Periodic Variations in Stratospheric-Mesospheric Temperature from 20–65 km at 80°N to 30°S

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ABSTRACT

The 12-year mean temperature and the amplitude and phase of the quasi-biennial oscillation (QBO) and first three harmonics of the annual wave are presented on height-latitude sections, 20 to 65 km, 80°N to 30°S. New features include adjusting the long-term mean temperature for errors due to solar radiation effects and for biasing by the diurnal tide. Due to the longer period of record used here, the extratropical QBO differs from that reported previously in the literature. Amplitudes of the annual wave at 30°S are larger than those at 30°N at all levels; the amplitude ratio is greatest near 50 km. The largest amplitude (7°C) of the semiannual wave in the stratosphere or mesosphere is near 75°N at 32 km. The terannual wave's amplitude near 35 km at 55°N is as large as the amplitude of the semiannual wave there and is larger than the well-known tropical semiannual wave. These thermal properties of the upper atmosphere require theoretical explanations, stratospheric modelers should be able to reproduce them, and continued observations are needed to describe their hemispheric differences at high latitudes and altitudes.

1. Introduction

This paper presents periodic analysis results of Meteorological Rocket Network (MRN) temperatures for the long-term mean, the quasi-biennial oscillation, and the first three harmonics of the annual wave. Differences from previous findings in the literature and the effects of temperature corrections are discussed.

2. Data and method

MRN stations and the period of record of each are listed in Table 1. The source of meteorological rocket data was the World Data Center, Asheville, N. C. The Woomera data consist of grenade (Groves, 1967) and falling-sphere observations (Pearson and Johnson, 1973), both down to 40 km, and radiosonde data up to 30 km, which explains the distribution of observations there. Other rocket stations were not used because their relatively small numbers of observations led to large statistical errors in the periodic analysis. Monthly mean radiosonde temperatures at stations near 90°W at about 5° latitude intervals were used at 50, 30 and 10 mb (assigned to 20, 24 and 30 km, respectively) to obtain best available space and time continuity.

The amplitudes and phases of the long-term periodic components of the time series of individual MRN temperature observations were determined at 4 km height intervals using a joint, periodic regression technique. This technique and its advantages have been described by Belmont *et al.* (1974). Beside the long-term mean, frequencies included in the basic analysis were the quasi-biennial oscillation (QBO) and the first six harmonics of the annual wave. As the second three harmonics of the annual wave generally had small amplitudes, large statistical error estimates, and erratic phase progression, only the results for the mean, QBO, and first three harmonics of the annual wave will be presented. A period of 29 months was used for the QBO in order to be consistent with previous analyses of the wind (Belmont *et al.*, 1974).

Tabulated values of amplitudes and phases for each frequency, together with their statistical errors, are given in Nastrom and Belmont (1975). Those tables give data at 10 km intervals only, but it should be remembered that all figures here utilize intermediate values.

3. Long-term mean

Due to the differing but ill-defined characteristics of rocket temperature sensors and the corrections applied, if any, station-to-station comparisons of the long-term means are hindered. For example, USSR data are significantly different from all others (Finger *et al.*, 1975) and were therefore not used for the long-term mean above 50 km. At all other MRN stations, below about 56 km, the most important sources of systematic errors are due to solar radiation and biasing by the diurnal tide. As described below, adjusting the results for these two effects significantly changes the long-term means at high altitudes.

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TABLE 1. Rocket station list

Station	Latitude*	Longitude*	Years	Number of observations at 20 km	30 km	40 km	50 km	60 km	64 km
Heiss	80	−58	2/62– 1/70	182	186	176	135	119	113
Thule	77	69	6/65–12/72	343	348	358	296	135	64
Greely	64	146	4/61– 5/72	644	673	668	563	285	113
Churchill	59	94	1/61–12/72	942	916	952	884	560	196
Primrose	55	110	7/64–12/72	352	357	349	312	224	146
Volgograd	49	−45	9/65– 1/70	136	137	139	130	119	116
Wallops	38	87	1/61–12/72	859	799	769	674	211	26
Pt. Mugu	34	119	1/61–12/72	1437	1319	1324	1226	571	103
WSMR	32	107	1/61–12/72	1363	1120	1095	988	704	336
Kennedy	28	76	1/61– 5/72	1314	1302	1274	1142	520	126
Hawaii	22	160	4/62–12/72	1072	960	953	898	419	110
Gr. Turk	21	71	9/63–12/66	166	183	181	148	27	24
Antigua	17	62	6/63– 5/72	509	491	464	371	66	38
Sherman	9	80	3/66–11/72	468	463	459	422	235	65
Kwajalein	8	167	3/63–12/72	307	303	309	305	184	28
Ascension	−8	15	10/62– 5/72	1004	959	951	937	598	167
Wommera	−31	−137	2/61– 8/72	860	780	15	75	76	76

* Negative values, °S or °E.

Heating of the temperature sensor by incident solar radiation causes the reported measurements to be in error. Hoxit and Henry (1973) have developed a scheme for correcting data taken with the Arcasonde 1A temperature sensor by adjusting known correction factors for the error due to solar radiation. While their scheme is intended for the Arcasonde 1A, a survey of other correction schemes revealed there was little difference between solar radiation corrections for Arcasonde and Datasonde temperature sensors (Nastrom and Belmont, 1975). Thus, for an estimate of the long-term mean we applied the correction scheme of Hoxit and Henry to each observation regardless of sensor type, except that values reported as already corrected were not changed.

The diurnal tide can also bias the long-term mean temperatures as the majority of MRN observations are taken near the same local time each day. In an effort to determine the importance of this effect we reanalyzed the data corrected for solar radiation errors and included the 24 h wave with the other eight waves. The distribution of observations throughout the day was adequate at several stations to yield reliable estimates of the mean yearly diurnal wave in temperature. The results for the diurnal wave will be presented in a separate paper; of interest here is the change in the long-term mean after the bias of the diurnal wave has been removed. Estimates of the adjustments to the long-term mean with both solar

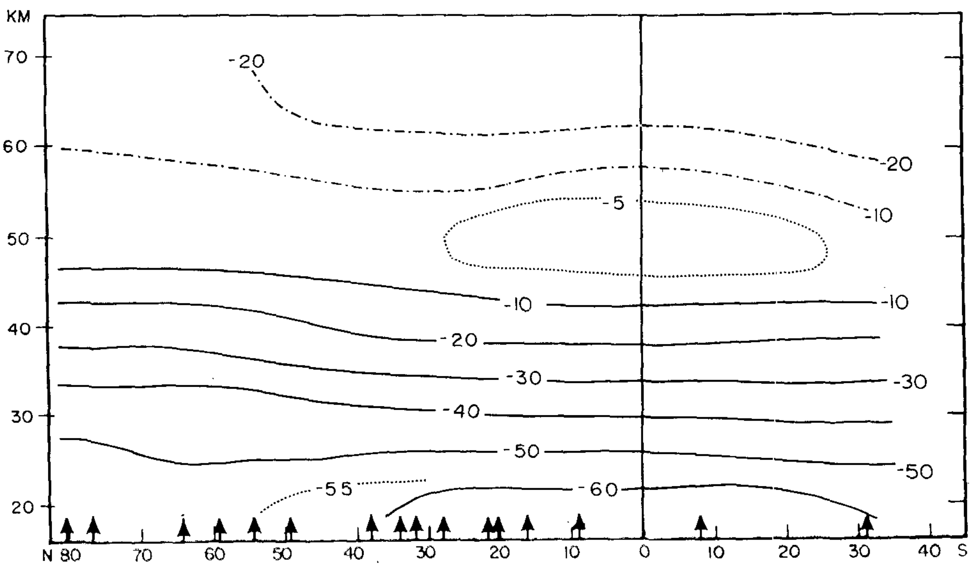

FIG. 1. Twelve-year mean temperature (°C). Arrows show latitudes of sounding stations.

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TABLE 2. Difference (°C) between long-term mean temperatures (based on data as reported), and means after correcting data for solar radiation errors and tidal biasing (uncorrected minus corrected).

Altitude (km)	Latitude 77°N	59°N	38°N	28°N	17°N	9°N	−8°S
60	7.0	6.6	6.7	5.4	—	6.8	4.2
50	1.3	3.1	2.9	1.1	1.1	2.2	1.3
40	0.5	1.3	1.1	0.8	2.1	2.1	1.7

TABLE 3. Long-term mean temperatures (°C) from CIRA 1972 mean model for 30° latitude, average of White Sands and Kennedy using data as reported, and average of White Sands and Kennedy after correcting for solar radiation errors and tidal biasing.

	Altitude (km) 40	50	56	60
CIRA, 30°N	−17.9	−1.6	−11.0	−23.9
WSMR and Kennedy (uncorrected)	−17.3	−2.7	− 8.0	−12.9
WSMR and Kennedy (corrected)	−17.9	−4.8	−12.2	−17.9

radiation and tidal influences removed are given in Table 2.

For these reasons, Fig. 1 is based on MRN data corrected for solar radiation and tidal biasing. Its absolute values are thus apparently the only corrected estimates presently available, and update Nastrom and Belmont (1975) where the corrections were discussed, but not applied to the corresponding figure. The effect of these corrections is sufficient to almost remove the upward slope of the stratopause toward the pole.

The most recent published mean annual temperature data appear to be that in the COSPAR International Reference Atmosphere (CIRA) for 30° latitude, based on Groves (1971) whose data extended through 1968. Table 3 gives temperature values used in developing the CIRA 1972 model (COSPAR, 1972) which is for 30° latitude, and the average of Cape Kennedy (28°N) and White Sands (32°N) both with and without the above adjustments. The values used in CIRA below 55 km are based on MRN data not corrected for solar radiation errors. At 55 km and higher levels they are based on falling-sphere and grenade measurements, which are not influenced by solar radiation. At 40 and 56 km the results for corrected MRN data agree well with CIRA 1972, but at 50 and 60 km they differ significantly. The difference at 60 km is probably due to errors such as instrument lag and aerodynamic heating in the MRN data, so the CIRA values at 60 km in Table 3 are likely more reliable as they do not rely on MRN data at that level. Thus, results above 56 km in Fig. 1 are drawn with dash-dotted lines to indicate this uncertainty. At 50 km, however, the difference is probably due to the omission of corrections for solar radiation errors and tidal biasing in the CIRA 1972 model.

4. Periodic analysis results

Height-latitude sections and profiles of the amplitude and phase of each of the component waves are presented in Figs. 2–9. All available stations were used since the longitudinal differences were considered minor compared to the loss of latitudinal resolution which would result if only stations near a particular meridian were used. Periodic analysis results, which

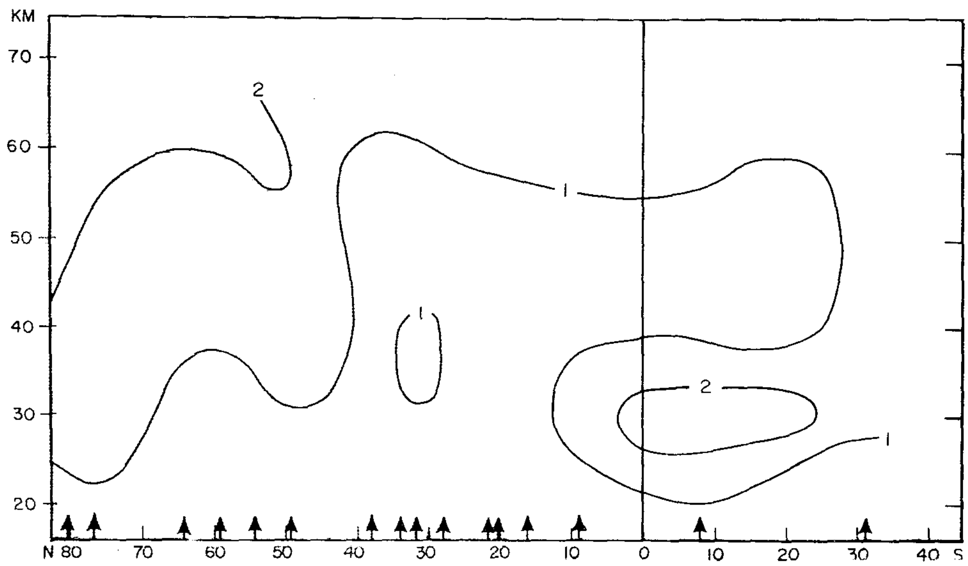

FIG. 2. Amplitude (°C) of quasi-biennial variation in temperature.

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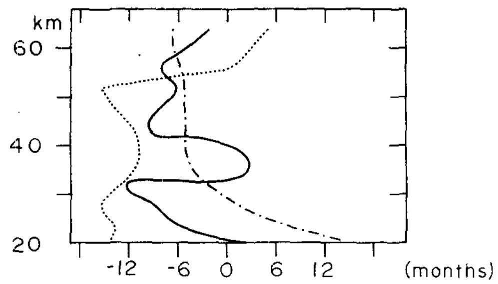

FIG. 3. Relative phase progression of the QBO with altitude for Kennedy (solid), Thule (dotted), Ascension (dashed-dotted).

describe variations from each station's mean, are valid for comparison on an inter-station and geographic basis. Each source of instrument error is fairly constant from sounding to sounding, and always biases observations in the same algebraic sense (Ezemenari, 1972). Changes to the periodic analysis results, after removing the effect of the solar radiation errors and the diurnal tide from the data, were insignificant compared to the statistical error estimates. Figs. 2–9 are therefore based on observations as reported, which generally are not corrected for solar radiation or tidal biasing.

a. The quasi-biennial oscillation

The amplitude of the QBO (Fig. 2) has relative maxima near 30 km in the tropics and above 60 km north of 50°N. The displacement of the tropical maximum into the Southern Hemisphere is indicated below 30 km by analysis of radiosondes, and above 30 km by analysis of MRN data at Sherman (9°N), Kwajalein (8°N) and Ascension (8°S). MRN data for Gan (0°S) and Natal (5°S) were too few to use to further verify this feature. Angell and Korshover (1970) found the amplitude of the QBO to be in excess of 2.5°C near 35 km at Fort Greely, although their standard deviation of amplitude was also large, while our estimates of the QBO amplitude at Fort Greely do not exceed 1.1°C below 50 km. This seeming discrepancy probably arises because our period of record is about four years longer than that available to Angell and Korshover. The high-latitude QBO in temperature at 50 mb at Eureka has been shown to be highly variable in both amplitude and phase (Angell and Korshover, 1964) and if the oscillation is equally incoherent at higher levels then the averaging over our longer period of record would result in smaller amplitudes.

Averaging of the QBO over differing periods of record also affects phase propagation estimates in regions where the QBO is highly variable with time. For example, the mid- (Kennedy) and high-latitude (Thule) phase profiles shown in Fig. 3 often differ widely from the mid- and high-latitude profiles given by Angell and Korshover (1970). The differences are not due solely to small amplitudes and consequent phase instabilities (when amplitude approaches zero all values of phase become equally probable), for at Ascension the relative phase progression in Fig. 3 is very similar to theirs despite the small amplitudes there at 20 km and above 40 km.

b. Annual wave

The amplitude of the annual wave in Fig. 4 is maximum near 70°N at 40–45 km with values slightly over 22°C. There is a much smaller secondary maximum above 50 km in the tropics. These maxima are separated by a band of minimum amplitudes which

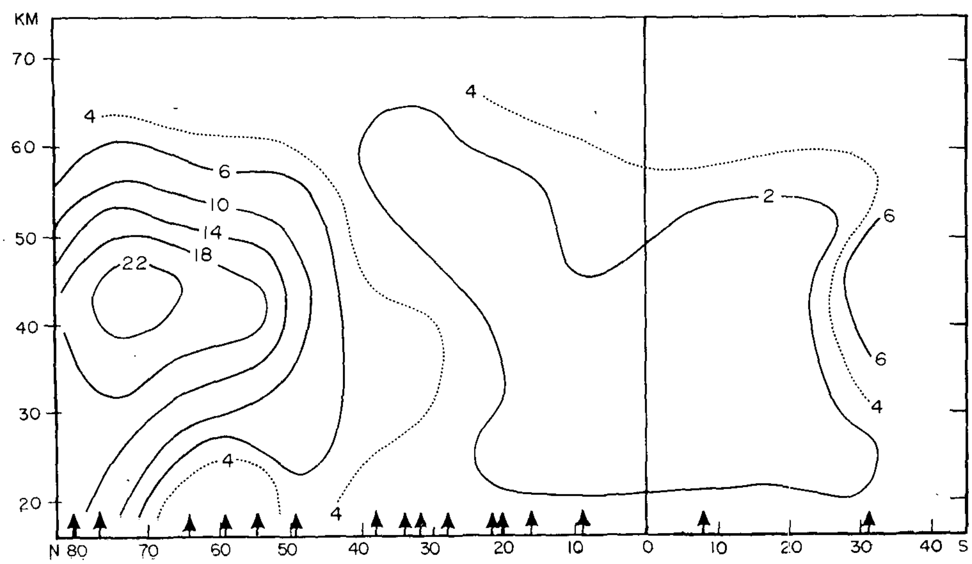

FIG. 4. Amplitude (°C) of annual variation in temperature.

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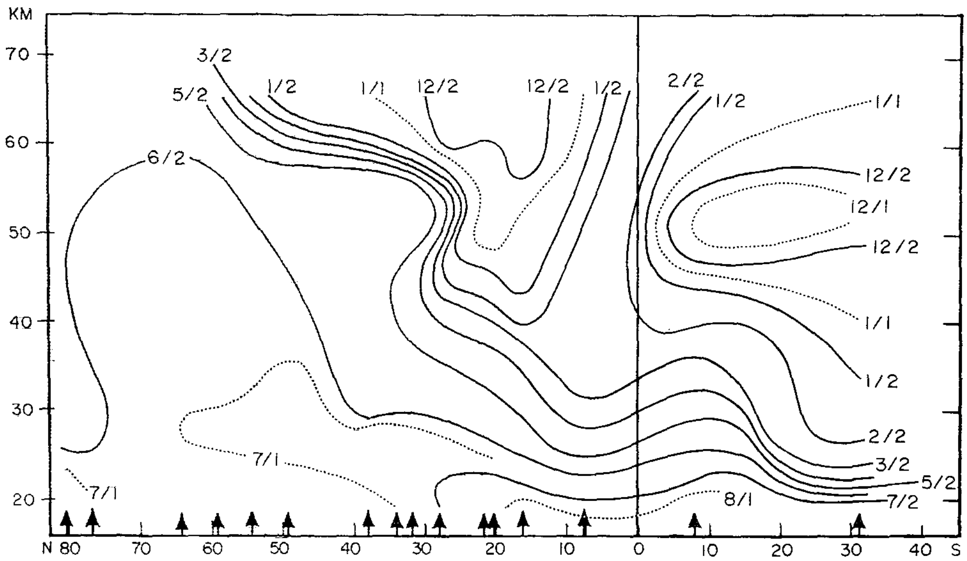

FIG. 5. Date of maximum of the annual variation in temperature (3/2 is the second half of March).

slopes northward and upward such that at 60 km the minimum amplitude is near 40°N. Results presented in Fig. 4 are very similar to those given by Angell and Korshover (1970), Cole and Kantor (1974), and the values of van Loon *et al.* (1973) for each paper's separate geographic locations.

The different values at 30°S and 30°N correspond closely to those of van Loon *et al.* (1973) below 30 km. At 40 km the amplitude at 30°S is about 1.5 times as large as that at 30°N, which could be compared with the ratio 1.6 at 40° latitude for Channel A of the Selective Chopper Radiometer (SCR) estimated from Barnett (1974). The 30°S/30°N ratios from Fig. 4 at 50 and 60 km are 3.0 and 2.8, respectively. A similar asymmetry in the amplitude of the annual wave in zonal wind has been noted by Belmont *et al.* (1974), who suggested it could be due to the ellipticity of the earth's orbit. Barnett (1974) has discussed hemispheric asymmetries in detail and concludes that orbital ellipticity is important but that dynamic processes are also important, especially in the upper stratosphere.

The date of maximum temperature (Fig. 5) is earliest (second half of June) at all altitudes in high latitudes, spreading downward and equatorward to 20 km at 15°N about two months later. In southern subtropical regions the annual maximum occurs first at 50 km and propagates downward, but near 20°N it starts above 60 km. The early center at Ascension (8°S) is well confirmed by very large sample size and a very small statistical error of ±8 days, compared to a ±40 day error at Sherman (9°N). The tropical and polar waves are separated by a region of rapid phase change near 30°N above 50 km. The similarity of the annual wave's phase dates at high latitudes to that of the solar declination, lagging it by only two weeks, suggests that the polar wave is very closely coupled with solar heating. The phase of the tropical wave, on the other hand, shows no such similarity. Also, the abrupt shift of phase near 30°N suggests that there are two centers of oscillation which may not be caused by the same mechanism. Cole (1968) and Fritz (1974) have attributed the tropical annual wave to dynamic influences.

c. Semiannual wave

Maxima in the amplitude of the half-yearly component (Fig. 6) occur at 32 km near 75°N and 40 km near the equator with magnitudes of about 7°C and 3°C, respectively. A tongue of relatively large amplitude extends southward from the arctic to about 35°N at 40–45 km. There are bands below 55 km of minimum amplitude near 30°N and 20°S, and near 50 km at all latitudes. The semiannual amplitude increases above 55 km at all latitudes.

The polar stratospheric maximum is more intense than recognized previously. Its causes may be the insolational heating of the polar ozone reservoir, or the occurrence of sudden warmings which are frequently in late January or early February, or both. The phase date of early February (Fig. 7) supports both possibilities. Cole and Kantor (1974) attempted to reduce the "noise" of polar winter rocket temperature distributions by using monthly medians rather than mean data or individual observations in computing their harmonic analyses. This resulted in decreasing the amplitude of the stratospheric polar maximum to about 4°C which was their weakest amplitude center at high latitudes. On the contrary,

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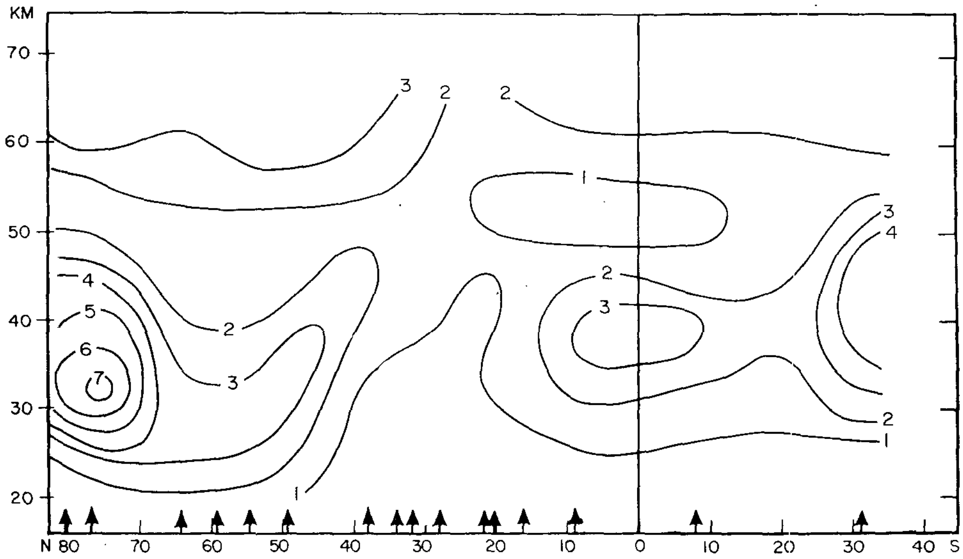

FIG. 6. Amplitude (°C) of semiannual variation in temperature.

TABLE 4. Amplitudes of the semiannual wave.

	Data source	Semiannual amplitude (°C) 20 km (50 mb)	30 km (10 mb)	40 km (2 m)
(MRN)	Thule (77°N, 69°W; 1965–72)	0.4*	6.2*	5.5*
	Heiss Island (80°N, 58°E; 1962–70)	1.6*	6.5*	5.0*
(SCR)	Zonal Mean (80N; Nov. 70–Nov. 71)	3.5	5.7	8.4**
(R/S)	Resolute (75°N, 95°W; 1964–71)	1.2**	2.2**	—
	Eureka (80°N, 86°W; 1964–71)	1.6	2.1	—

* Used in Fig. 6.
** Close to values of van Loon *et al.* (1972).

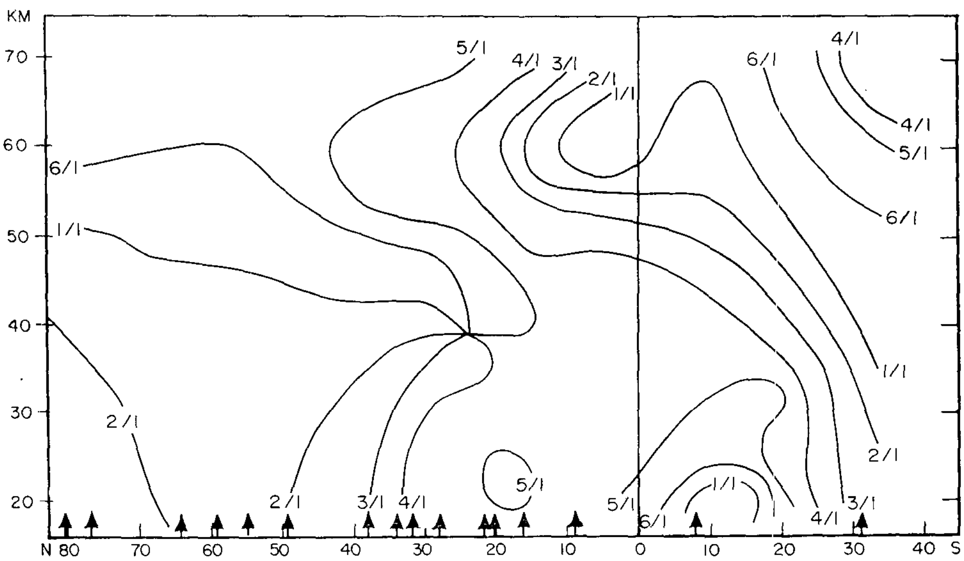

FIG. 7. Date of first maximum of the semiannual variation in temperature (3/1 is the first half of March).

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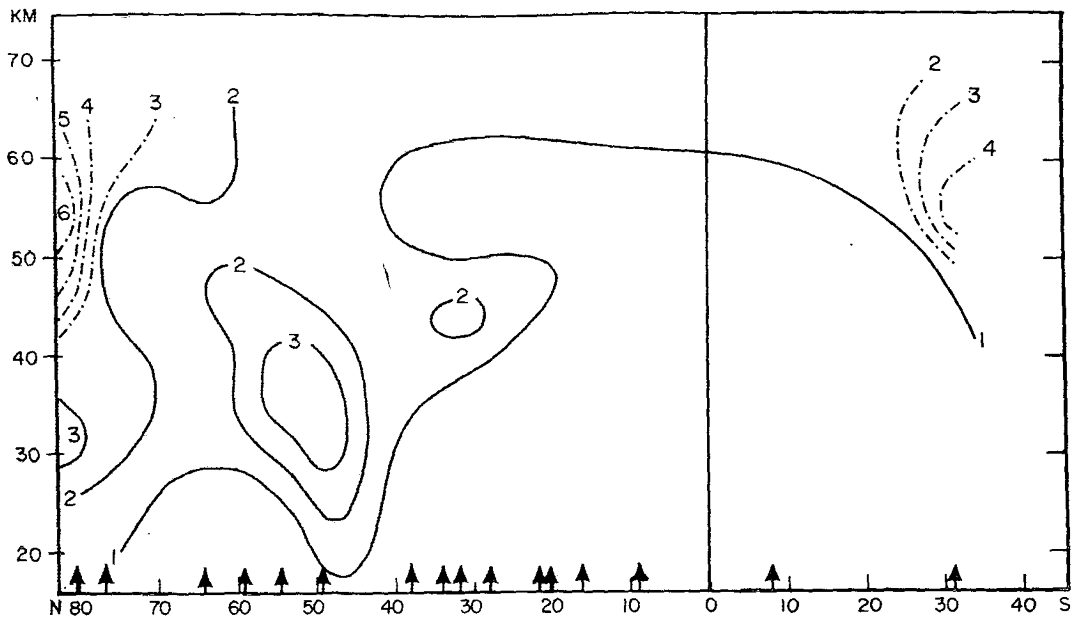

Fig. 8. Amplitude (°C) of terannual variation in temperature.

it appears to be the major semiannual oscillation in the atmosphere below the mesopause. The mesospheric center indicated at the top of our Fig. 6 is more fully shown in Cole and Kantor's Fig. 7 to reach a maximum of about 5°C near 70 km.

The 32 km height of the lower polar semiannual amplitude maximum in Fig. 6 differs from that given by van Loon *et al.* (1972), who place it at 40 km. The present analysis is based solely on MRN data north of 50°N as MRN soundings are nearly always complete throughout the mid-stratosphere while radiosonde (R/S) soundings, although greater in number, are probably strongly biased toward particular atmospheric conditions (only a small fraction of all radiosondes released, especially at high latitudes, reach 10 mb during the winter). The results in Table 4 of the analysis of Selective Chopper Radiometer (SCR) data for November 1970-November 1971, from Barnett (1974), and of typical MRN and R/S data, illustrate this difference.

The SCR radiances are for an atmospheric layer approximately 20 km thick with the maximum of the weighting functions at about 2, 10 and 50 mb for Channels A, B and C, respectively. Thus, the analysis in Fig. 6 is believed to be the best estimate now available because MRN data have a more reliable period of record and have finer height resolution than the one year of SCR, and because there is less bias in MRN data than in radiosonde data near levels of 30 km and higher.

The time of first maximum (Fig. 7) of the semiannual wave is near the end of January over most of the polar regions below 45 km and in the last half of April at the equator near 35 km.

d. Terannual wave

The amplitude of the 4-month wave (Fig. 8) has a well-established maximum near 35 km at 50°N. The larger center suggested at 80°N is based on Heiss Island data, but as all the Heiss amplitude values have relatively large statistical errors, and as there is no confirmation from the Thule data at 77°N, its existence is doubtful and the analysis is shown in dashed isolines. Future data will be needed to clarify this feature. The small maximum near 30°N at 45 km is nearly congruent with the small secondary maximum of the terannual wave found in zonal wind (Belmont *et al.*, 1974). At low latitudes and low altitudes the amplitudes become very small. However, since the values at the 55°N maximum are as large or larger than the semiannual amplitude there or in the tropics, it is surprising that this wave has not previously been recognized in the literature.

This wave presumably arises from the square-wave character of the seasonal temperature changes, especially at high latitudes. Graphs of the mean monthly temperature (not shown) indicate there are small changes during the summer and winter seasons with large gradients during spring and autumn. In a pure square wave the phase of the third harmonic lags that of the first harmonic by one-sixth the period of the first harmonic. From Fig. 9 it can be seen that near 50°N at 35 km, where the amplitude of the

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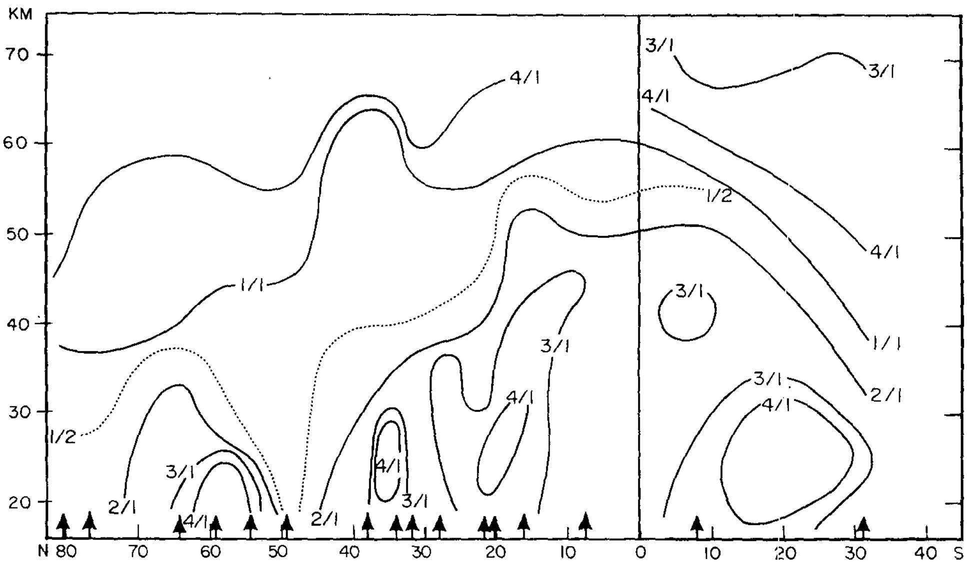

FIG. 9. Date of first maximum of the terannual variation in temperature (3/1 is the first half of March).

terannual wave is large, the phase date is the first part of January (and of May and of September) or exactly 2 months lag with respect to the phase of the annual wave there (Fig. 5).

5. Conclusion

These large-scale periodic oscillations of the thermal field require theoretical explanations which must account also for the corresponding, but different, properties of the wind fields. Theories will have to explain the multi-layered horizontal stratification with height of the various oscillatory centers extending through the stratosphere and mesosphere and higher. And stratospheric modelers must recognize that to be realistic, their models should reproduce these observed variations, among others. Finally, continued rocket and satellite observations are required to more fully describe, and later explain, the hemispheric differences at high latitudes and altitudes.

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