Periodic Variations of Total Ozone and of Its Vertical Distribution[1]

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ABSTRACT

Amplitudes and phases of the annual, quasi-biennial (QBO) and semiannual oscillations of Northern Hemisphere total ozone (1957–72) and North American ozonesonde (1962–74) data are presented. For total ozone, the annual wave has a maximum amplitude (120 m atm cm) along the east coast of Asia, where it occurs in February. The QBO has its largest amplitude (20 m atm cm) also over extreme eastern Siberia. The maximum amplitude (25 m atm cm) of the semiannual wave occurs at high latitudes and its first maximum tends to occur in late winter over most of the hemisphere. In general, these periodic variations have their maxima where standing waves indicate maxima in northward transport. It appears that these results are not greatly affected by differences in Dobson and M-83 instruments.

Eight years of new ozonesonde data at Resolute improve the estimates of monthly vertical distribution and periodic variability at high latitudes. The vertical distribution of ozone shows a maximum concentration about 10 km above the tropopause, and the largest amplitude of the periodic variations also parallels the tropopause. The amplitude of the annual wave (18×10^{11} cm^{-3}) is near 16 km in the arctic and decreases to 4×10^{11} cm^{-3} at 30°N. The annual maximum occurs in February–March throughout the stratosphere north of 40°N. The maximum amplitude of the QBO (5×10^{11} cm^{-3}) is centered in the arctic near 13 km and the level of the maximum rises to 24 km in the tropics, where the amplitude is smaller. The QBO appears to progress both upward and downward from near 20 km at all latitudes, taking 8 months to reach 13 km in the arctic. The semiannual wave's maximum amplitude (4×10^{11} cm^{-3}) occurs in the arctic near 18 km where the first maximum occurs in February–March.

1. Introduction

In recent years, many climatological studies of atmospheric ozone have been published (e.g., Angell and Korshover, 1964, 1973; Hering and Borden, 1965; Wu, 1973; Dütsch, 1974; Krueger and Pressman, 1975; London *et al.*, 1976). However, no complete study of periodic variations of total ozone over the hemisphere or of its vertical distribution has been found, although the first two harmonics of the mean zonal total ozone were included recently in London (1976). The present paper gives the periodic time variations in the vertical distribution of ozone and in total ozone and updates our previous report (Wilcox *et al.*, 1975) which contains details on the data. For reference, charts of the annual and monthly vertical distribution over North America are also included.

Total ozone data for the period 1957–72 at 84 Northern Hemisphere stations were obtained from the World Data Center for Ozone, Toronto. Almost all of the western stations use the Dobson spectrophotometer for total ozone, and almost all Soviet Bloc nations employ the M-83 filter ozonometer. The Dobson spectrophotometer is thought to have relative accuracy on the order of 2% (Dütsch, 1971), while the filter ozonometer appears subject to errors up to 30–40% (Bojkov, 1969). It is unknown what corrections if any have been applied to the filter measurements (Morrison, 1976, personal communication).

Ozonosonde data for variable periods from 1962–74 (Table 1) were obtained from World Data Center-A (Meteorology), Asheville, and the World Data Center for Ozone, Toronto, including an 8-year series of weekly soundings at Resolute Bay, which provide the first long-period data for the arctic region. Three years of soundings at Boulder were extracted from Dütsch (1966) and Dütsch *et al.* (1970). No Umkehr data were used in this study. Craig (1965) discusses the various types of sondes and their accuracies, but no adjustments to the data for differences in instrumentation have been attempted here.

2. Annual and monthly means

a. Total ozone.

For convenient reference, Fig. 1 shows the annual mean total ozone over the Northern Hemisphere (1957–72). Comparison with London (1963, 1976) shows Fig. 1 to have lower maxima between 50–60°N. Nevertheless, the differences lie within one standard

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TABLE 1. Ozonesonde stations.

Stations	Latitude (°N)	Longitude (°W)	Period of record	Total ascents	Instrument type*
Thule	76.5	68.8	01/63–01/66	92	R
Resolute	74.7	95.0	01/66–12/73	353	R
Fairbanks	64.8	147.9	01/63–12/65	107	R, CI
Ft. Churchill	58.8	94.1	01/63–12/65	100	R
Goose Bay	53.3	60.4	01/63–05/69	207	R, M
Seattle	47.4	122.3	01/63–12/65	148	R
Madison	43.1	89.4	01/63–12/65	83	R
Bedford	42.5	71.3	12/62–03/71	586	M, R
Fort Collins	40.6	105.1	01/63–06/67	209	R
Boulder	40.0	105.2	08/63–07/66	494	M
Sterling	39.0	77.5	08/62–06/66	179	R, CI, M
Wallops Is.	37.8	75.5	02/67–12/74	202	M
Albuquerque	35.0	106.6	01/63–12/65	208	R
Tallahassee	30.4	84.3	01/63–12/65	138	R
Cape Kennedy	28.4	80.5	02/66–05/69	135	M
Grand Turk	21.5	71.1	12/63–05/69	129	M, R
Canal Zone	9.0	79.6	01/63–05/69	126	R, M

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

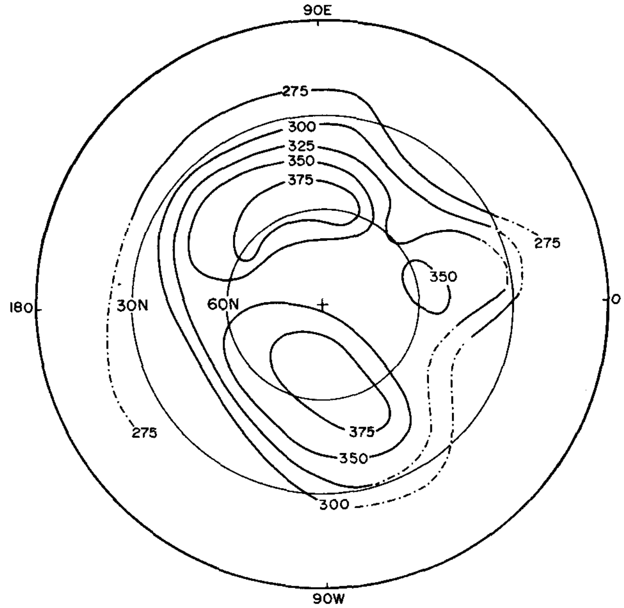

FIG. 1. Annual mean total ozone (m atm cm) for the years 1957–72 based on monthly means at stations. Dash-dot lines indicate relative uncertainty.

deviation and this relatively good agreement between the 16-year and 10-year periods of record suggests that the statistics are becoming almost stationary. The agreement in our and London's (1976) means extends as well to the mean latitude-month sections so the new 16-year charts are not reproduced here. Standard deviations of station means with respect to the zonal mean were prepared as a measure of longitudinal variability. The largest longitudinal standard deviation occurred, as expected, in winter. However, an unexpected secondary maximum in the deviations appeared also at latitudes $>60°$ in summer which one is tempted to attribute to differences between the Dobson and filter instruments. As interpretation of that feature, and the charts which follow, is dependent on instrument biases, it is necessary to discuss that aspect in detail.

Direct comparisons of the Dobson and M-83 ozonometers have been made by Bojkov (1969) and by Dziewulska-Losiowa (1973). Bojkov reports that the M-83 is biased by solar elevation and turbidity, and gives too little ozone in summer and too much ozone in winter. In summer and winter these biases should produce a discontinuity in total ozone at the perimeter of the M-83 area; or, as that area covers almost half the circumference at high latitudes, this should affect the

TABLE 2. Comparison of filter ozonometer and Dobson stations. "Gradients" are either east-west or north-south components of the vector gradient.

Station	Instrument	Latitude (°N)	Longitude (°E)	Monthly means (Dobson units) March	June	September	December	Annual amplitude	Gradient of annual amplitude
Murmansk	M-83	69	33	424	326	270	333	77	
Tromso	Dobson	70	19	416	347	278	245	81	
Riga	M-83	57	24	433	335	300	331	71	0.57*
Aarhus	Dobson	56	10	432	359	301	331	63	0.54*
Eskdalemuir	Dobson	55	3	406	370	307	308	56	
Kiev	M-83	50	30	414	325	288	310	60	0.67*
Belsk	Dobson	51	21	401	352	296	321	54	0.50*
Potsdam	Dobson	52	11	396	362	310	327	49	
Bolshaya Elan	M-83	47	143	447	329	276	385	86	3.8**
Sapporo	Dobson	43	141	445	369	307	381	71	3.7**
Tateno	Dobson	36	140	376	341	287	310	45	

* Dobson units per degree longitude.
** Dobson units per degree latitude.

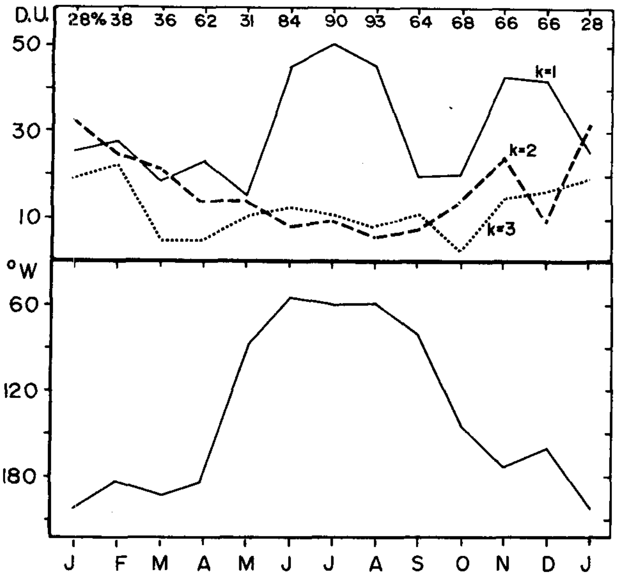

FIG. 2. Upper: Amplitude of the first three zonal waves in total ozone at 60°N, by month. One Dobson Unit is 1 m atm cm. Lower: Phase (longitude of maximum) of the first zonal wave in total ozone. Note the solsticial maxima in wave 1 and the reversing of phase from summer to winter; these features may be due to instrument biases. Figures at top are percentage of variance explained by wave 1.

amplitude of zonal wavenumber 1. Further, the systematic biases in summer and winter should increase the amplitude of the annual wave at an M-83 station compared to a Dobson station.

To check on these hypotheses, solsticial and equinoctial monthly means at nearby filter and Dobson stations are compared in Table 2. The first station in each group uses the M-83 and the other one or two stations use the Dobson or Dobson (Japan) instrument. In June, Riga and Kiev are smaller than Dobson values, as expected. However, Kiev is not larger than the Dobson values in December, only in March. The values at Murmansk are higher than Tromso in winter–spring and lower in summer. The amplitudes of the annual waves do not seem to be discontinuous at the border of the M-83 area. The spatial gradients appear reasonable and an expected discontinuity between M-83 and Dobson data cannot be verified by the present simple tests.

To examine this further, zonal harmonic analysis results for waves 1–3 at 60°N are given in Fig. 2. Wave 1 ($k=1$) accounts for most of the longitudinal variance from June through December, and has maximum amplitudes in summer and early winter, although the circulation in summer is almost zonal and only a small amplitude in the ozone waves would thus be expected. The phase of wave 1 at 60°N is off Labrador in summer, but over northeastern Siberia in winter. [Note that similar phases are depicted by the model of Cunnold *et al.* (1975).] This phase feature would also be anticipated from Bojkov's results, since an M-83 absolute minimum in summer over the USSR would allow the value over Labrador to be a relative maximum. However, the decreased amplitude of wave 1 from January through March is not anticipated from instrument differences. It is suggested that a possible cause of the decrease in wave 1 and increase in wave 2 in January is the influence of sudden warmings which are most frequent in January and are often associated with wave 2. Table 3 compares waves 1, 2 and 3 in total ozone with the corresponding waves in geopotential height at 115 mb at 60°N in January, from van Loon *et al.* (1973). It is clear that the relative amplitudes of these waves are the same for total ozone as for geopotential and that all three waves have nearly the same phase lag, and thus circulation influences seem to dominate

TABLE 3. Comparison of zonal harmonic waves in total ozone at 60°N in January and in geopotential height. Height data are for 115 mb (van Loon *et al.*, 1973).

Wave-number	Amplitude: Height (m)	Amplitude: Total ozone (D.U.)	Ratio to Amplitude of wave 1: Height	Ratio to Amplitude of wave 1: Ozone	Ratio of phase lag (height minus ozone) to period
1	115	26	100%	100%	0.33
2	145	32	126%	123%	0.48
3	72	19	63%	73%	0.50

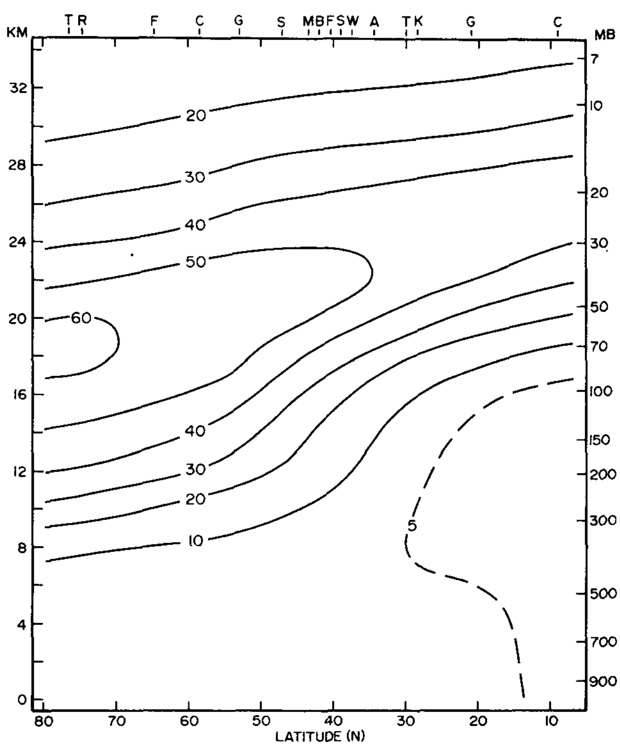

FIG. 3. Annual mean vertical distribution of ozone (10^{11} molecules cm^{-3}) over North America. Ozonosonde stations are indicated at the top of the figure; Table 1 gives periods of record.

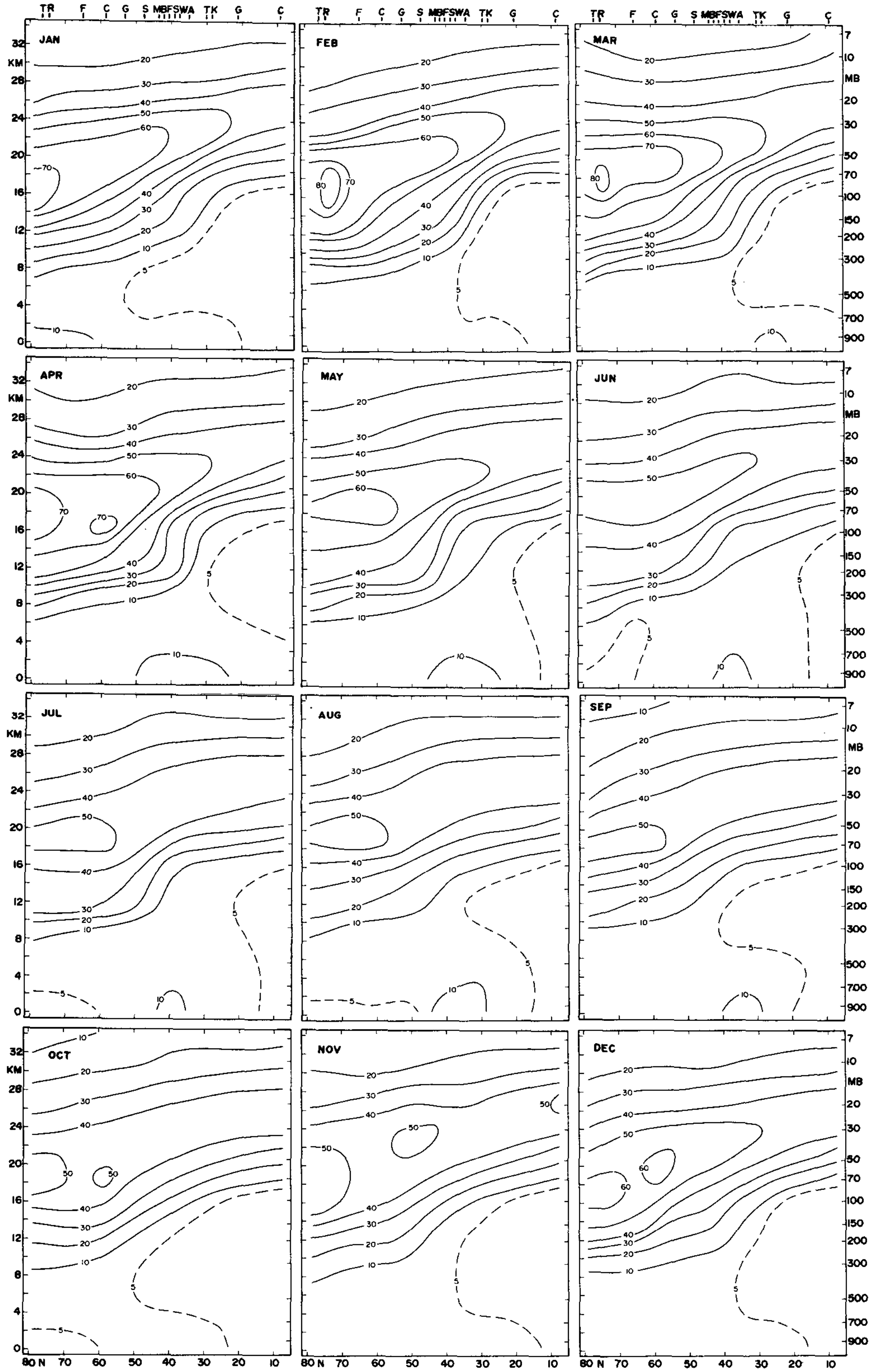

FIG. 4. Vertical distribution of ozone (10^{11} molecules cm^{-3}) over North America by month. Ozonesonde stations are indicated at the top of the figure.

over any instrument differences during late winter. Waves 2 and 3 show seasonal variations of about 50% in amplitude, but except during late winter they are only a small portion of the total variance.

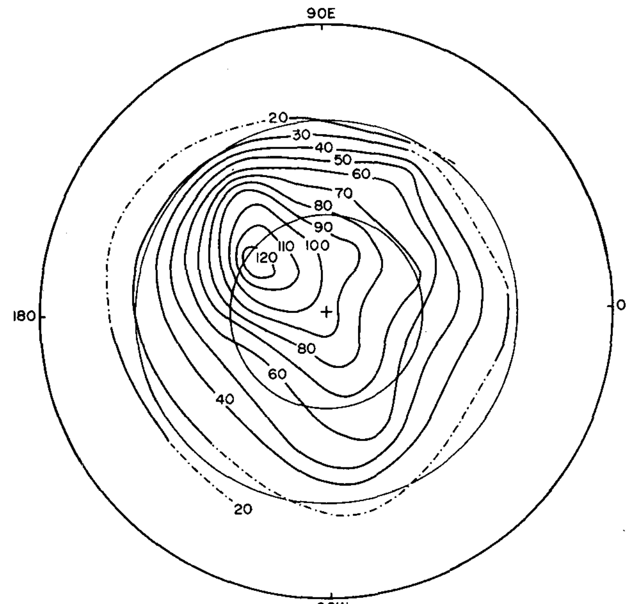

FIG. 5. Amplitude of the annual wave in total ozone (m atm cm) over the Northern Hemisphere.

There appears, then, to be conflicting evidence concerning the probable effect of M-83 errors on the periodic analysis. On one hand, Fig. 2 and the aforementioned summer spatial standard deviation maximum, as well as Bojkov's (1969) results, indicate that the errors must affect the annual wave analysis somewhat. However, from Tables 2 and 3 it can be reasonably concluded that neither the annual mean (Fig. 1) nor the periodic analysis results (given below) should be greatly affected by the difference in instruments.

b. Vertical profiles.

Fig. 3 presents the annual mean vertical distribution of ozone concentration over North America. Monthly mean vertical profiles are shown in Fig. 4. The stations used are listed in Table 1 and are indicated by letter at the top of the section. Seasonal patterns at the U. S. Air Force network of ozonesonde stations have been prepared for 1963–64 (Hering and Borden, 1965) and for 1963–65 (Wu, 1973). The present set are the first monthly sections, and the data extend to 1974 for a few stations. The major improvement is in the arctic where 11 years of Resolute-Thule sondes permit more reliable estimates of location and magnitude of the maximum centers near 20 km, and the monthly progression from the summer minimum in August–September to the winter–spring maximum in March can be easily followed.

3. Periodic analysis

Periodic analysis of the time series of both monthly mean total ozone and monthly mean vertical distribution were made using the same periodic regression technique as previously applied to wind and temperature (Belmont *et al.*, 1974; Nastrom and Belmont, 1975). This method accommodates unevenly spaced data and yields relative errors of estimate which help in assessing the reliability of amplitude and phase. Note that in all periodic analysis phases become meaningless as amplitudes become very small. Dash-dot phase lines in the following figures indicate relative uncertainty due to inadequate data or small amplitudes. The distribution of ozonesonde stations is much more sparse than that of total ozone stations and results could not be mapped, although it is expected that there is significant variation with longitude. Therefore, only eastern and central North American stations were used, approximating a meridional section. The observation series at Sterling and Wallops (220 km apart), at Tallahassee and Kennedy (430 km apart) and at Thule and Resolute (750 km apart) were consecutive rather than concurrent, so they were combined.

a. Annual oscillation

The amplitude and phase (time of the maximum) of the annual oscillation in total ozone are shown in Figs. 5 and 6. The maximum amplitude, over 120 m atm cm, occurs over northeastern Siberia, with smaller amplitude ridges over eastern North America and central Europe. The phase of the annual wave is in early February over Siberia, and progresses radially from there reaching 30°N in two or three months.

The gross features of the annual wave, i.e., small in the tropics and large near the pole, are due to a combination of photochemical and transport processes (Cunnold *et al.*, 1975). The longitudinal variations of the annual wave are apparently induced by the circulation in the lower stratosphere. The locations of both the Siberian and eastern North American maximum ampli-

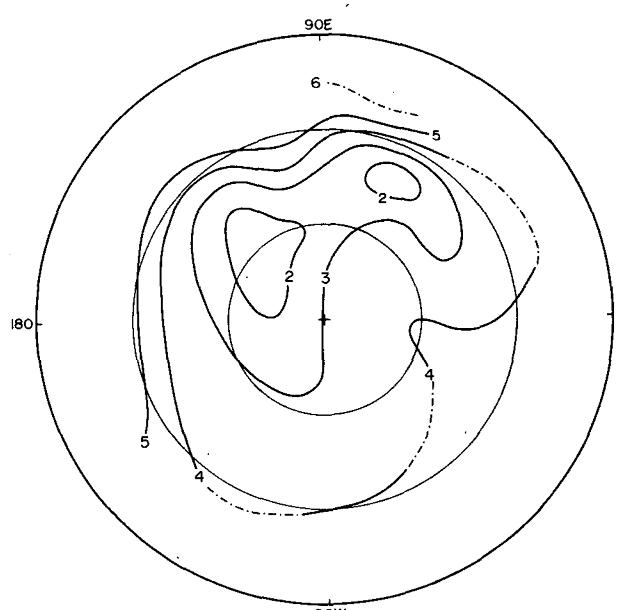

FIG. 6. Phase (time of the maximum) of the annual wave of total ozone over the Northern Hemisphere. Isopleths correspond to the first half of the month with which they are labeled.

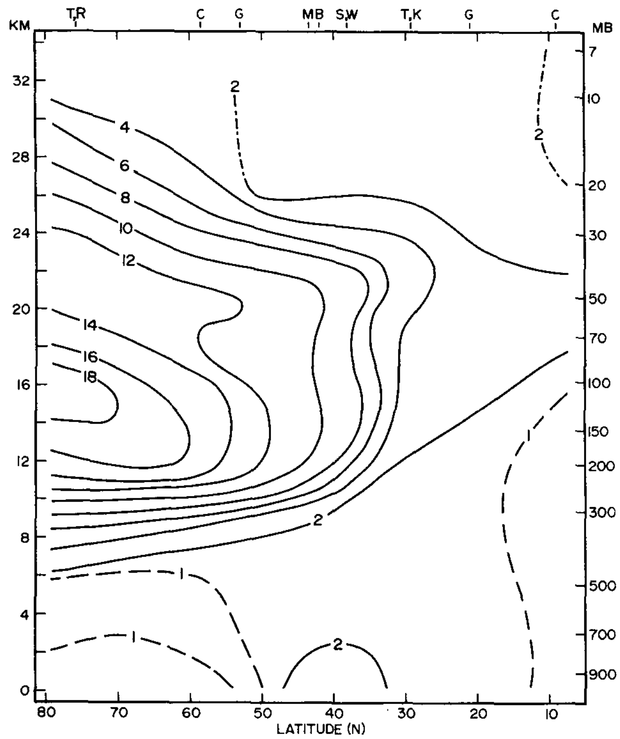

FIG. 7. Amplitude of the annual wave in ozone concentration (10^{11} molecules cm^{-3}) near 80°W.

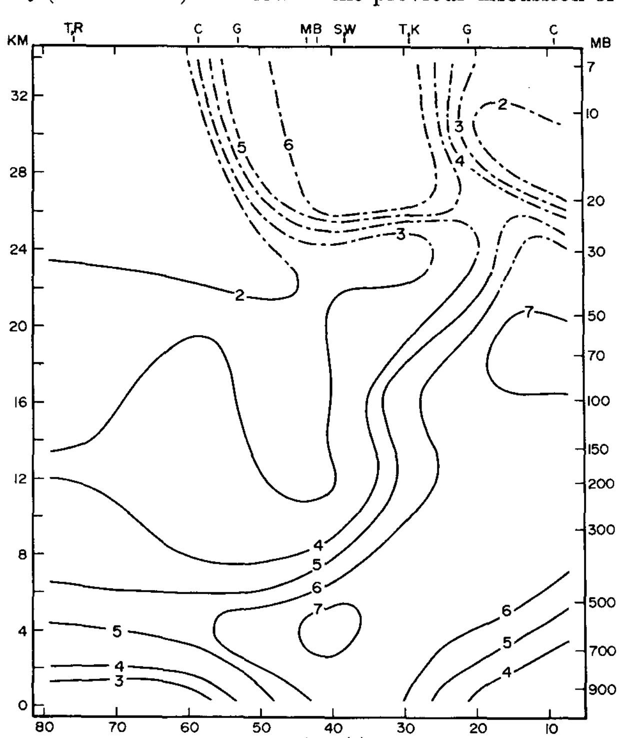

FIG. 8. Phase of the annual wave in ozone concentration near 80°W. Isopleths correspond to the first half of the month with which they are labeled.

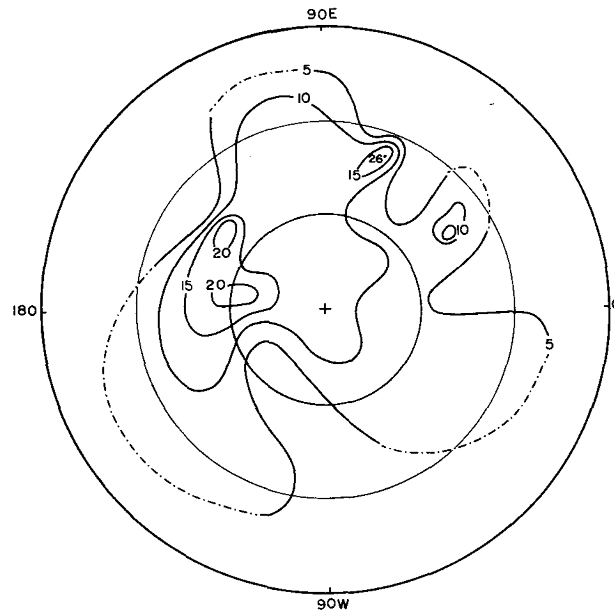

FIG. 9. Amplitude of the quasi-biennial (29 month) oscillation in total ozone (m atm cm) over the Northern Hemisphere.

tudes coincide with that of autumn–spring northward winds (van Loon *et al.*, 1972) at the level of maximum O_3 (near 50 mb). In view of the previous discussion of systematic M-83 errors, the maximum amplitude over Siberia may be somewhat overstated, but it is felt that basically this feature is real. Note in particular that van Loon shows a stronger mean northward wind over eastern Asia than over eastern North America in all seasons but summer. This strongly suggests that the maximum amplitude is correctly placed.

The vertical distribution of the amplitude of the annual wave over eastern North America (Fig. 7) shows a maximum at high latitudes near 16 km. This maximum rapidly becomes weaker from 40° to 30°N, and is quite small in the tropics at any altitude. The annual phase (Fig. 8) is earliest (February) at highest altitudes and latitudes and progresses southward and downward. Above 26 km at mid-latitudes, although the wave is small in amplitude, its phase is consistently in the summer. This agrees with the Arosa (47°N) results of Dütsch and Ling (1973) who attribute this feature to photochemical processes.

b. The quasi-biennial oscillation (*QBO*)

The amplitude of the 29-month average QBO in total ozone is presented in Fig. 9. As it does with the annual wave, eastern Siberia displays the largest QBO amplitude. However, large values with small statistical errors are also reported at Dushanbe (39°N, 69°E) and Odessa (46°N, 31°E). These may be genuine features of the O_3 distribution caused, for example, by local topographic effects on vertical motions, but many of the interstation irregularities are probably statistical apparitions.

As the QBO is not a regular cyclic variation, inconsistencies are to be expected when the periods of record differ among stations. The phase of the QBO is more sensitive than is the amplitude to inhomogenieties in

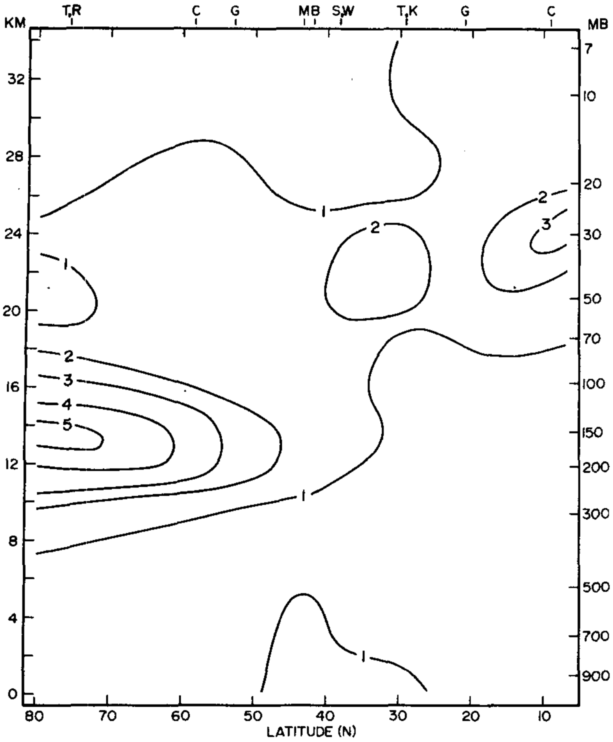

FIG. 10. Amplitude of the quasi-biennial (29 month) oscillation in ozone concentration (10^{11}molecules cm^{-3}) near 80°W.

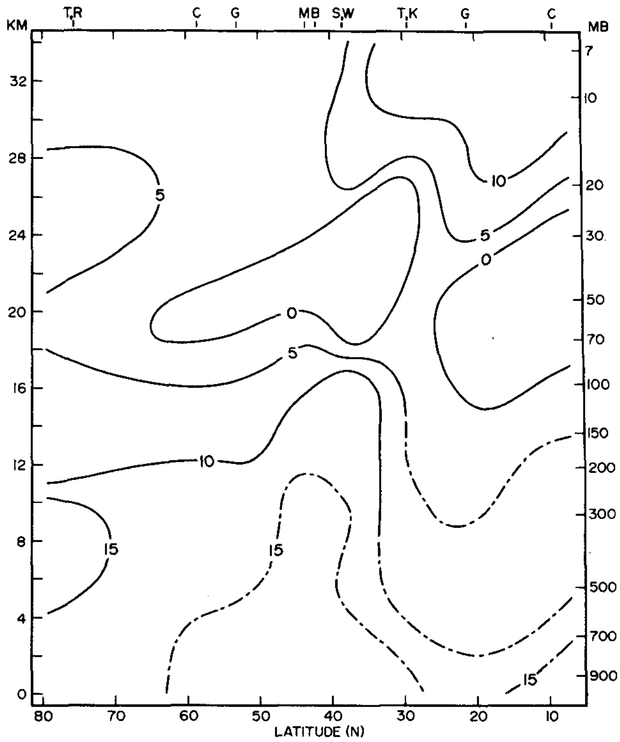

FIG. 11. Phase of the quasi-biennial (29 month) oscillation in ozone concentration near 80°W. Isopleths are labeled with the number of months after 1 January 1963 that the first maximum occurs.

the data so it is not surprising that the patterns of the QBO phase in total ozone are too uncertain to include here.

The vertical distribution of QBO in O_3 over eastern North America is shown in Fig. 10. Similar to the annual wave, the QBO is largest in the lower polar stratosphere. The phase is earliest near 20 km at all latitudes and is latest in the mid-latitude troposphere.

When considering the vertical distribution of the QBO in O_3, it should again be remembered that the periods of record at most stations are variable and rather short, ranging from just over one to about four QBO periods. The phase diagram (Fig. 11) shows that a low-latitude maximum in O_3 occurred about January 1963, i.e., during maximum easterly winds in the tropics. This again substantiates a theory of Dütsch and Ling (1973) in which enhanced Hadley circulation during the tropical QBO easterly phase permits greater advection of O_3 to near 25–30° at the level of maximum ozone, i.e., 20–25 km, which leads to an increased poleward transport by the quasi-horizontal eddies at this level. The arctic maximum, at 50–80°N near 14 km, occurs about eight months after the low-latitude maximum.

c. The semiannual wave

The amplitude of the semiannual wave in total ozone over the Northern Hemisphere is mapped in Fig. 12. The maximum amplitude is in polar regions where it is about one-fourth the amplitude of the annual wave. The phase (not shown) indicates the first maximum of the year occurs in February at low latitudes and

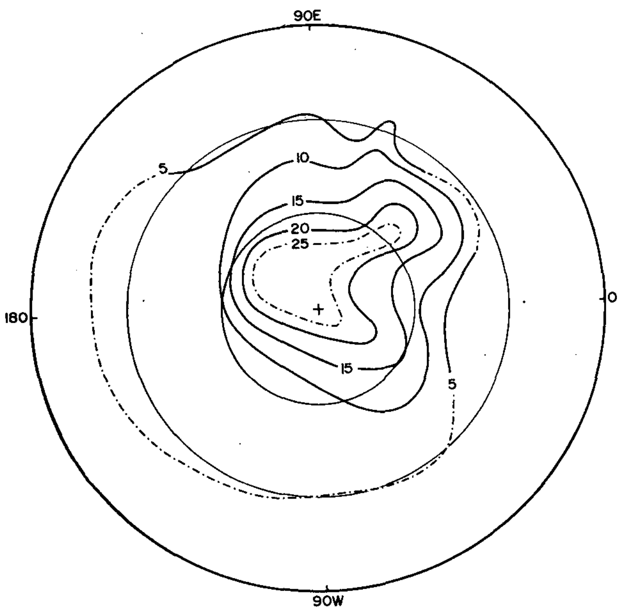

FIG. 12. Amplitude of the semiannual wave in total ozone (m atm cm) over the Northern Hemisphere.

rapidly progresses to almost everywhere else within one month.

The vertical distribution of the semiannual wave in ozone is shown in Figs. 13 and 14. The maximum amplitude lies near 18 km at all latitudes, but is largest at 50–80°N, at about one-fourth the amplitude of the annual wave. The first maximum occurs in January at low latitudes and progresses northward reaching the pole in March.

4. Summary

The periodic changes in ozone (i.e., annual, semiannual and QBO) have been quantified for the first time as functions of latitude, longitude and altitude. They can be summarized as follows:

1) Annual oscillation

The largest annual wave amplitude (over 120 m atm cm) in total ozone occurs over eastern Siberia, although part of this amplitude is possibly due to systematic filter ozonometer errors. The maximum occurs in early February over eastern Siberia, and progressively later away from this center, generally occurring in April at 30°N. Concerning the vertical distribution, along 80°W, the maximum amplitude is in the arctic lower stratosphere, and it occurs in March.

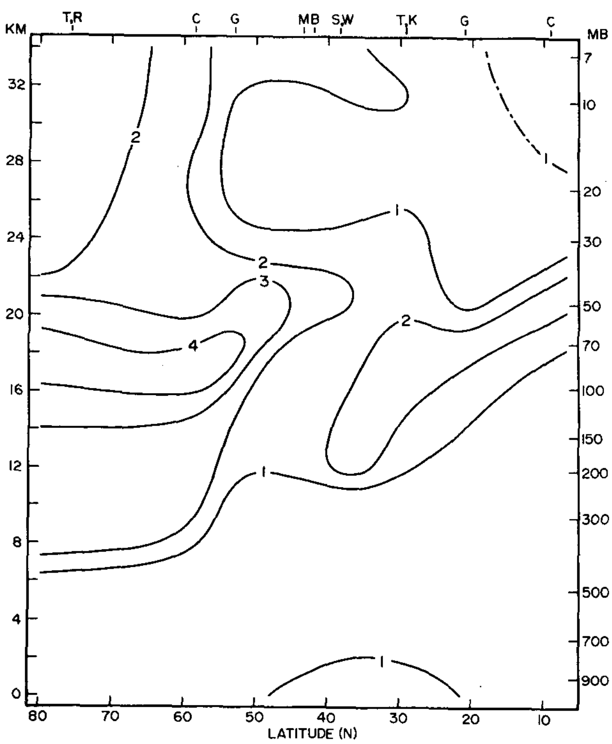

FIG. 13. Amplitude of the semiannual wave in ozone concentration (10^{11} molecules cm^{-3}) near 80°W.

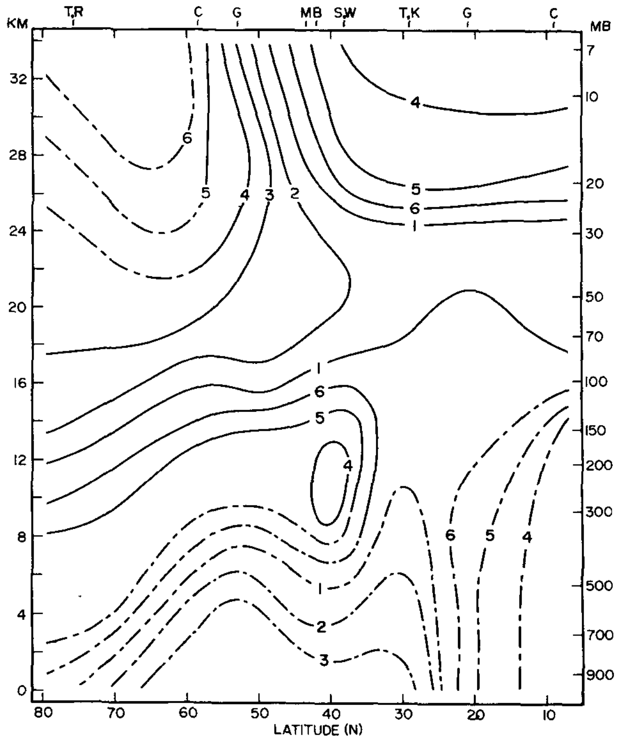

FIG. 14. Phase of the semiannual wave in ozone concentration near 80°W. Isopleths correspond to the first half of the months with which they are labeled.

2) Quasi-biennial (29 month) oscillation

In total ozone, the region of maximum amplitudes coincides with that of the annual wave, i.e., eastern Siberia. This suggests that the QBO is effected through the same sort of transport process (i.e., standing waves) which govern the annual oscillation. The major feature of the QBO in the vertical distribution is the maximum amplitude in the arctic just above the tropopause.

3) Semiannual wave

The maximum in total ozone lies in the arctic, displaced slightly to the Siberian side. In the vertical, its maximum amplitude is near 18 km. The phase appears to progress poleward, with maxima at high latitudes occurring in March–April (and September–October).

4) Instrument differences

Instrument differences influence the results but without more information on possible prior corrections of the data, their effect is unknown. Comparisons with satellite data may make this possible.

5) Relative importance of the oscillations

Table 4 compares the maximum amplitudes of these oscillations to get a rough perspective of their relative importance. For reference, some values of standard

TABLE 4. Comparison of maximum amplitudes of ozone's principal periodic variations (regardless of their location).

	Total ozone (D.U.) Absolute value	Percent of mean	Percent of annual wave	Vertical concentration (10^{11} cm^{-3}) Absolute value	Percent of mean	Percent of annual wave
Annual mean	380			62		
Annual wave	125	33		19	31	
QBO	21	6	17	5.1	8	27
Semiannual wave	30	8	24	4.3	7	23
Daily standard deviations		25* (Jan) 15* (Jul)		20** (winter)	30	
				12** (summer)	20	

* London et. al., 1976.
** Wilcox et al., 1975.

deviations of the daily data are also included. It can be seen that evaluation of small trends in the means can be quite difficult, due especially to the irregular QBO.

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