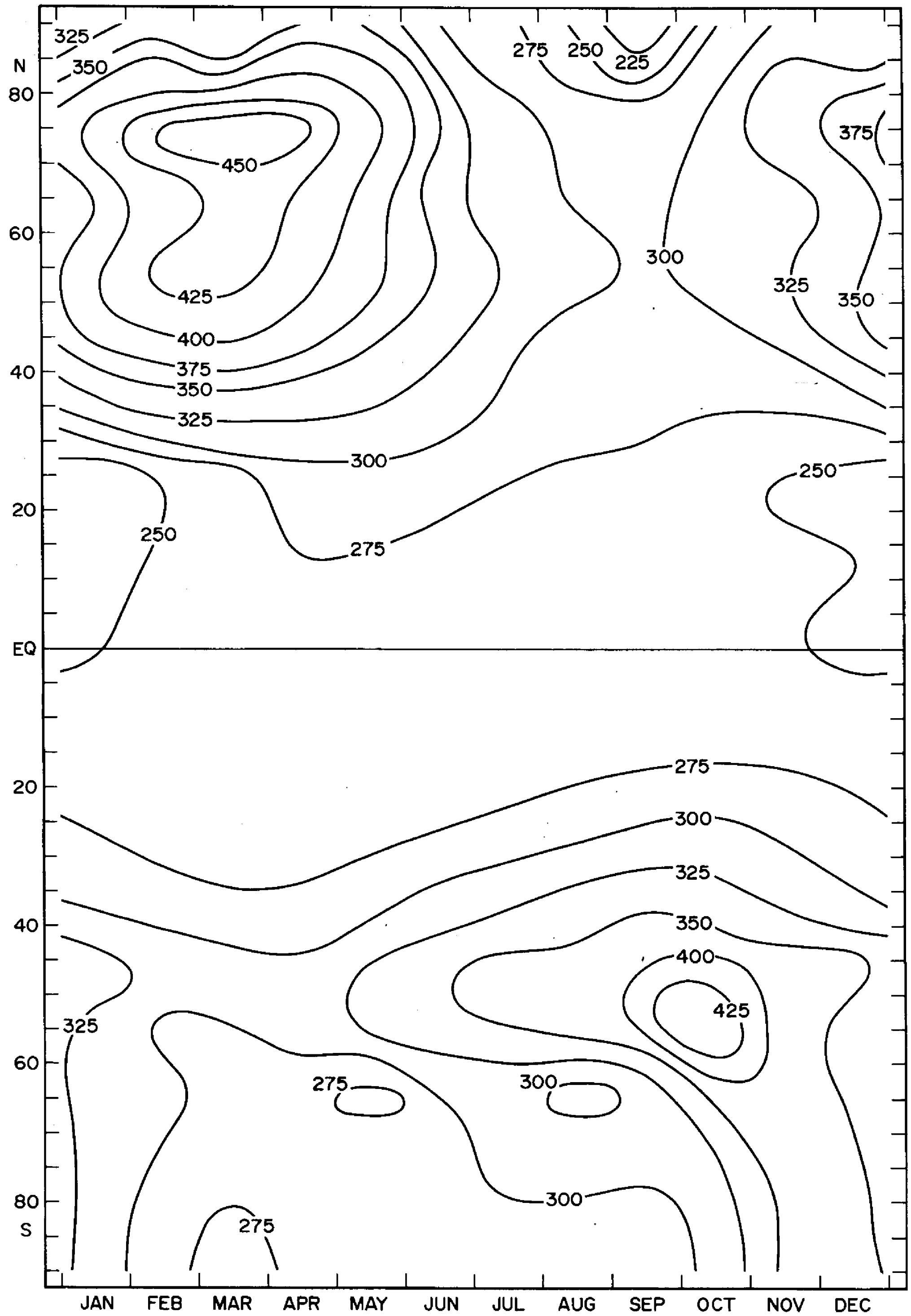

Figure 3. Weighted zonal monthly means of total ozone. Units: m atm cm.

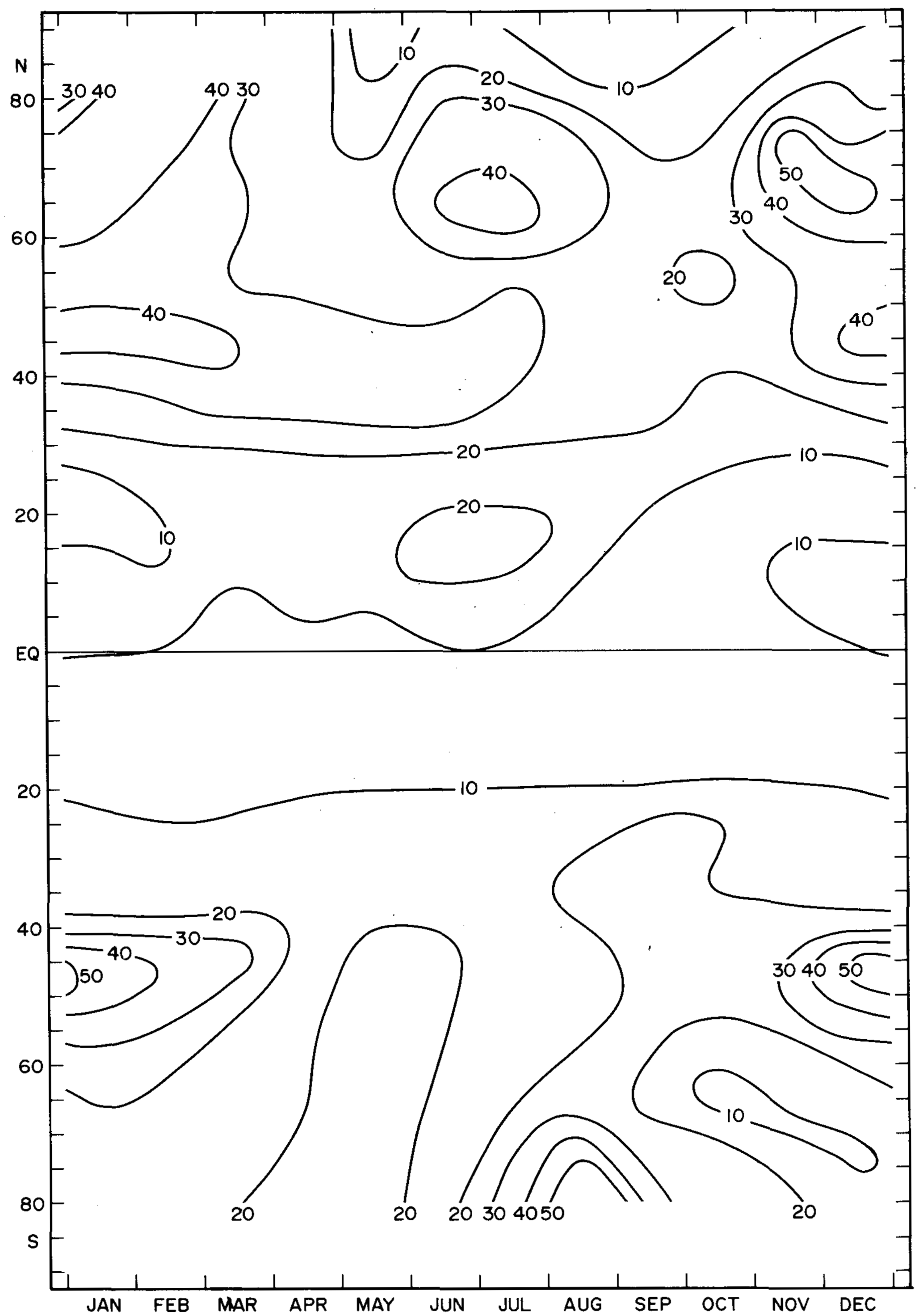

Figure 4. Weighted standard deviation of the means in Figure 3 (m atm cm).

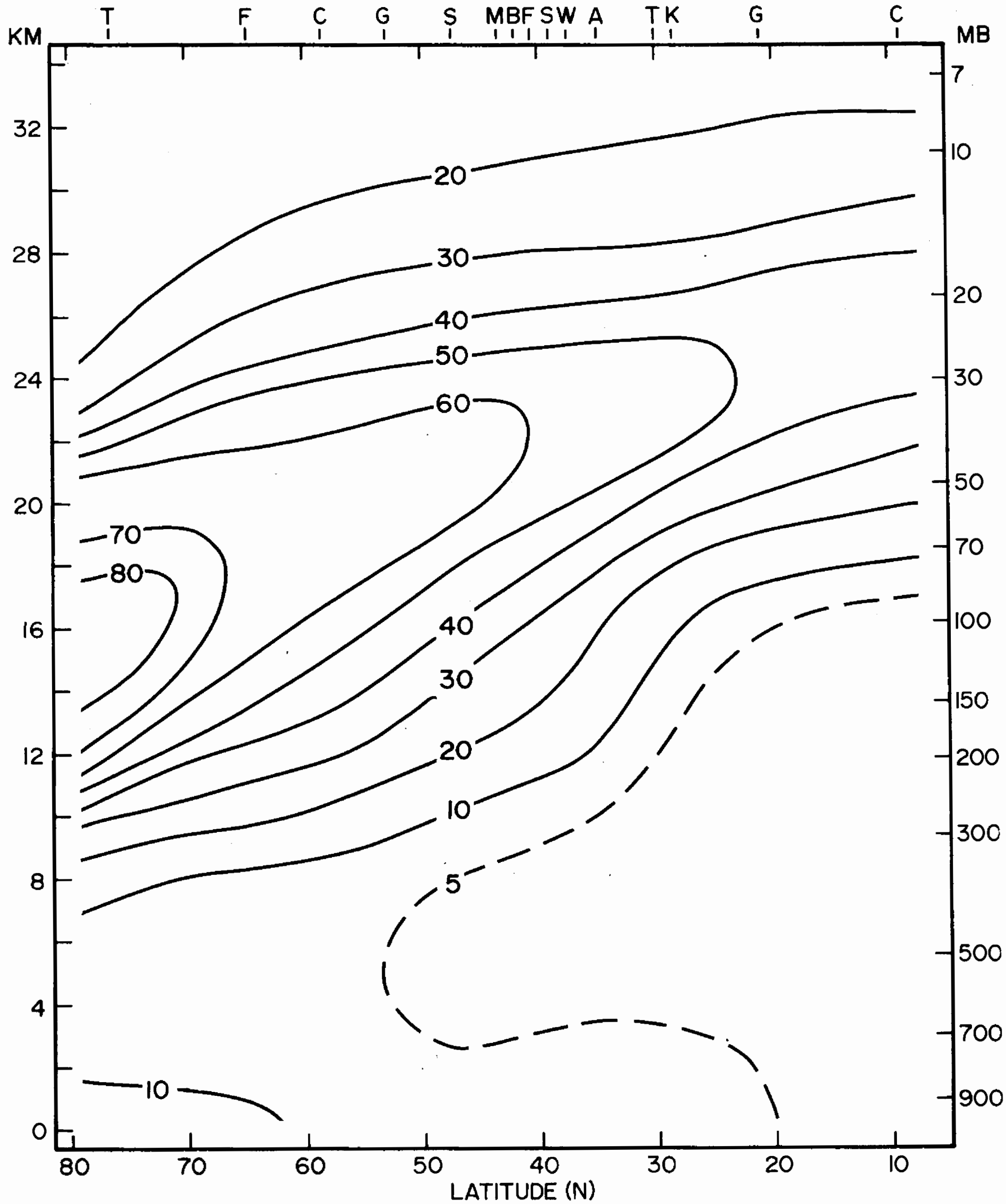

Figure 5. Vertical distribution of ozone concentration for January over North America. Units are 10^{11}molecules cm^{-3}. Ozonesonde stations used are indicated at top of figure; see Table 2 for periods of record at each.

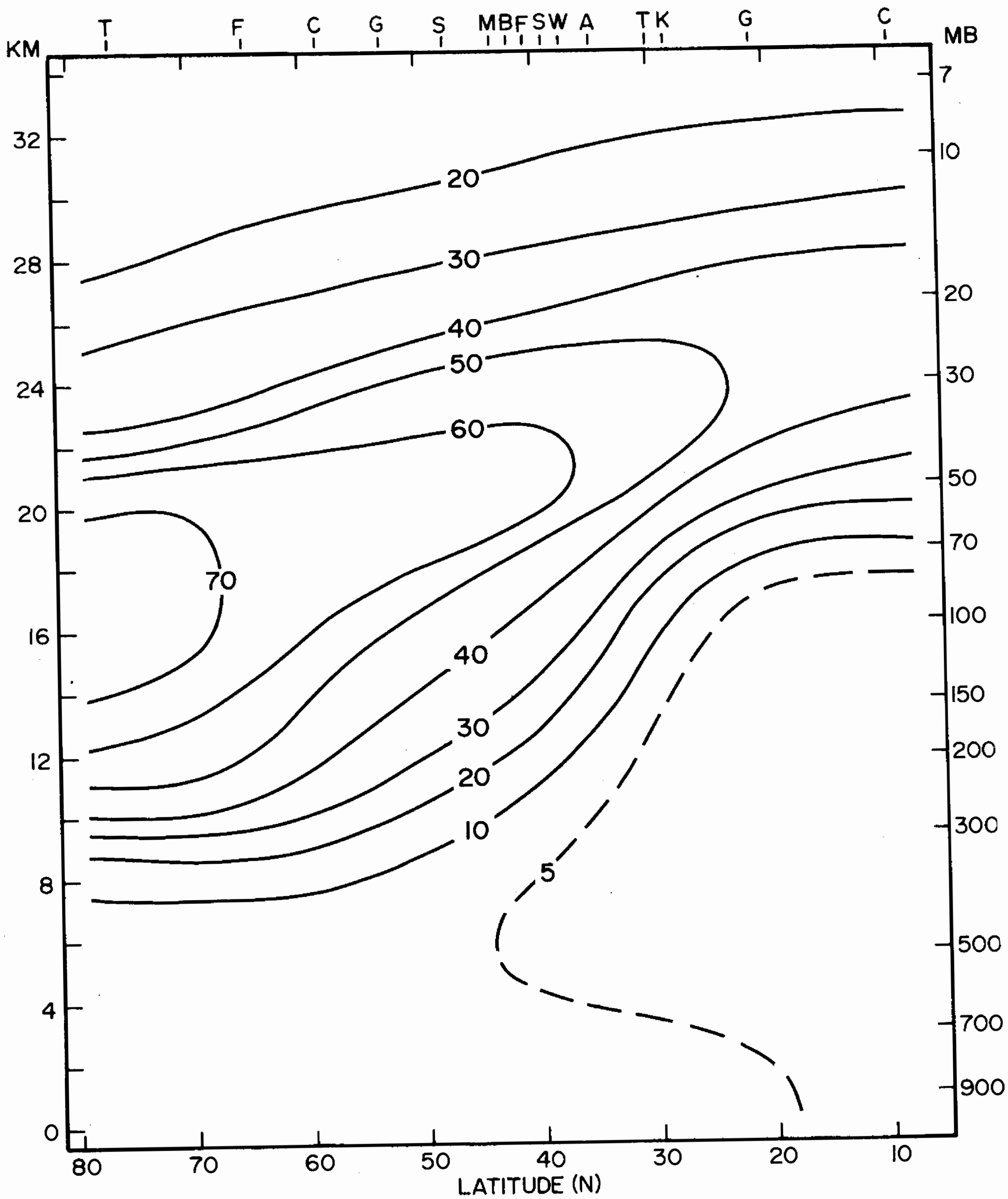

Figure 6. Same as Figure 5 except for February.

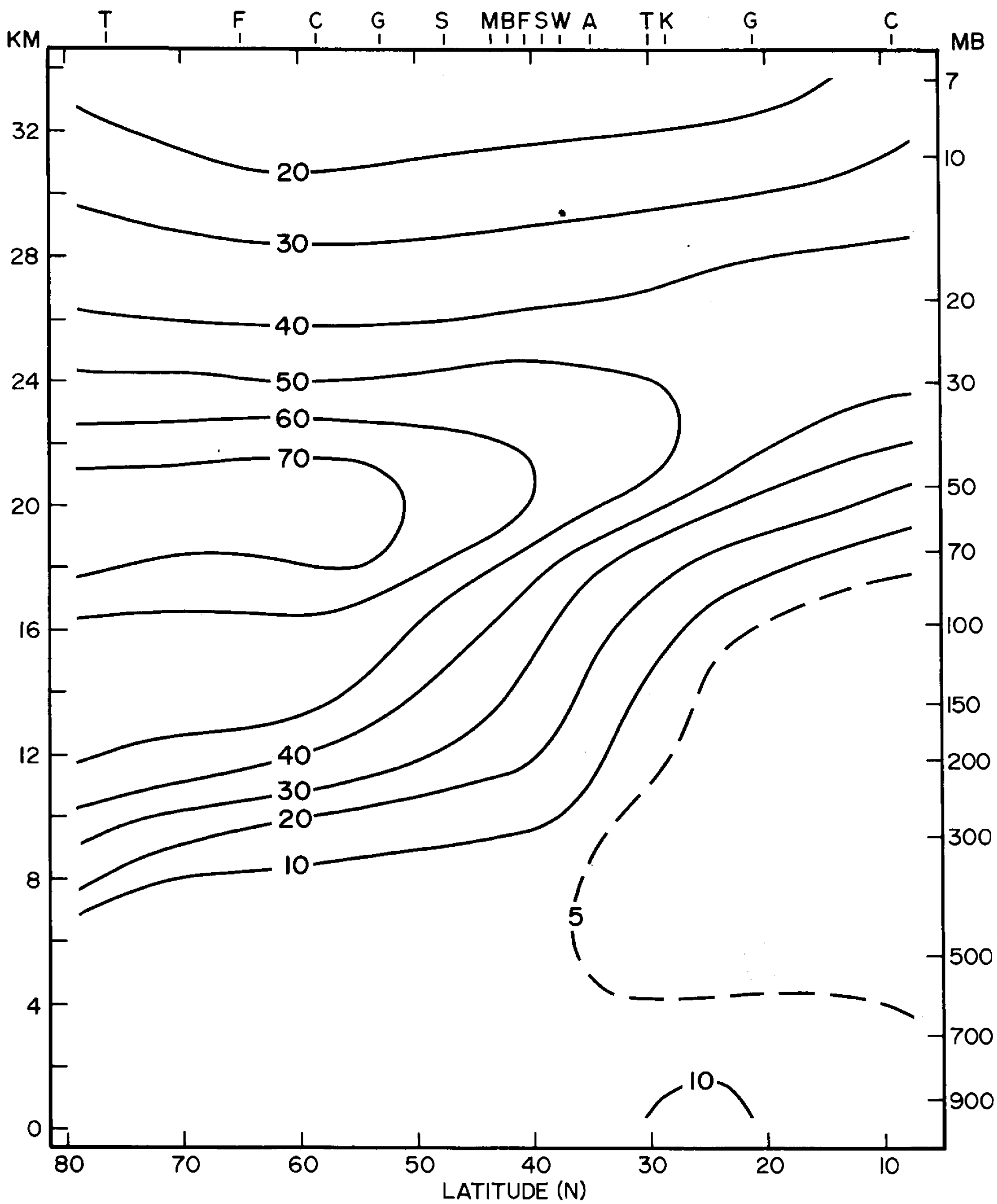

Figure 7. Same as Figure 5 except for March.

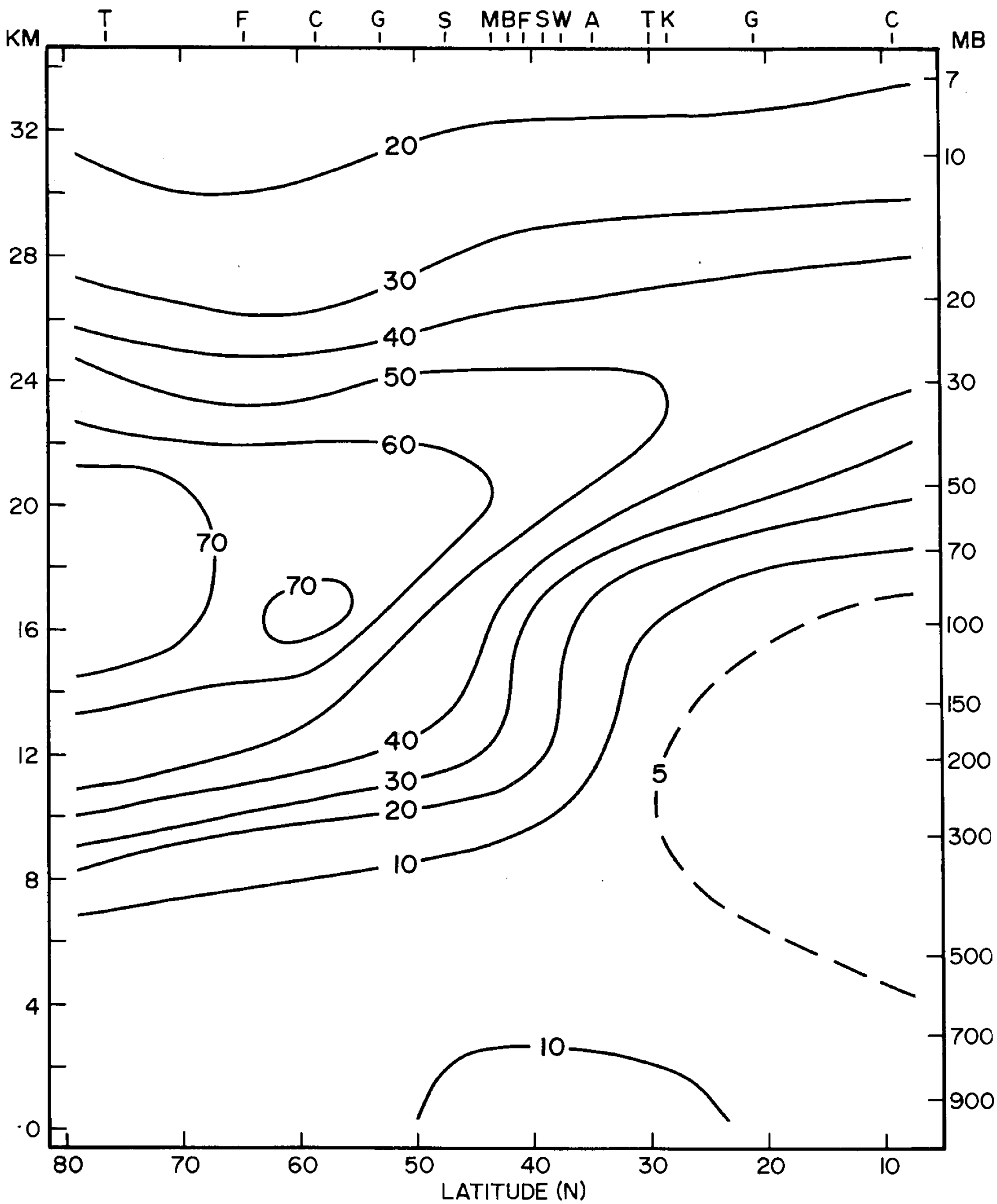

Figure 8. Same as Figure 5 except for April.

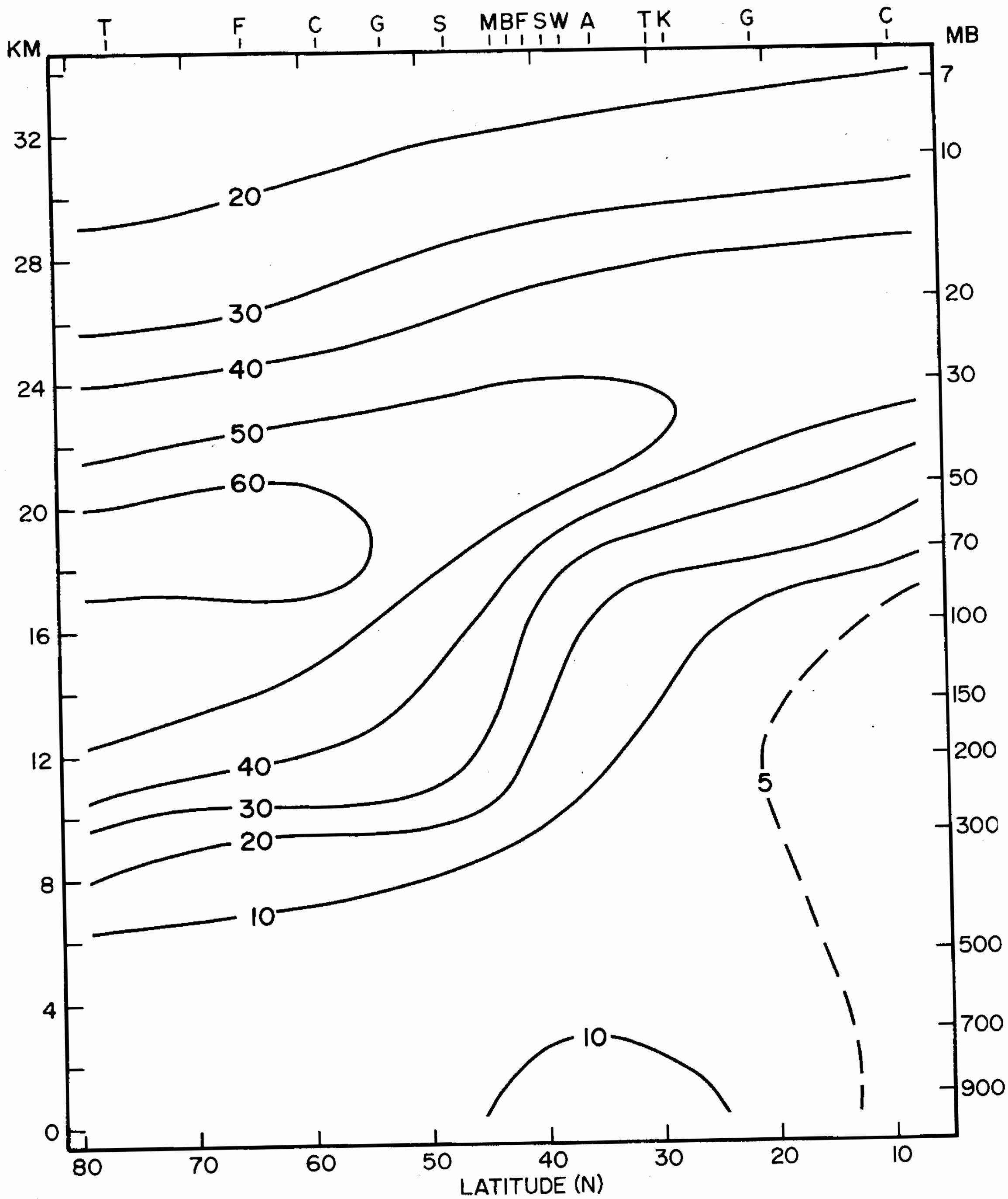

Figure 9. Same as Figure 5 except for May.

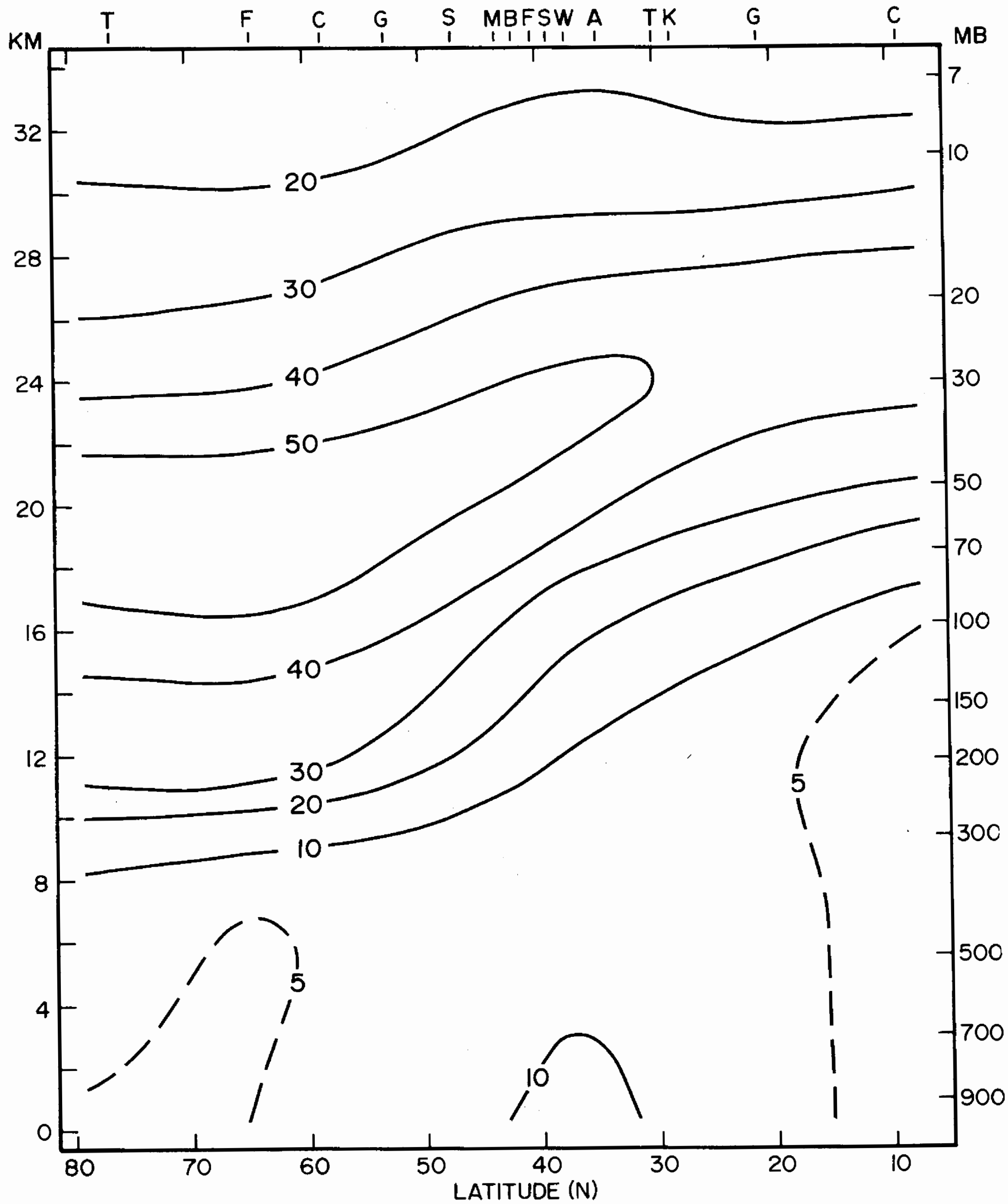

Figure 10. Same as Figure 5 except for June.

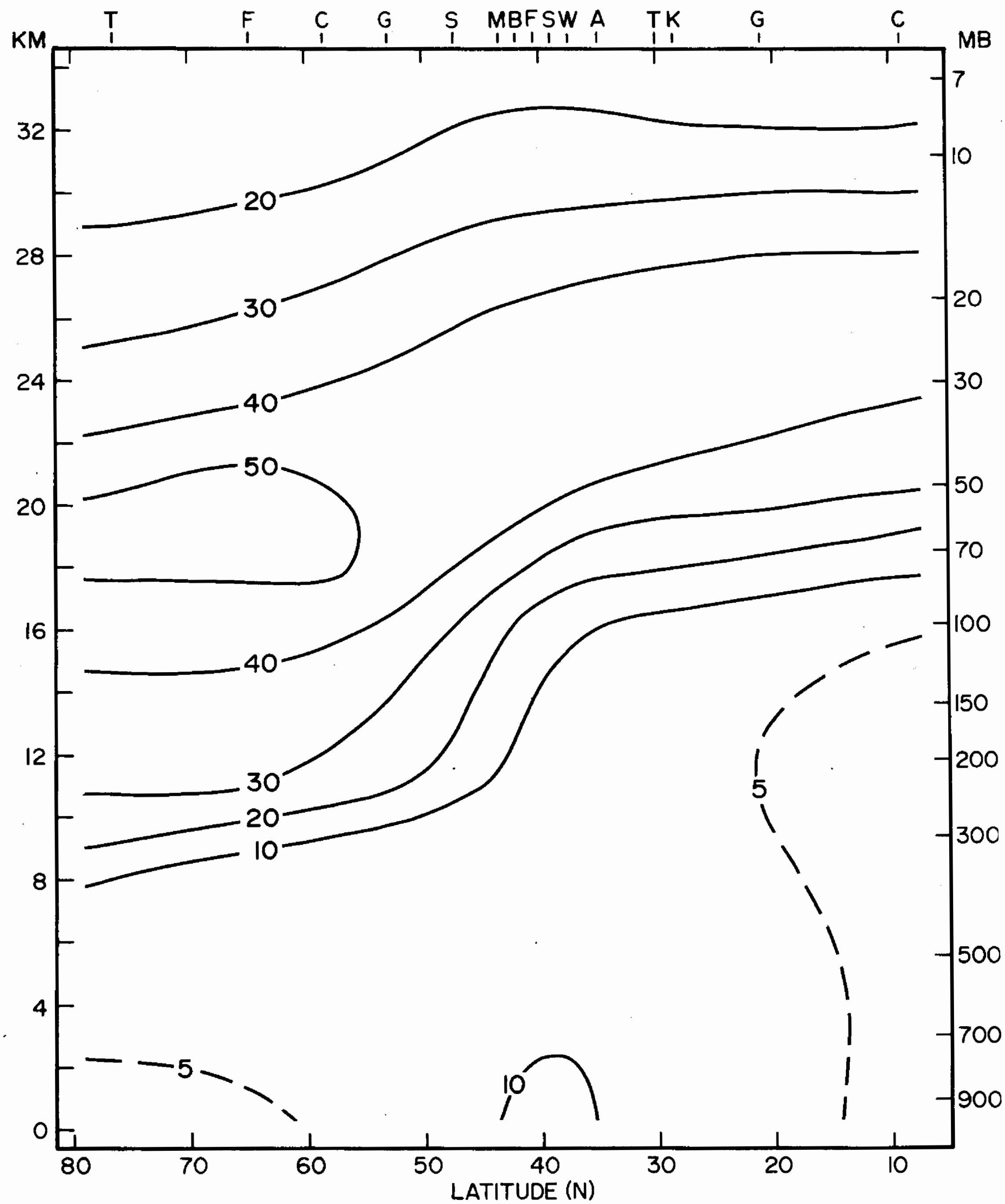

Figure 11. Same as Figure 5 except for July.

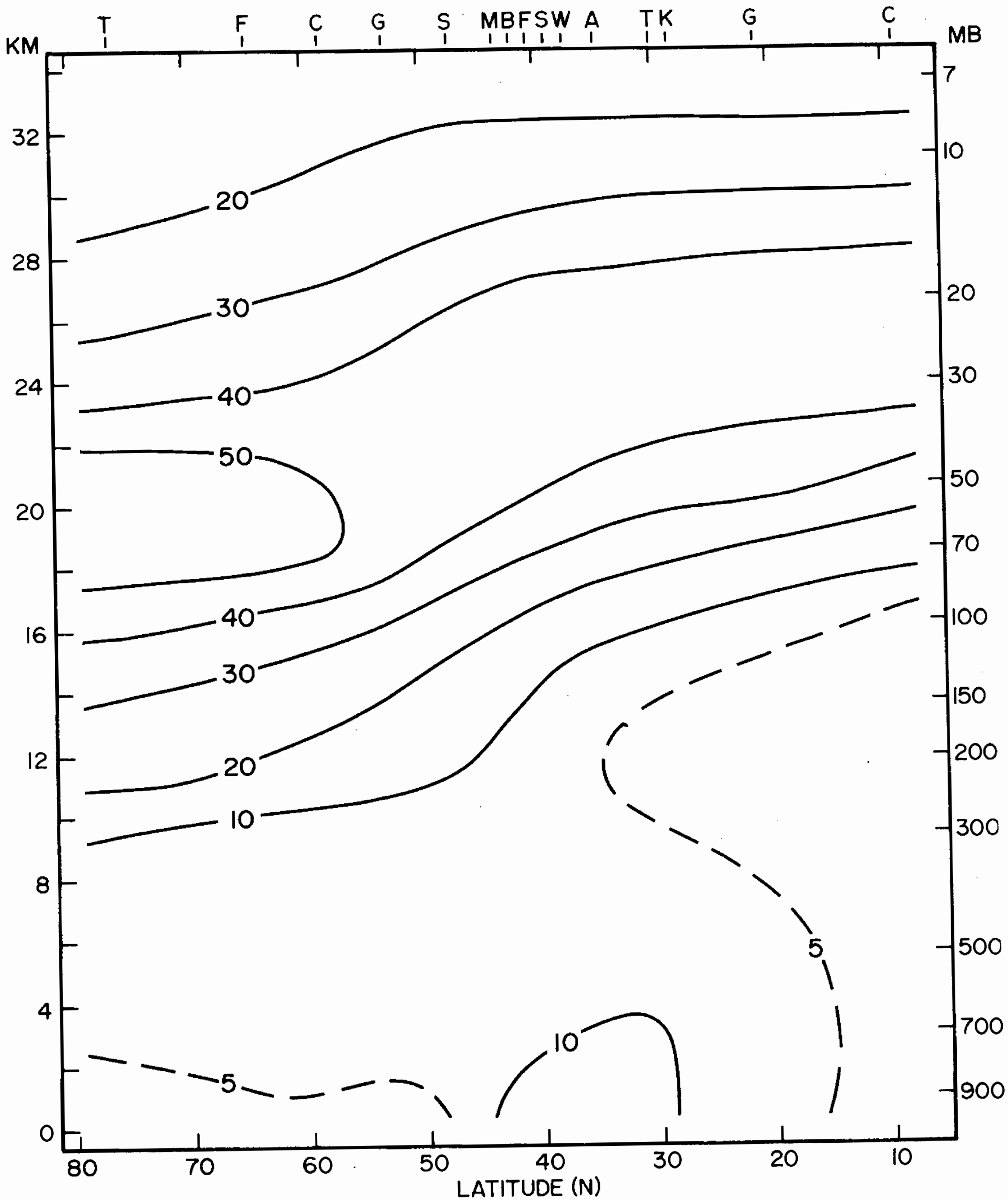

Figure 12. Same as Figure 5 except for August.

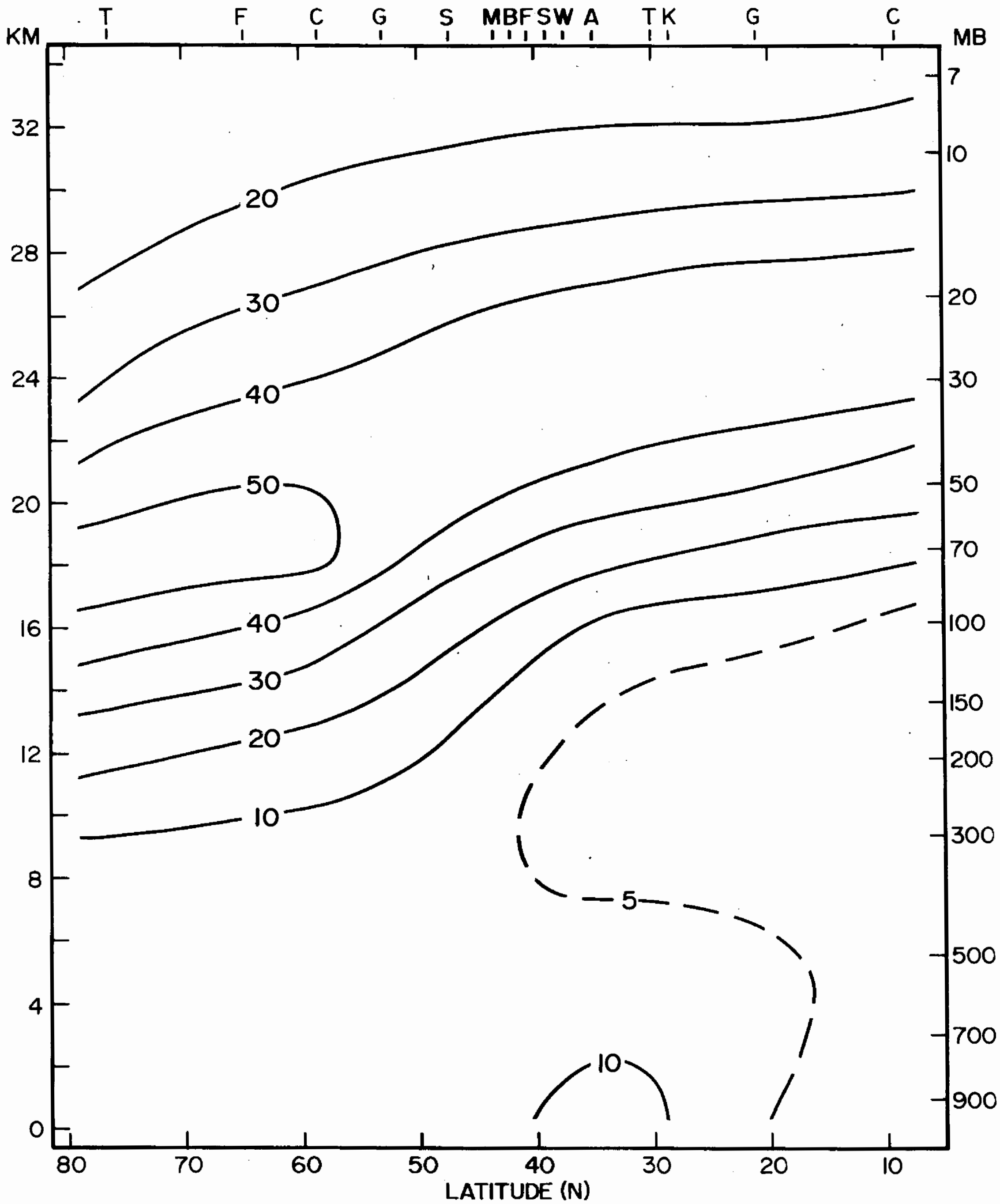

Figure 13. Same as Figure 5 except for September.

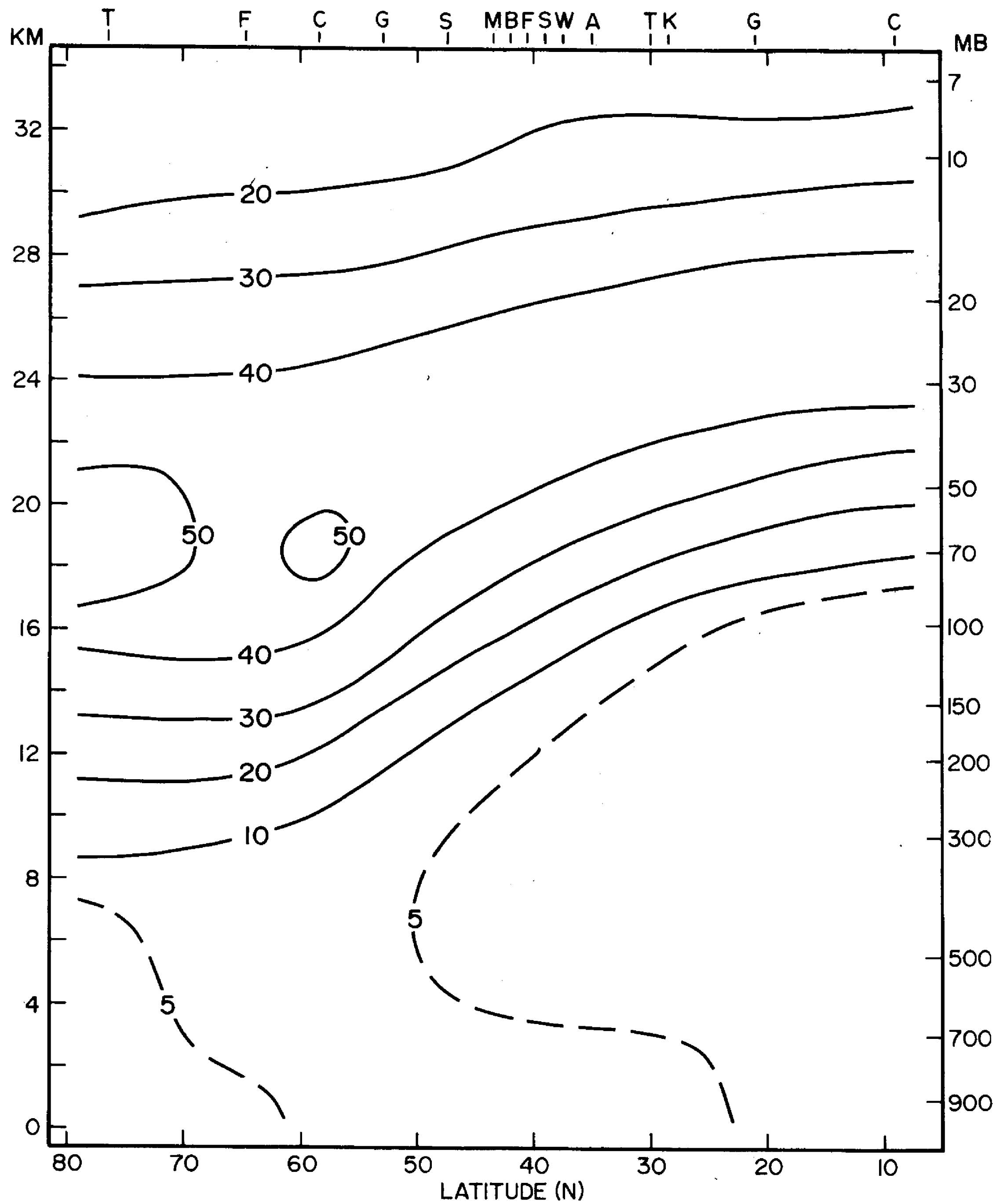

Figure 14. Same as Figure 5 except for October.

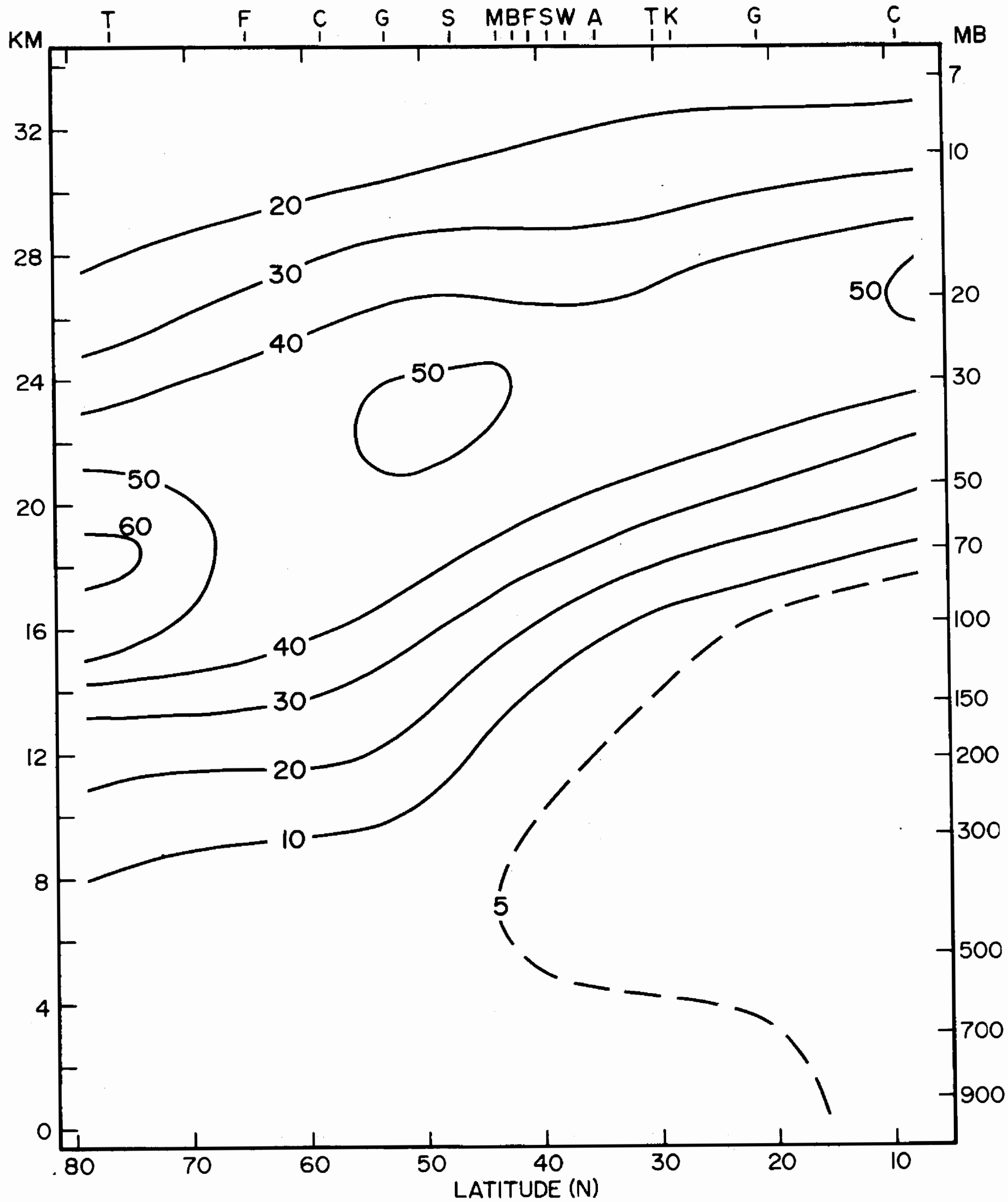

Figure 15. Same as Figure 5 except for November.

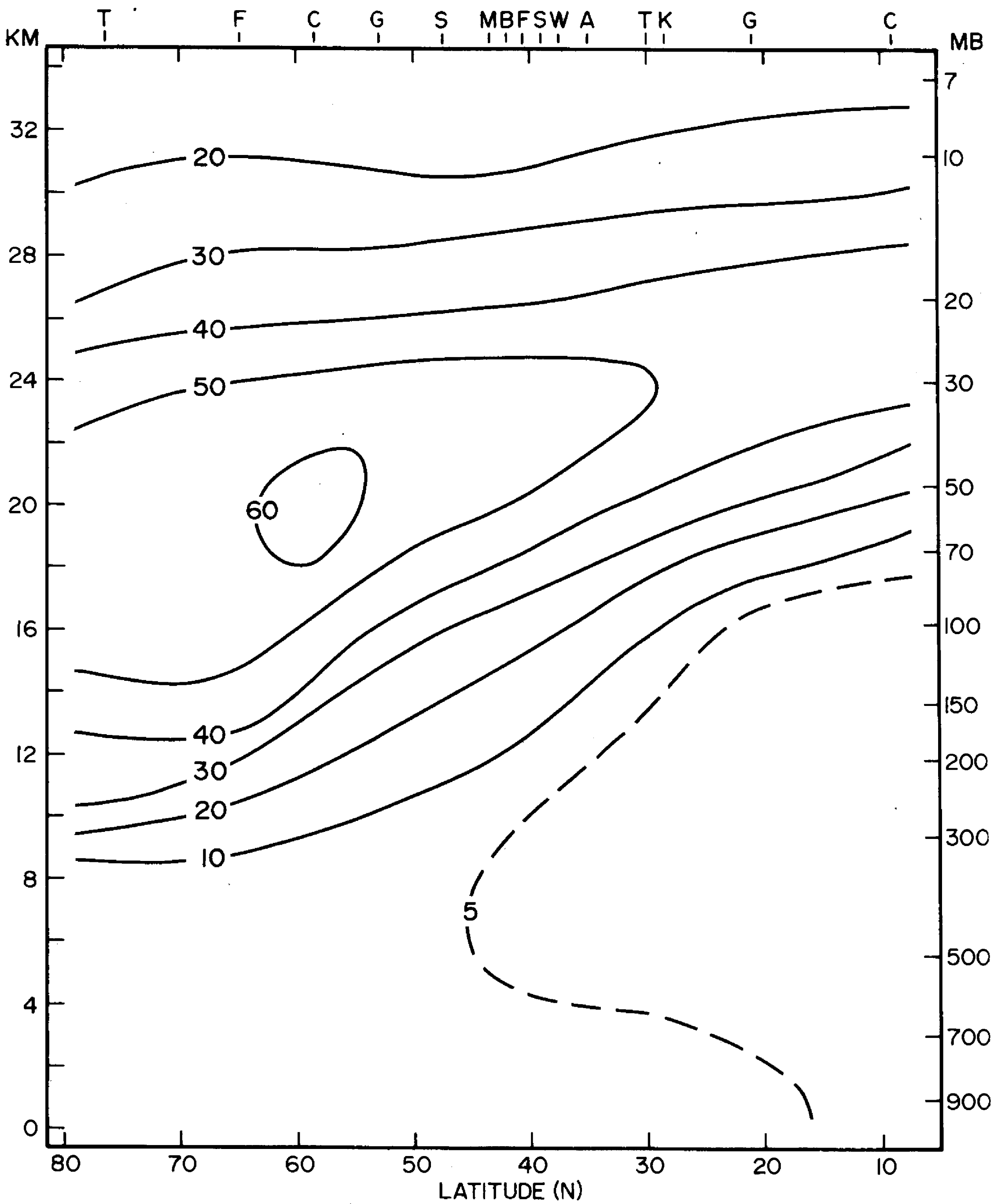

Figure 16. Same as Figure 5 except for December.

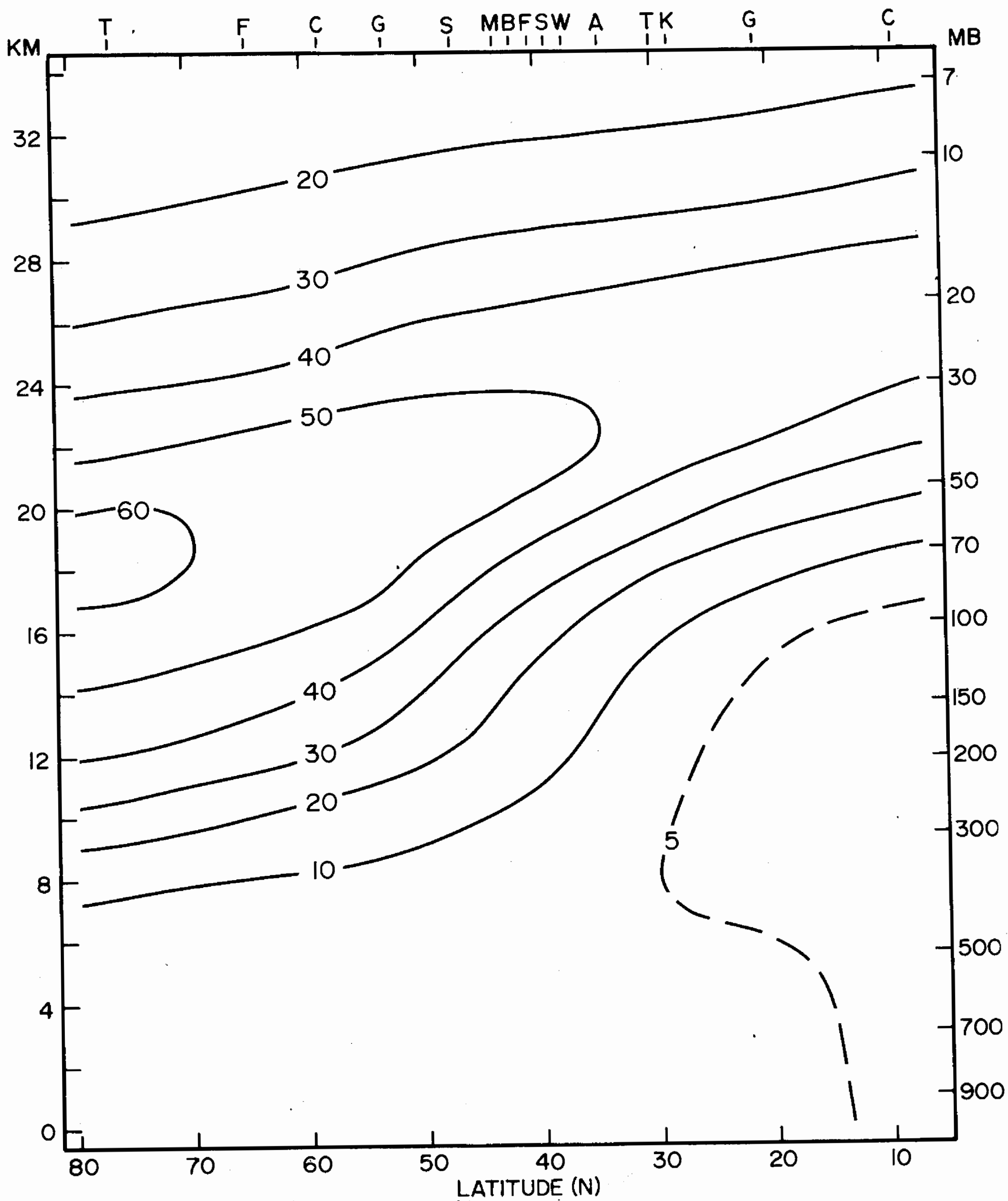

Figure 17. Same as Figure 5 except for annual mean.

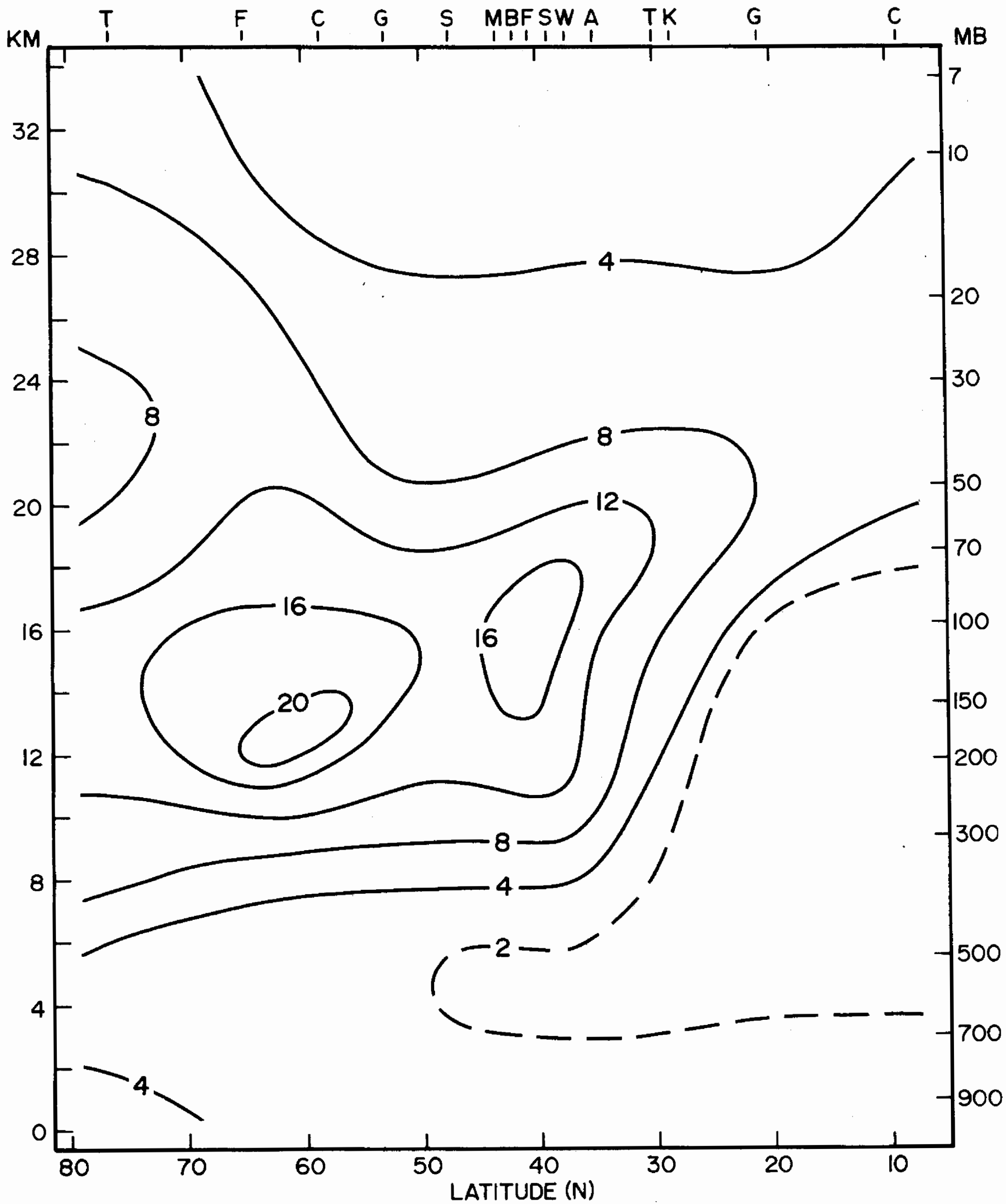

Figure 18. Standard deviation about the seasonal means, for January - March data. Units: 10^{11} molecules cm^{-3}.

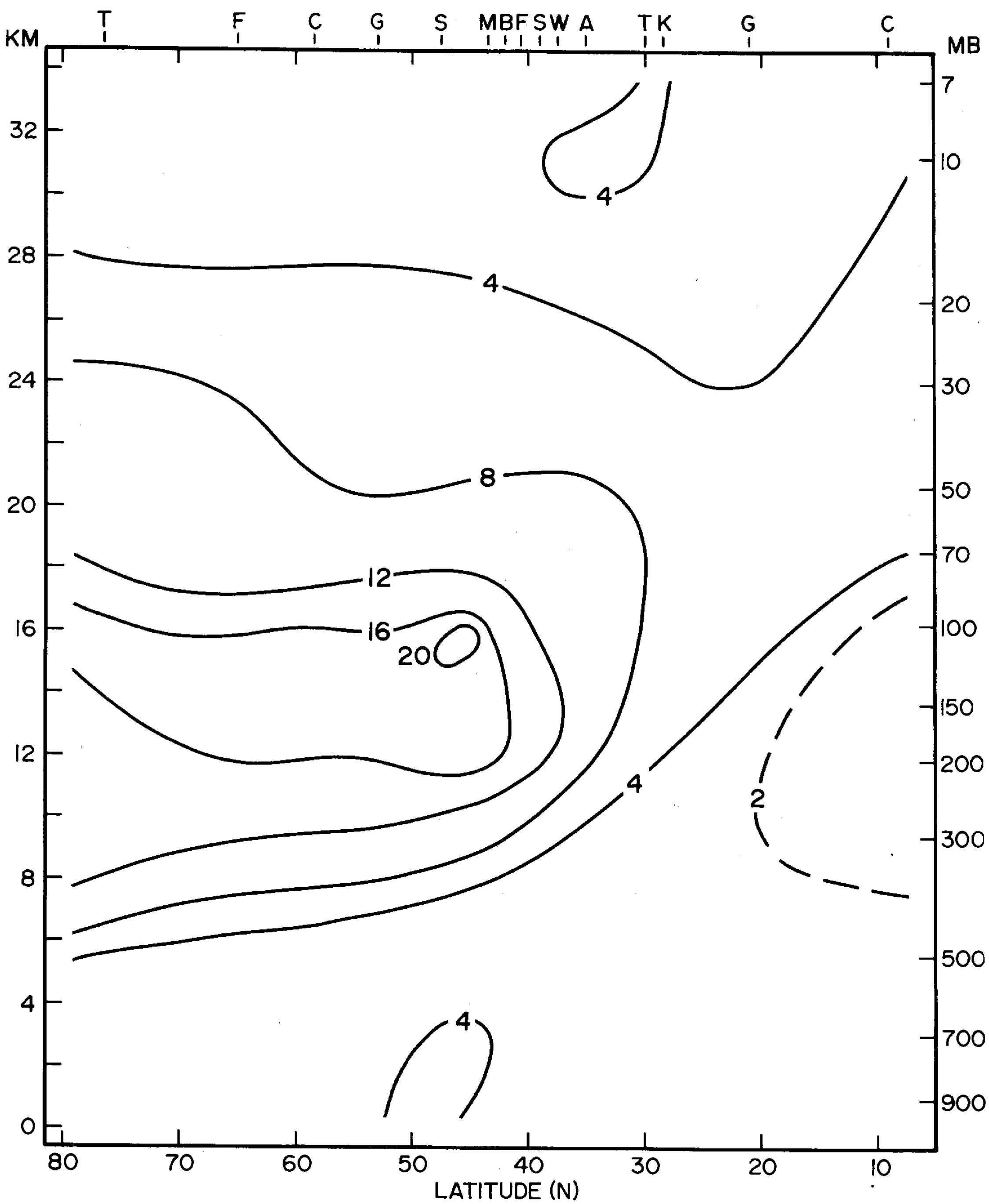

Figure 19. Same as Figure 18 except for April - June.

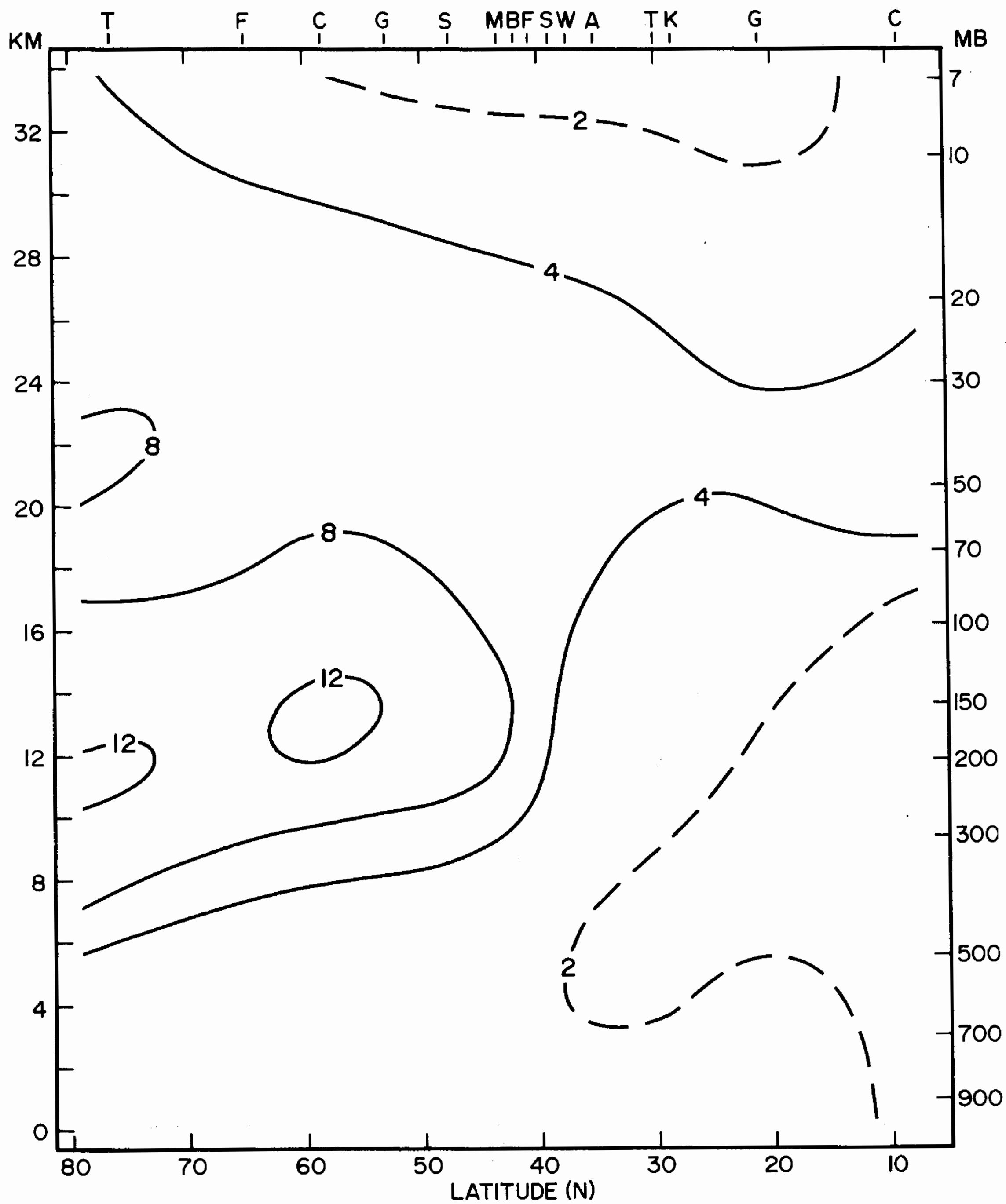

Figure 20. Same as Figure 18 except for July - September.

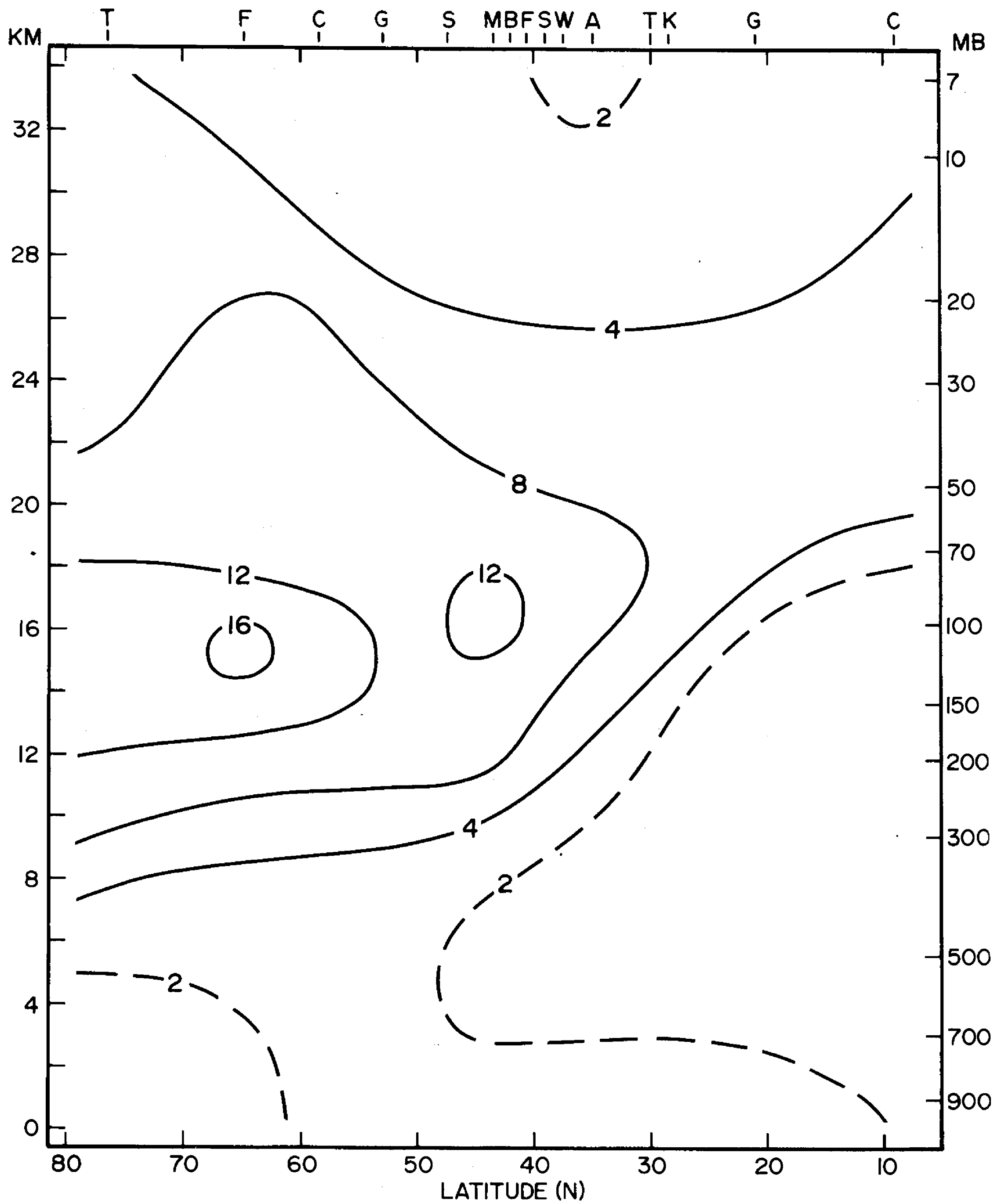

Figure 21. Same as Figure 18 except for October - December.

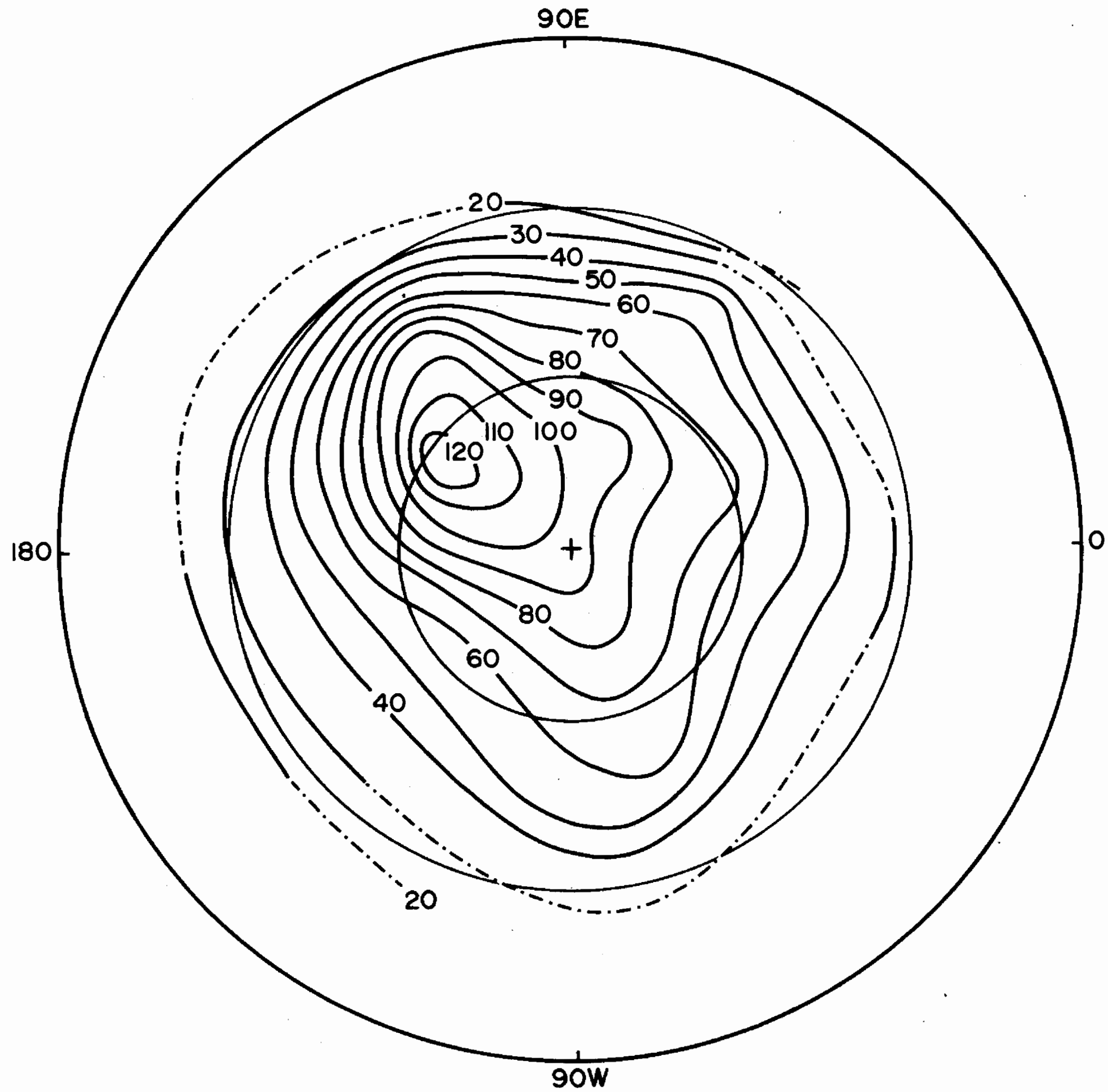

Figure 22. Amplitude of the annual wave of total ozone over the Northern Hemisphere. Units: m atm cm.

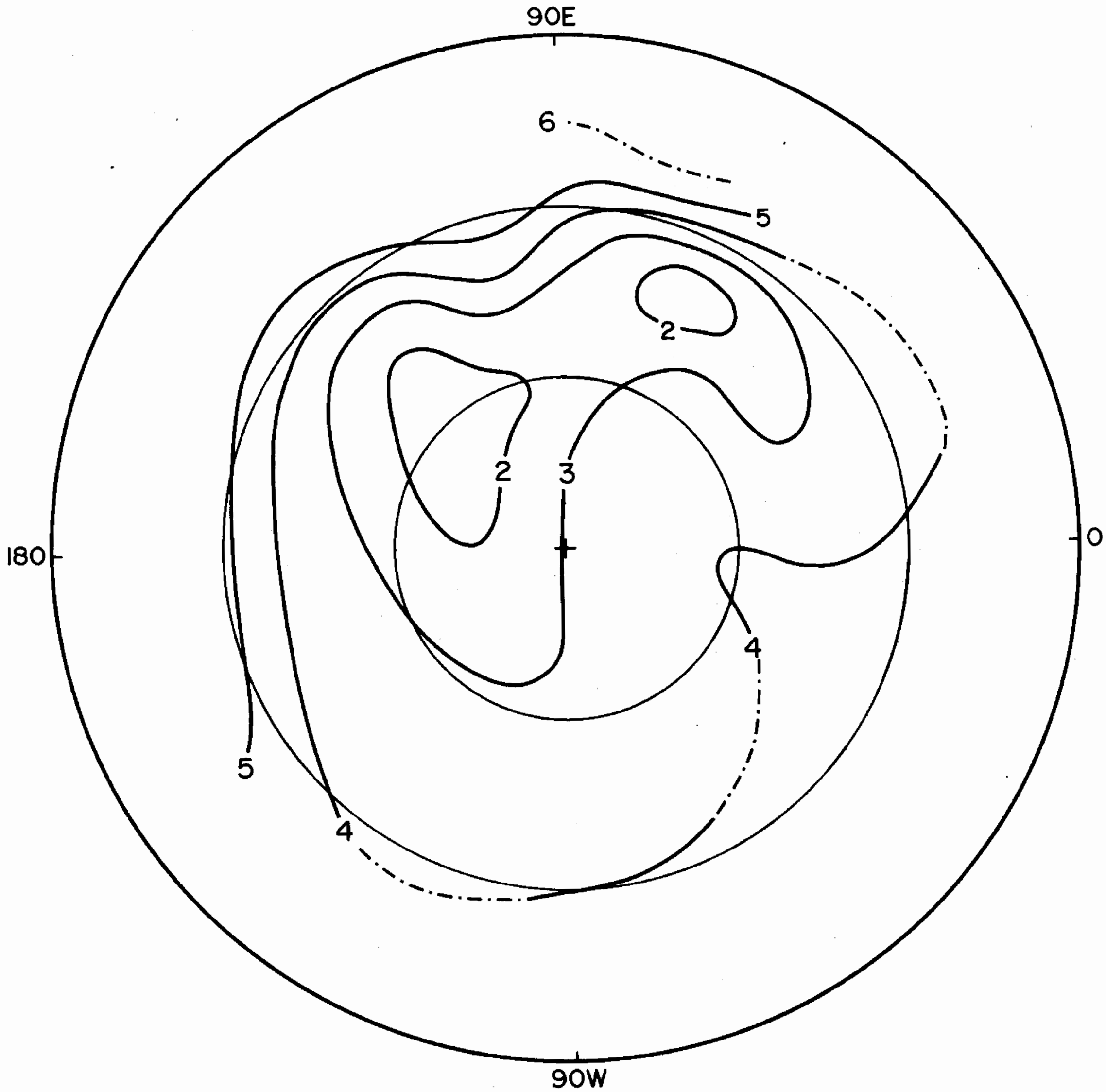

Figure 23. Phase (time of the maximum) of the annual wave of total ozone over the Northern Hemisphere. Isolines correspond to the first half of the month with which they are labelled.

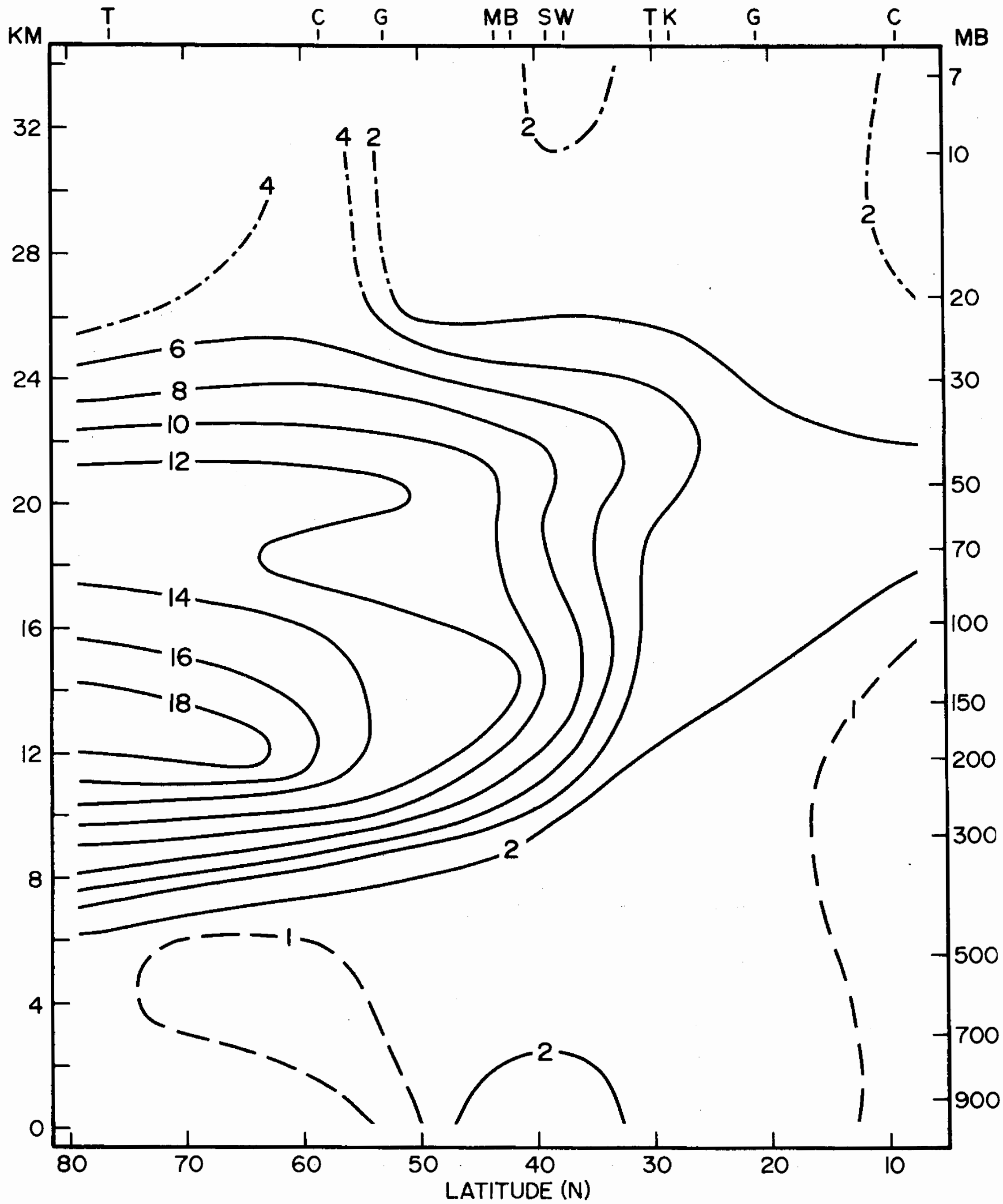

Figure 24. Amplitude of the annual wave in ozone concentration near 80°W in a height-latitude section. Units: 10^{11} molecules cm^{-3}.

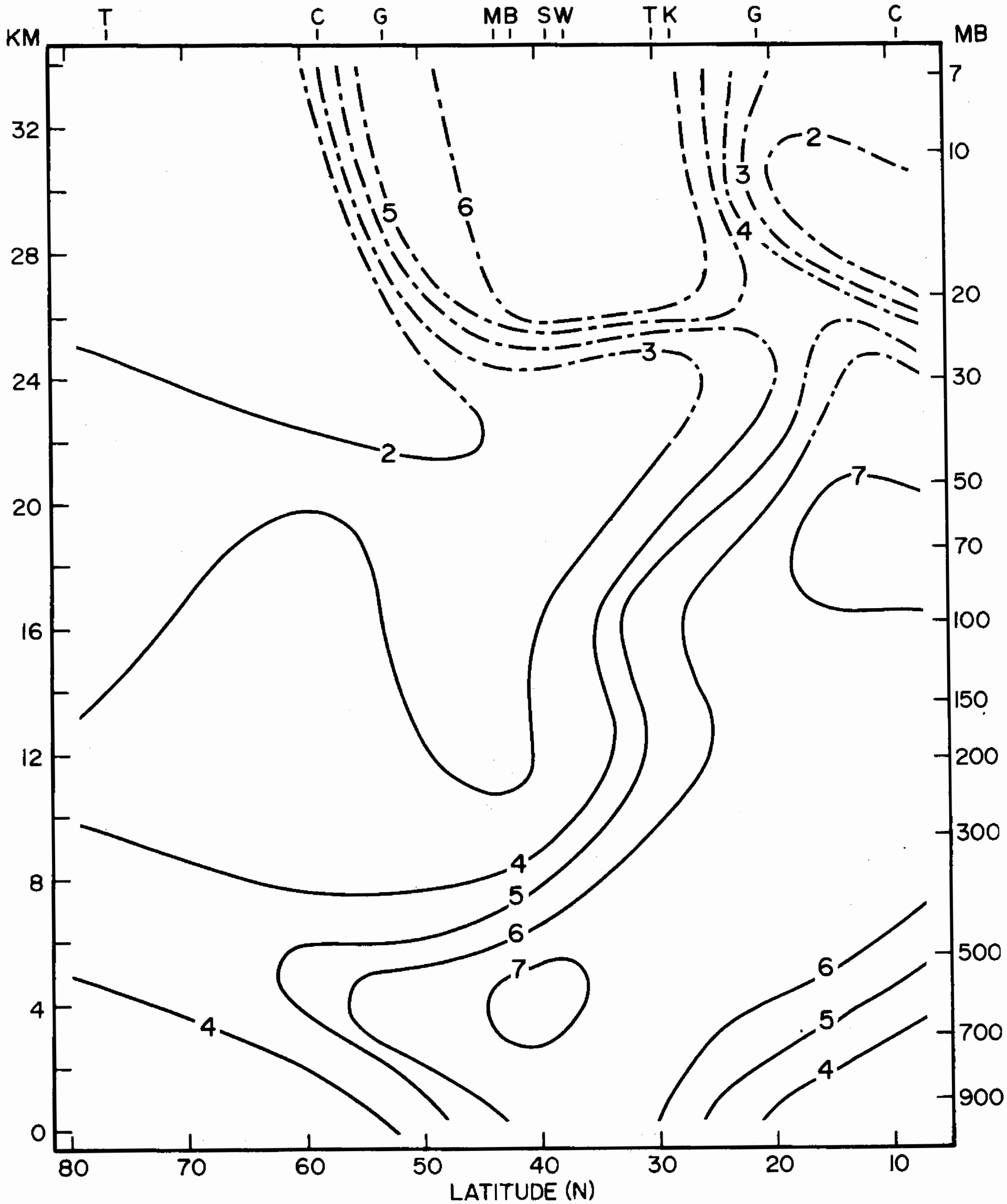

Figure 25. Phase of the annual wave in ozone concentration near 80°W in a height-latitude section. Isolines correspond to the first half of the month with which they are labelled.

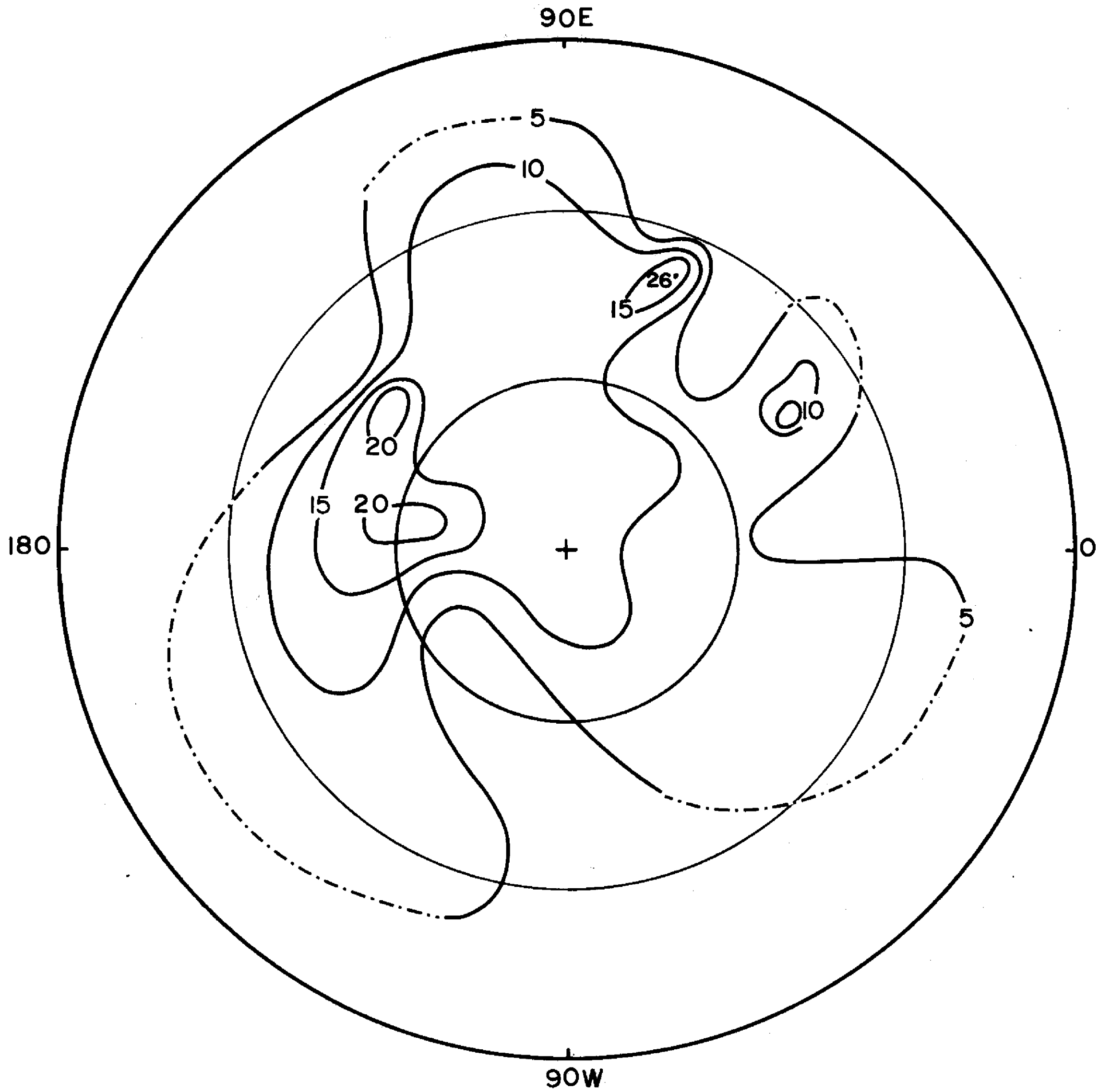

Figure 26. Amplitude of the quasi-biennial (29 month) oscillation in total ozone over the Northern Hemisphere. Units: m atm cm.

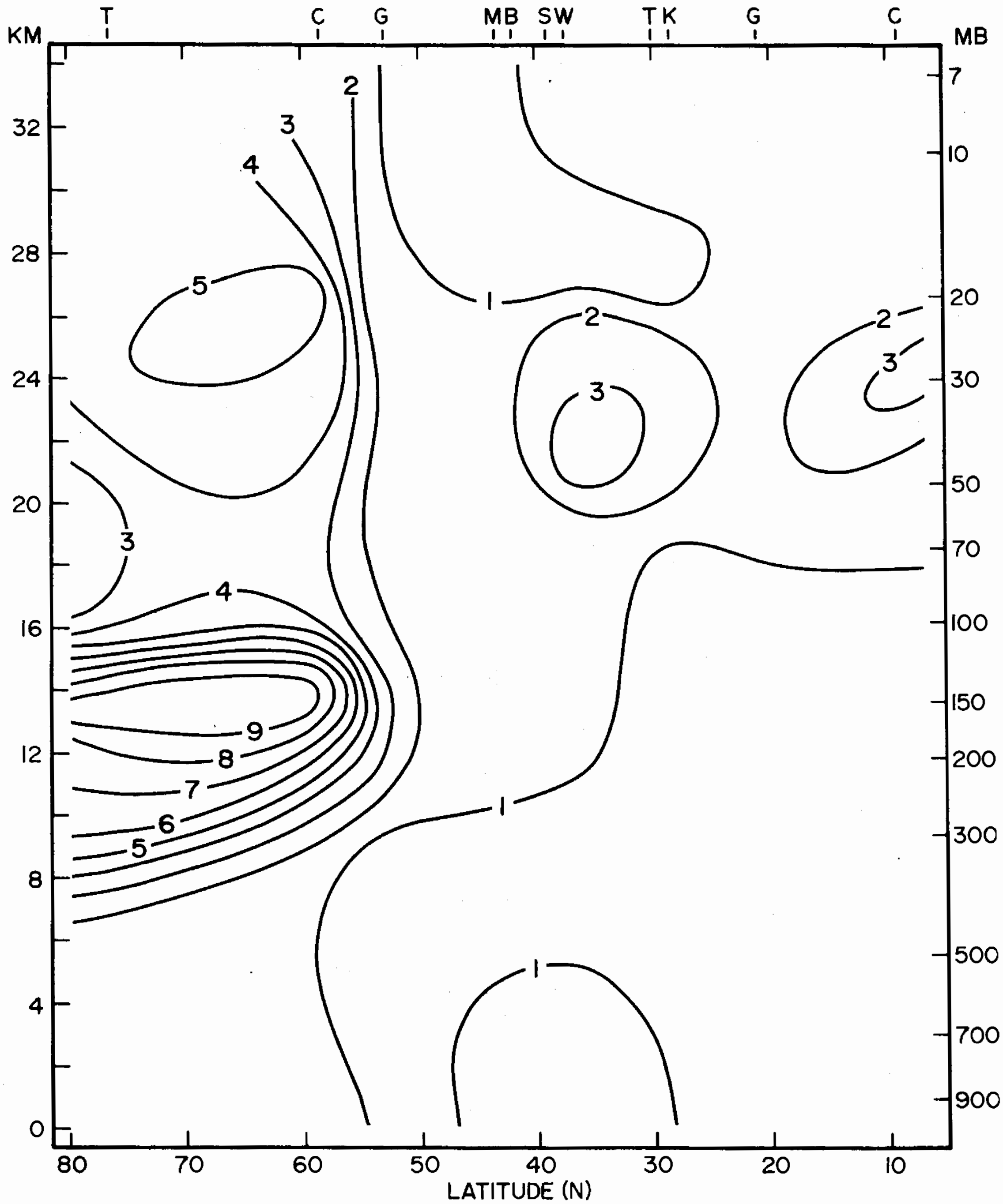

Figure 27. Amplitude of the quasi-biennial (29 month) oscillation in ozone concentration near 80°W, in a height-latitude section. Units: 10^{11} molecules cm^{-3}.

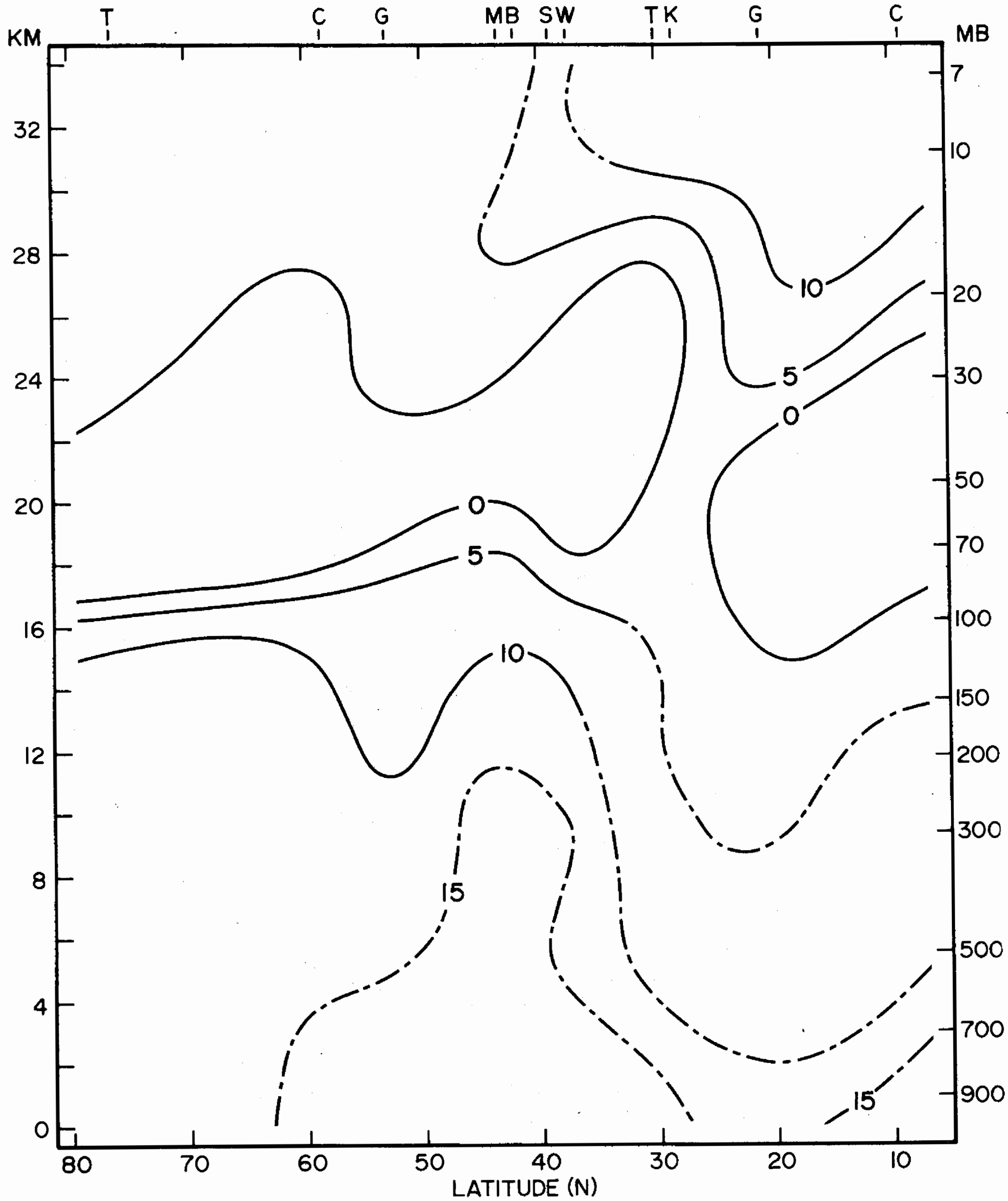

Figure 28. Phase of the quasi-biennial (29 month) oscillation in ozone concentration near 80°W, in a height-latitude section. Isolines are labelled with the number of months after 1 January 1963 that the maximum occurs, e.g. "10" means a maximum occurred near 1 October 1963.

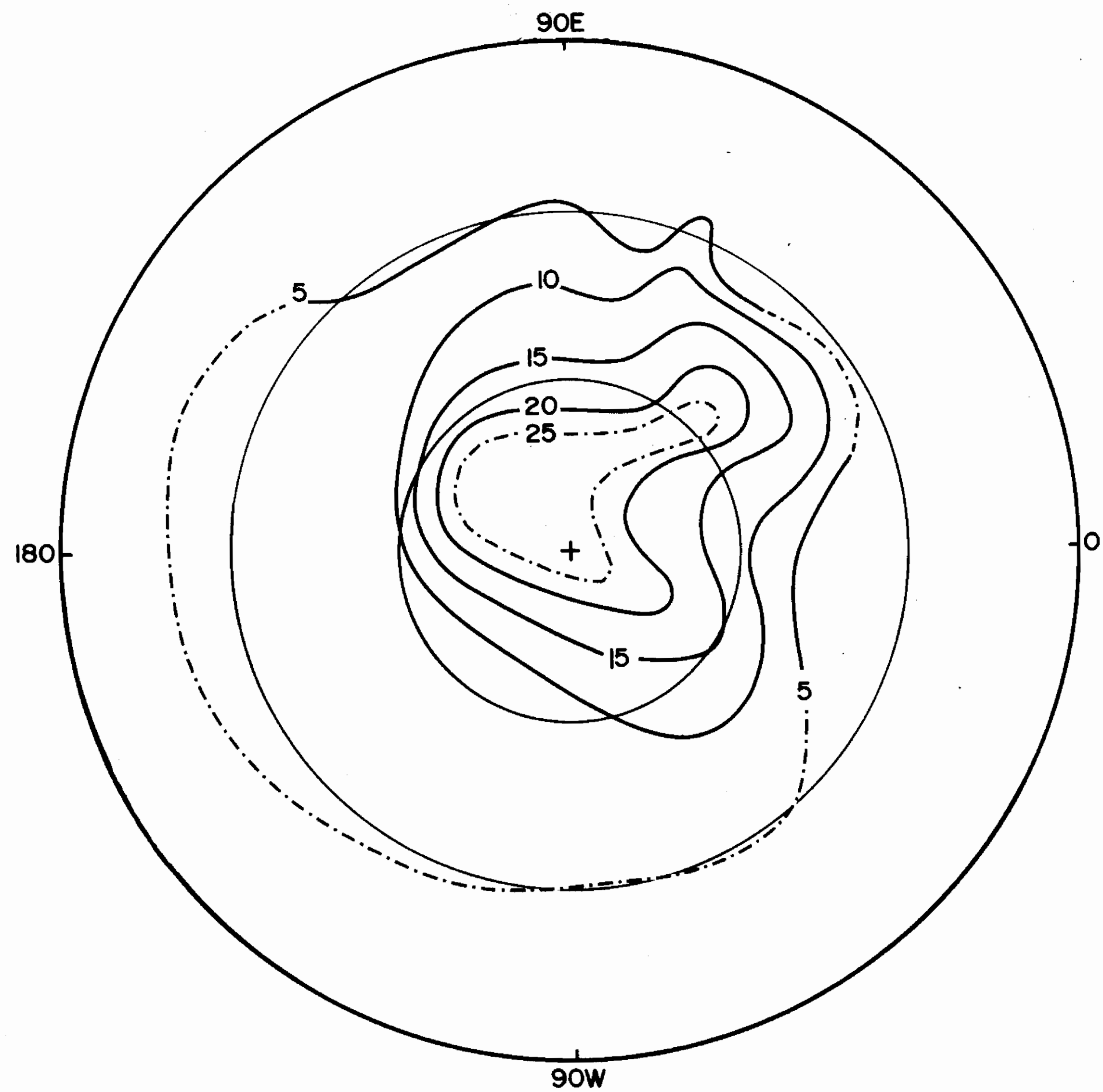

Figure 29. Amplitude of the semiannual wave in total ozone over the Northern Hemisphere. Units: m atm cm.

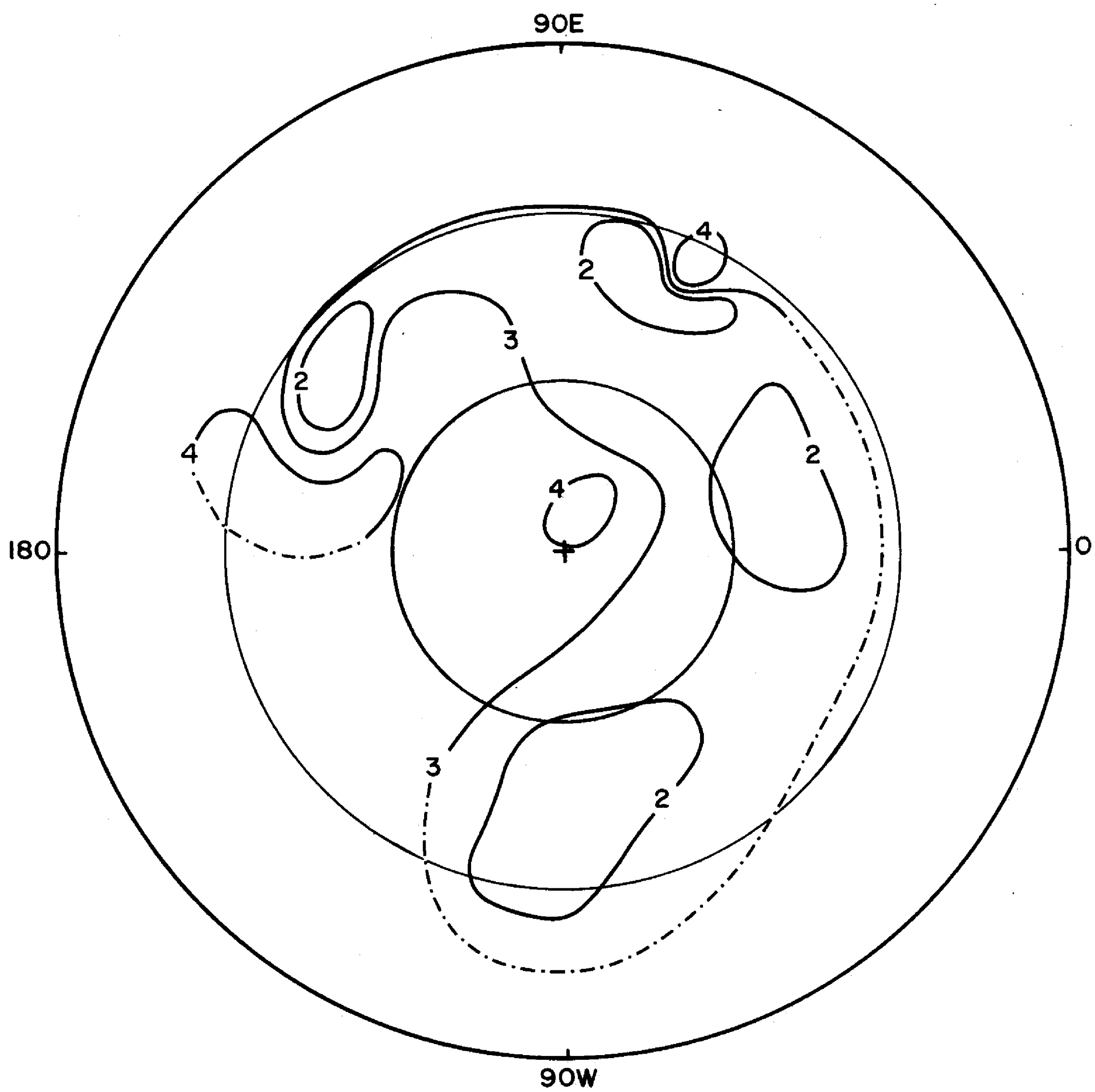

Figure 30. Phase of the semiannual wave in total ozone over the Northern Hemisphere. Isolines correspond to the first half of the month with which they are labelled.

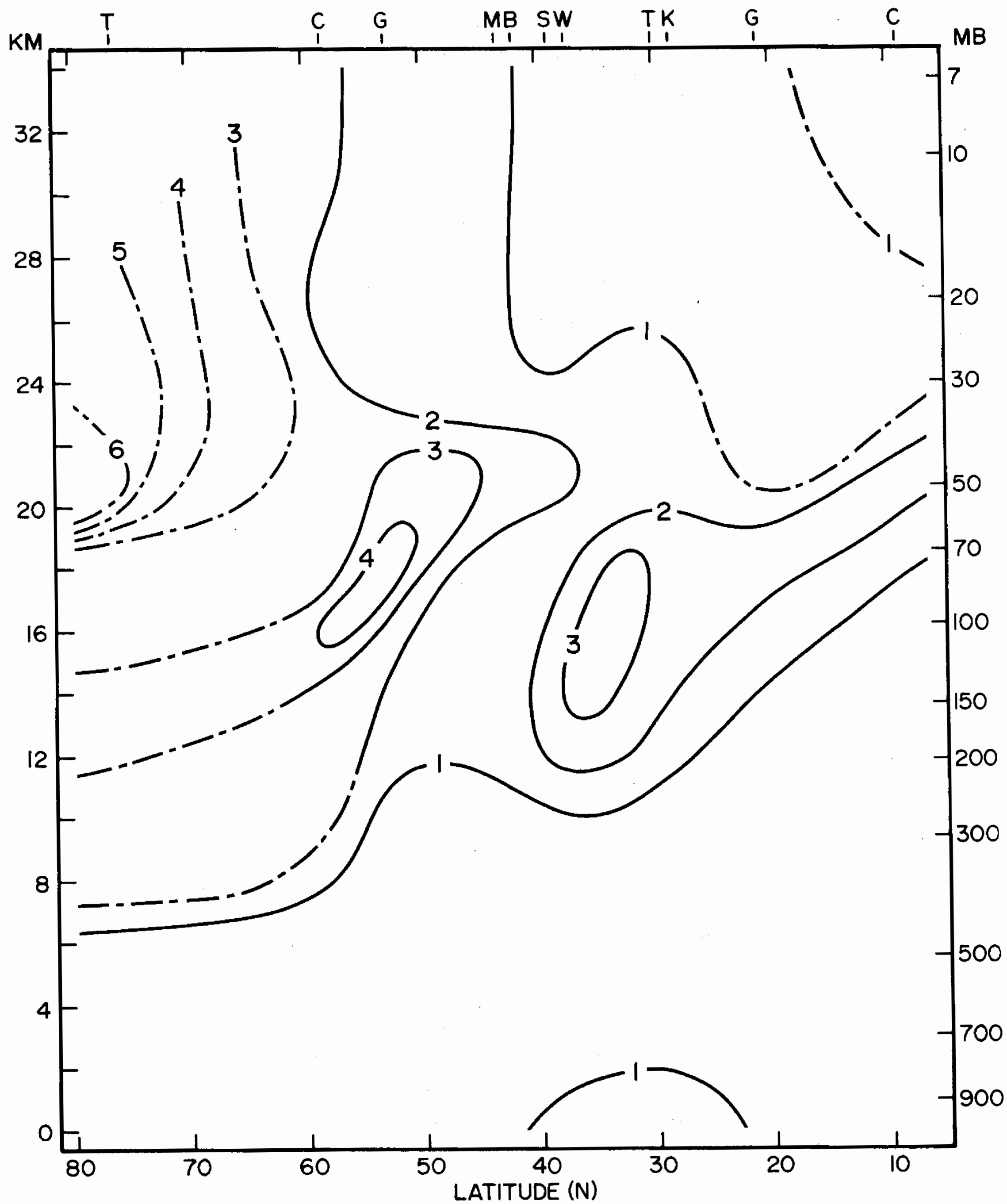

Figure 31. Amplitude of the semiannual wave in ozone concentration near 80°W, in a height-latitude section. Units: 10^{11} molecules cm^{-3}.

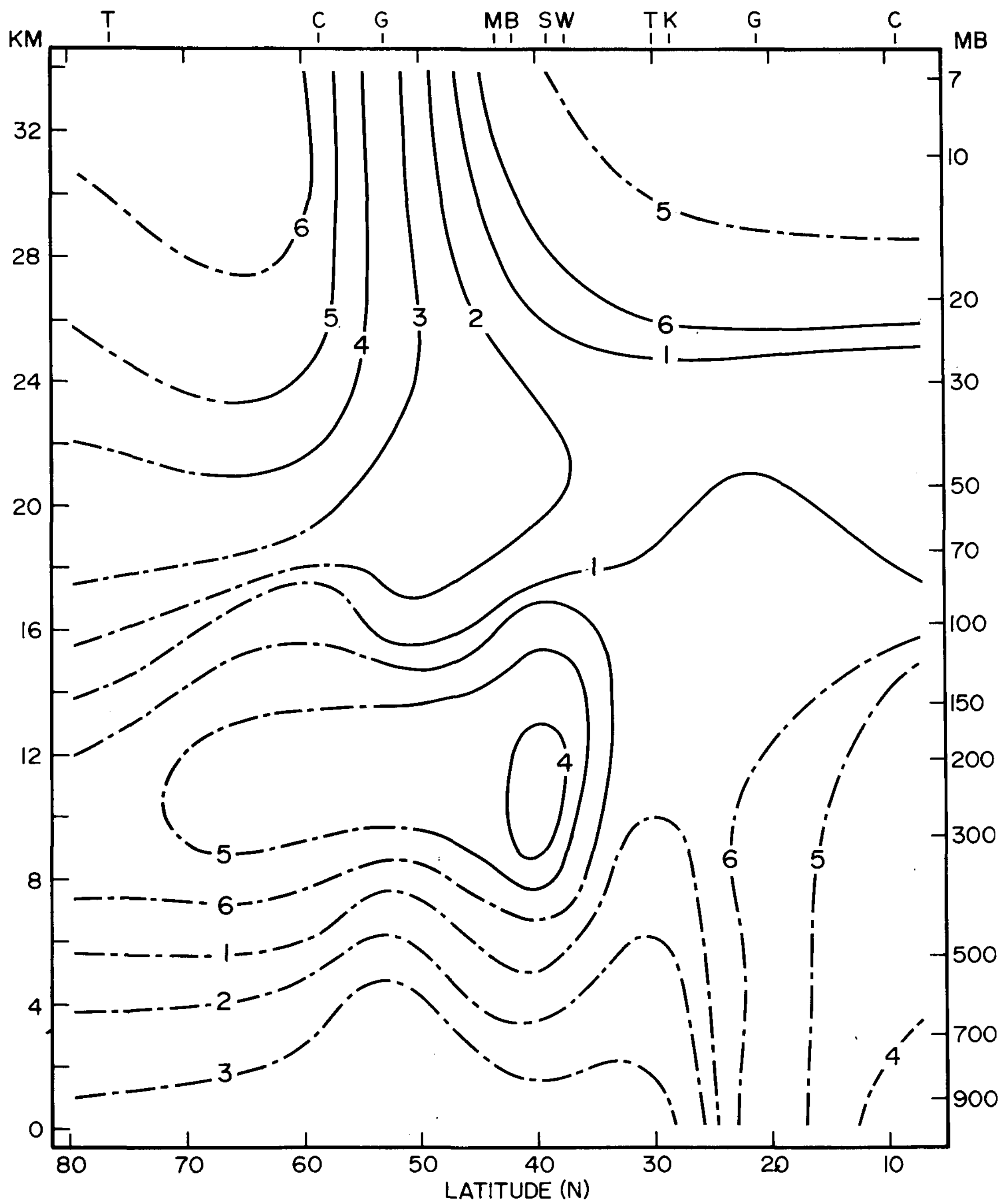

Figure 32. Phase of the semiannual wave in ozone concentration near 80W, in a height-latitude section. Isolines correspond to the first half of the months with which they are labelled.