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PERIODIC VARIATIONS IN STRATOSPHERIC TEMPERATURE FROM 20-65KM AT 80°N TO 30°S

By G.D. Nastrom and A.D. Belmont

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16. Abstract

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I. INTRODUCTION

Comparative studies of time series of temperature based on Meteorological Rocket Network (MRN) observations are clouded not only by the usual statistical uncertainty of the measurements, but by the need for application of correction factors which have not yet been precisely determined for the various sensors used. This makes difficult the analysis of seasonal variations through the use of time-latitude or height-latitude sections, as we have done with the wind components, since the observed variations may be due to real geographic differences, or instrument differences, or both (Schmidlin, 1974). On the other hand, each source of error is fairly constant from one sounding to the next (except solar radiation effects), and always tends to bias the observations in the same algebraic sense (Ezemenari, 1972). Thus, examining seasonal variations by the use of periodic analysis, where only relative variations from each station's mean are compared, should yield results valid for comparison on an inter-station and geographic basis.

The interpretation of periodic analysis of MRN temperatures is also clouded, however, by the time distribution of the observations and by the need for corrections to be applied to the data. Finger and Woolf (1967) concluded that an error of several degrees K may be caused by solar radiation heating of a rocketsonde temperature sensor and Hoxit and Henry (1973) suggest that the magnitude of this error varies with solar zenith angle. Also, the observed temperatures are affected by the presence of the diurnal variation, which may vary on a seasonal basis. Inasmuch as the bulk of MRN soundings are made near the same local time each day there is reason to believe that the periodic amplitudes and phases may require adjustment for the above processes. A corollary goal of this study then, is to estimate the effect of temperature corrections and diurnal variations on the long-term periodic analysis results.

II. DATA AND METHOD

The source of all original MRN data was the World Data Center, Ashville, N.C. (WDCA), except as noted in Table 1. MRN stations and the period of record of each are as listed in Table 2. Individual radiosonde observations at rocket locations were used to extend the analysis down to 20 km, and to improve latitudinal coverage. Monthly mean radiosonde temperatures were analyzed between rocket stations. Radiosonde data at intermediate latitudes, taken at standard pressures of 50, 30 and 10 mb, were assigned to 20, 24 and 30 km. At rocket stations, radiosonde data had already been interpolated to standard heights, and these data were weighted more heavily in those instances in which the two data sources analysis differ.

The amplitudes and phases of the long-term periodic components of the time series of individual MRN temperature observations were determined using a joint, periodic regression technique as described by Belmont, et al (1974). The analysis was done at constant height levels with 4 km resolution, 20-68 km. Frequencies included in the basic analysis were the long-term mean, quasi-biennial oscillation (QBO), and the first six harmonics of the annual wave. The second three harmonics of the annual wave generally had small amplitudes, large statistical error estimates, and erratic phase progression, making their intrepretation tenuous if not meaningless. Thus, 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). Periodic analysis results are given in Table 2.

The periodic regression technique can be used to analyze a time series of irregularly spaced data points and can include frequencies that are not integral divisions of the period of record. Also, this technique simultaneously determines a statistical estimate of the errors in amplitude and phase for each frequency included. These error estimates were essential when evaluating the spatial patterns of the amplitude and phase of the component waves. The statistical errors in Table 2 arise primarily from three sources: Lack of completeness of the MRN time series, the presence of high frequency variability in the time series, and using a fixed sine wave for the QBO. It is well known that the QBO is only approximately sinusoidal, and that its amplitude and period are not constant (Dartt and Belmont, 1964).

III. ERROR SOURCES AND RELIABILITY

A. Temperature Corrections

The calibration of meteorological measurements made under differing conditions is often a difficult task, but necessary if the results are to be compared. In the case of MRN temperature measurements the dominant factors for which adjustments are required are aerodynamic heating, infrared radiation, solar radiation, thermal lag, conduction, and ohmic heating (Hoxit and Henry, 1973). Since our goal here is to examine the periodic variability, only the correction for solar radiation will be considered because the other terms all act to bias the observations in the same sense and with fairly constant magnitude (Hoxit and Henry, 1973; Ezemenari, 1972). Although the amount of correction for solar radiation has not yet been completely resolved, a comparison of some recent estimates in Table 3 shows that they range from 1 to 7 degrees, depending on level. The values given in Table 3 are based on a low sun shining directly on the sensor. As Hoxit and Henry (1973) point out, the required amount of correction varies with solar elevation angle, and they present a straightforward technique for taking account of this. In order to estimate the effect of corrections for solar radiation upon the periodic analysis results, their scheme was applied to the entire twelve year time series of temperatures at each MRN station.

Sometimes the observations are reported with corrections already applied, in which case we made no additional adjustment. Corrected observations prior to 1969 were merely indicated as corrected or uncorrected, while those for 1969-1972 had the correction scheme used identified and included the amount of correction applied at each altitude. It was initially planned to use the given correction amounts to study the effect of corrections upon periodic analysis results, but as can be seen in Table 1, only Barking Sands, White Sands, and Point Mugu were reported with corrections applied for more than a few percent of the time during 1969-1972. Further, these three stations did not all use the same correction scheme. By using the correction method of Hoxit and Henry at all MRN stations maximum latitudinal coverage and consistency from station-to-station can be obtained. It is believed that these latter advantages outweigh the errors introduced by applying a correction method intended primarily for the Arcasonde 1A to a variety of sensor's data (see Table 1 for typical sensors used).

Basically, the scheme requires adjusting the correction amounts given by Staffanson, et al, (1972) for variations of solar zenith angle. The solar zenith angle is a function of location, time of year, and local time, and a discussion of its variability with respect to these parameters has been given by Belmont and Dartt (1970). Once the solar zenith angle has been determined for an observation, the required correction amount is estimated according to

$$C = [f(\alpha) + A]\,[C_s/0.85] \tag{1}$$

where C is the required correction, $f(\alpha)$ is a function of solar zenith angle with magnitudes between about 0.3 and 0.6, A is earth albedo (taken to be 0.3), and C_s is the radiation correction given by Staffanson, et al (1972). The time series of corrected observations were then analyzed for periodic variability as described above and the results compared with those based on uncorrected data. The differences in amplitude (uncorrected minus corrected) at 40, 50 and 60 km are given in Table 4. Since the corrections for solar radiation never act in a positive algebraic sense (although they are zero at night), it is not surprising that the largest effect was found to be on the long-term mean. Note that the mean at nearly all stations after correction is about 5 degrees colder at 60 km, and about .5 degrees colder at 40 km. The annual wave's amplitude is decreased at nearly all locations while other periodic waves seem to be changed randomly. Undoubtedly this arises from both seasonal and diurnal variations of zenith angle, thereby contributing some variability at all frequencies, but most significantly, and at all stations, to the annual variation. This is graphically illustrated in Figure 1, where the 11 year consolidated monthly means of the corrected and uncorrected time series at 60 km for Churchill are plotted. The two scales for the curves in Figure 1 have been shifted to facilitate comparison. Note that the shapes of the two curves are nearly congruent during the winter months but that the corrected curve is consistently below the uncorrected one during the summer, resulting in a reduced annual wave. The erratic changes in February and March are probably responsible for the increased amplitude of the terannual wave after correction (Table 4), and illustrate how solar corrections can affect periodic waves other than just the annual. Phase estimates for all waves were changed very little after correction.

It is instructive to consider that the earth albedo term of Equation 1 is of the same order of magnitude as the solar zenith angle term. Thus, it may be that the solar radiation corrections are underestimated due to the assumption of a constant albedo (0.3) throughout the preceeding computations. The relative importance of a fluctuating albedo was estimated by using the monthly albedo values for $60^{\circ}N$ given by Winston (1971) for the Atlantic sector and recalculating the periodic amplitudes and phases. The differences of the corrected minus uncorrected amplitudes at Churchill at 60 km were as follows:

Change in long-term mean	Constant albedo (0.3)	-4.8 C
	Variable albedo (0.3 to 0.5)	-5.2
Change in annual wave amplitude	Constant albedo	- .6
	Variable albedo	- .5

Apparently, the relative effect on the mean is small and the variable albedo nullifies part of the effect of solar corrections on the annual wave, in this case. The above values are intended merely to be indicative of a subtle source of aliasing error and the significance of these values must be interpreted only after taking account of the possible errors in the albedo values and of the weight given to them in Equation 1.

B. Aliasing by the Diurnal Tide

Another potential source of aliasing error in the periodic analysis results is the diurnal tide. Since most MRN observations are taken at nearly the same local time each day (see Table 1), the long-term mean should be aliased by an amount equal to the magnitude of the diurnal tide at that time of day, assuming that the tide is constant throughout the year. The diurnal tide may also influence the other periodic components however, since there is reason to believe (Chapman and Lindzen,1970) that the amplitude, and possibly the phase, of the tide may vary on a seasonal basis. The case of constant tide will be treated first.

1. Constant Diurnal Tide

In the effort to estimate the possible aliasing of periodic analysis results by the diurnal tide, time series of individual observations corrected for solar radiation were simultaneously fitted with the long-term periodic components and a diurnal variation. This first effort assumes a diurnal wave that is constant over the entire period of record at each station. While this approach does not take into account possible seasonal variations of amplitude or phase, the error is probably no larger than that of taking data for a single season, say summer, or of adjusting the hourly observations for seasonal variations as Hoxit and Henry (1973) have done. In fact, this approach is nearly identical to that of Hoxit and Henry except that we fit the long-term components simultaneously with the diurnal variation rather than first subtracting them from the time series.

Estimates of the amplitude and phase of the diurnal variation, along with statistical error estimates, are given in Table 5. These values should be considered mean annual estimates and a study of them must not be divorced from the accompanying error values. Considering the 24 hour distribution of observation times at MRN stations, a surprisingly high degree of consistency among the values given here is present. Also, these estimates compare well with previous studies (Finger and Woolf, 1967; Beyers and Meirs, 1968; Hoxit and Henry, 1973). Some further points are noted:

- Amplitude profiles at Sherman, Kwajalein, and Ascension (9°, 8°, and -8° latitude) are very similar to each other and agree qualitatively with the profile predicted by Lindzen (1967), although they are about a factor of two larger. The observed phase variations among these three stations are not considered contradictory since Belmont and Dartt (1970) have shown that phase variations exist across the equator and with longitude in the lower stratosphere. Further, there is evidence (Ballard, et al, 1972) that orographic effects on the diurnal tide occur at least as high as 50 km.

- There is a steady decrease of amplitude between the tropics and 28°N at 40 km and above. This general pattern is predicted by theory but the absolute values are once again observed to be larger than predicted.

- Greely, Churchill, and Primrose (64, 59, and 55° latitude) are fairly consistent at and above 50 km. Also, Lindzen's theory predicts a relative maximum in amplitude between 40 and 50 km at 45° and 60° latitude; such a maximum is found at Wallops (38°) but not at higher latitude stations.

- The decrease of amplitude at high altitudes as the pole is approached from sub-polar latitudes is qualitatively predicted by Lindzen (1967), but the observed absolute values are several times larger than theoretical values.

2. Seasonally Varying Diurnal Tide

Analysis of the diurnal tide on a seasonal basis is seriously hampered by the scarcity of observations throughout 24 hours. Indeed, some of the relatively large error estimates shown in Table 5 for the mean yearly diurnal waves result from the heavy bias at many MRN stations toward the same observation time each day. Churchill, followed by White Sands, has the "best" 24-hour distribution of observations so a seasonal analysis of the diurnal tide was made at these two stations. Even at these stations it is necessary to group data by seasons rather than on a monthly basis. Data corrected for solar radiation were stratified into four seasons (March, April, May is spring), and into six four-hour time groups of the day. Harmonic analysis results by season at Churchill are presented in Figure 2, where the number of observations available at 40 km each season is also given in order to indicate a relative level of confidence. Values at 30 km may be influenced by mixing radiosonde and rocketsonde data.

Using the amplitudes and phases given in Figure 2, noontime values of the diurnal tide were calculated for each season. A harmonic analysis of these four values yielded annual amplitudes of the variation in the noontime tidal values of 2.6 and 1.4C and phases of 15 August and 1 March at 40 and 50 km, respectively. Thus, the tendency for most MRN observations to be made near the same local time each day coupled with seasonal changes of the diurnal tide may significantly alias the estimated amplitudes and phases of longer period waves. This aliasing of the annual variation arises from a linear interaction between the "true" annual wave and the seasonal fluctuations of the diurnal tide, while the semiannual and terannual waves are influenced by a non-linear interaction between the "true" annual wave and the seasonal variation of the diurnal tide. Harmonic analysis of seasonal mean temperatures at Churchill after the diurnal tide was removed resulted in annual amplitudes of 15.6 and 13.4C and semiannual amplitudes of 4.8 and 2.4C at 40 and 50 km, respectively. At 40 km these values are more than 2C different from those given in Table 2. This sample of seasonal variations of the diurnal wave shows that the diurnal (and likely the semi-diurnal) may have significant effects on all the waves discussed later in this report.

Harmonic analysis results for White Sands did not display the smooth profiles of Churchill's results, so are not presented here. These irregularities with height may result from inaccuracies produced by the less satisfactory 24-hour distribution of observation times at White Sands or they may be real. As there is no other independent data to verify these estimated values and since we have not yet developed a technique for computing a probable error to associate with each value, spatial continuity is the only criterion now available for establishing confidence in the profiles.

C. Longitudinal Variations

The representativeness of the periodic analysis results is described in part by the observed longitudinal variability. Previous analysis of the zonal wind has shown that there are longitudinal differences in the periodic amplitudes and phases of that parameter (Belmont, et al, 1974), so it seems likely that comparable differences will exist with respect to temperature. Profiles of the amplitude and phase of the QBO at Sherman and Kwajalein as displayed in Figure 3 show that there is little difference between these two stations at altitudes where the amplitude is large (20-40 km).

Similar profiles for the annual wave at Churchill and Greely are shown in Figure 4. Note that the phase is very similar below 55 km, but that the amplitude is slightly smaller at Churchill between 30 and 50 km. This is probably due to the difference in latitude of the stations. Longitudinal comparisons of the tropical and polar semiannual waves are shown in Figure 5 (Sherman and Kwajalein) and Figure 6 (Churchill and Greely), respectively. The tropical oscillation is very similar up to 50 km, and shows longitudinal differences, especially with respect to phase, only above 50 km. Due to the small amplitude there, the phase above 50 km has little significance as phase can take on any value when the amplitude goes to zero. In polar latitudes there are apparently two different semiannual waves (Figure 6), each of which shows a small amount of longitudinal variation The details of two different polar semiannual waves will be discussed later.

IV. PERIODIC ANALYSIS RESULTS

Height-latitude sections and profiles of the amplitude and phase of each of the component waves on constant height surfaces are presented in Figures 7-15. These figures were prepared using all available stations since the observed longitudinal differences were considered minor compared to the loss of resolution which would result if only stations near a particular meridian were used. Although the distribution of MRN stations, depicted by arrows in the figures, shows some large latitudinal gaps the analysis below about 30 km has been based upon radiosonde data. Further, the figures are based on analyses of observations not corrected for solar radiation or tidal aliasing. The estimated effects of these two factors have been discussed; the decision of whether or not to apply the estimated adjustments is left to the reader. The results presented here compare well with corresponding portions of previous work (Angell and Korshover, 1970; van Loon, et al, 1972; Cole, 1968; Groves, 1972).

A. Long-Term Mean (Figure 7)

Due to the differing characteristics of MRN temperature sensors, station to station comparisons of the long-term mean are the most difficult, so Figure 7 presents a highly smoothed analysis in which spatial continuity was demanded. In the long-term mean the stratopause is near 50 km from the equator to about 40^{o}N and then slopes gently upward to 60 km at 75^{o}N. Based on the Ascension and Woomera analyses, it appears the stratopause may begin to slope upward at a lower latitude in the southern hemisphere. At 20 km the coldest temperatures are at the equator with a maximum gradient at 40 to 50^{o}N; this appears to be relatively symmetric at least as far south as 30^{o}S.

B. QBO (Figure 8)

The QBO in temperature has a maximum amplitude of 2C near the equator at 30 km and north of 50^{o}N above 60 km. There is also indication of an increasing amplitude with height at 30^{o}S. Except in the regions of large amplitude, the phase progression of the QBO is so erratic as to make inter-station analysis impossible. This is likely due in part to the fact that we have used a coherent, 29 month approximation for the QBO while in reality the period changes in time at a given station, and also with latitude (Dartt and Belmont, 1964). We have included Figure 9 to illustrate vertical profiles of relative phase at typical latitudes.

C. Annual (Figures 10 and 11)

The amplitude of the annual wave is seen in Figure 10 to be a maximum near 70°N at 40 to 45 km with a broad region of minimum amplitudes between 20°N and 20°S below 50 km. The amplitude of the polar maximum is slightly over 22C. The bulge of relatively large amplitudes extending southward at 35 to 40 km at 35°N appears mirrored in the southern hemisphere.

The date of maximum temperature is earliest (second half of June) at all altitudes in high latitudes, spreading downward and southward to 20 km at 15°N about two months later. It appears that a similar phase progression occurs in the southern hemisphere to 30°S at lowest altitudes, also terminating at 20 km at 15° latitude. In tropical regions the annual maximum occurs first above 50 km and propagates downward, reaching 20 km about eight months later. Although lack of MRN stations near the equator prohibits detailed resolution of the amount of equatorial symmetry of phase of the annual wave, the presence of two centers of early phase date, one on each side of the equator but at different altitudes, seems fairly well defined. The northern hemisphere tropical and polar waves are separated by a region of rapid phase change near 30N above 50 km. Below 50 km the amplitude is so small as to make interpretation of the phase meaningless in the tropics.

The similarity of the annual wave's phase dates at high latitudes to that of the solar declination, lagging it by only a week or two, 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 these two centers of oscillation are not caused by the same mechanism. Thus, it seems likely that at least a large portion of the tropical annual wave may be due to dynamic influences as suggested by Cole (1968) and Fritz (1974).

D. <u>Semiannual</u> (Figures 12 and 13)

Maxima in the amplitude of the half-yearly component occur at 35 km near 75°N and at 40 km near the equator with magnitudes of about 7 and 3C, respectively. Also, a tongue of relatively large amplitude extends southward to about 35°N at 40 to 45 km. There are bands below 55 km of minimum amplitude at 20° to 30° latitude in both hemispheres, and north of 35°N near 50 km. In Figure 12 the high altitude semiannual oscillation is seen as a broad area above 50 km north of 30°N. The latter feature is presented in a different perspective in Figure 6; vertical profiles of amplitude and phase of the semiannual wave at Churchill and Greely. The amplitude has a distinct minimum at 40 to 45 km and the phase shifts about 90° at this minimum. This behavior suggests that the two regions of maximum amplitude have different physical causes or that these two regions respond differently to the same physical drives. Attempts to explain the temperature variability in this portion of the atmosphere from analytic and dynamic considerations should not neglect this feature. It is interesting that the temperature is found to have a relatively large semiannual wave at the same location as the zonal and meridional winds (Nastrom, et al, 1974) but that the phase in temperature lags that of both wind components by 90°.

Phase of the semiannual wave in the northern hemisphere (Figure 13) appears to rotate about a singular point located near 25°N at 40 km. The time of first maximum of the wave is near the middle of January over most of the polar regions below 45 km and in the last half of April at the equator near 35 km. Two aspects of equatorial symmetry can be seen in Figure 13: The phase progression with height at 30°S is nearly identical to that at 30°N, and a relatively late phase date occurs at low altitudes near 15° latitude.

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The 32 km height of the polar semiannual amplitude maximum in Figure 12 differs from that given by van Loon, et al (1972), who placed 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 fraction of all radiosondes released, especially at high latitudes, reach 10 mb during the winter). The following results of our (unpublished) analysis of selective chopper radiometer (SCR) data for April 1970 - April 1971, and of typical MRN and R/S data, illustrate this difference:

	DATA SOURCE	SEMIANNUAL AMPLITUDE			
		20(50)	30(10)	40(2)	KM(MB)
(MRN)	Heiss Island (Table 2D; 7 yrs)	1.6 C*	6.5 C*	5.0 C*	
(Sat.)	SCR (zonal mean, 75-80N; 1 yr)	2.3 C	6.5 C	7.8 C	
(R/S)	Resolute (75N, 95W; 1964-1971)	1.2 C	2.2 C	-	
	Eureka (80N, 86W; 1964-1971)	1.6 C	2.1 C	-	

* Used in Figure 12.

— Close to van Loon's (1972) values.

The SCR measures radiances for a slab of atmosphere 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 Figure 12 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 SCR, and because there is less bias in MRN data than in radiosonde data near levels of 30 km and higher.

E. Terrannual (Figures 14 and 15)

This wave presumably arises from the square wave character of the seasonal temperature changes, especially at high latitudes. Graphs of the mean monthly temperature 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 Figure 15 it can be seen that near 50°N at 35 km, where the amplitude of the terannual wave is large, the phase date is the first part of January (and of May and of September) or exactly two months lag with respect to the phase of the annual wave there (Figure 11).

The amplitude of the four-month wave (Figure 14) is a maximum at 55 km near 80°N, and near 35 km at 50°N. The latter maximum has a small extension to 25°N at 45 km, which 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 amplitude becomes very small.

V. PHASE LAG COMPARISONS

The phase lag of the annual oscillation in zonal wind relative to that in temperature is displayed in Figure 16. In the figure a value of +4 indicates that the wind wave reaches its maximum 4 months later than the temperature wave. Estimates of phase for the zonal wind given in Belmont, et al (1974), were used. Errors of the relative phase lags were estimated by adding the squares of the statistical errors of the wind and temperature waves and taking the square root of the sum; these errors were used when drawing contours. At high latitudes these two annual waves are nearly six months out of phase, and over the tropics at high altitudes they are nearly in phase. The zone of rapid change in the phase of temperature, seen in Figure 11, is reflected in Figure 16 at 50 to 60 km near 30°N where the phase of the zonal wind varies only slowly. The analysis has not been extended across the equator as both the wind and temperature waves have small amplitude and hence uncertain phase there. In fact, the phase of zonal wind has a singular point near the equator with very rapid phase change near there.

A similar comparison of relative phase lags for the semiannual oscillations is given in Figure 17. In the region 50° to 70°N the wind and temperature waves are nearly exactly out of phase below 35 km, and above 40 km the wind lags the temperature by about one-quarter wavelength. An approximately in-phase relationship exists in the tropics (10°-20°N) below 35 km and from 50 to 60 km with the two regions separated by a very large phase lag gradient between 35 and 40 km, which is where the singular point is found in the phase of temperature (Figure 15).

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TABLE 1. STATION LIST

Station	Range of Most Common OBS Hours (Local Time)	Percent of OBS at Most Common Time	Most Common Sensor* Used and Percent of Time Used		Percent of Soundings Reported as Corrected (1969-1972)
			Primary	Secondary	
1. HEISS	14-20	64	90(100%)		1
2. THULE	8-14	79	12(50%)	50(29%)	0
3. GREELY	8-14	95	60(35%)	12(42%)	0
4. CHURCHILL	9-15	60	60(50%)	12(42%)	0
5. PRIMROSE	8-14	95	60(52%)	10(28%)	0
6. VOLGOGRAD	10-16	61	90(100%)		0
7. WALLOPS	10-16	74	60(40%)	10(20%)	0
8. PT. MUGU	7-13	89	60(37%)	12(36%)	18
9. WHITE SANDS	8-14	74	60(37%)	12(15%)	66
10. KENNEDY	7-13	80	12(43%)	60(32%)	1
11. BARKING SANDS	7-13	84	60(38%)	12(34%)	29
12. GRAND TURK	10-16	78	(No OBS after 1966)		
13. ANTIGUA	8-14	84	12(57%)	10(40%)	0
14. SHERMAN	15-21	98	60(49%)	12(37%)	9
15. KWAJALEIN	9-15	85	60(98%)		0
16. ASCENSION	12-18	84	12(56%)	60(31%)	1
17. WOOMERA**	9-17	70	90(100%)		Unknown

* Sensor Types:
10 Arcasonde 1A
12 Arcasonde 4
50 AN/DMQ-9
60 Datasonde
90 Other

** Woomera data sources: WDCA, Groves (1967), Pearson and Johnson (1973)

Table 2. Periodic Analysis Results.

A. STATION LIST, NUMBER OF OBSERVATIONS, MEAN, AND ERROR OF THE MEAN

STATION	NAME	LAT	LON	YEARS	NUMBER OF OBSERVATIONS 20	30	40	50	60	64
1	HEISS	80	-58	2/62- 1/70	182	186	175	135	119	113
2	THULE	77	69	6/65-12/72	343	348	358	296	135	64
3	GREELY	64	146	4/61- 5/72	644	673	668	563	285	113
4	CHURCHILL	59	94	1/61-12/72	942	915	952	884	560	196
5	PRIMROSE	55	110	7/64-12/72	352	357	349	312	224	146
6	VOLGOGRAD	49	-45	9/65- 1/70	136	137	139	130	119	116
7	WALLOPS	38	87	1/61-12/72	859	799	769	674	211	26
8	PT.MUGU	34	119	1/61-12/72	1437	1319	1324	1226	571	103
9	WSMR	32	107	1/61-12/72	1363	1120	1095	988	704	336
10	KENNEDY	28	76	1/61- 5/72	1314	1302	1274	1142	520	126
11	HAWAII	22	160	4/62-12/72	1072	960	953	898	419	110
12	GR.TURK	21	71	9/63-12/66	166	183	181	148	27	24
13	ANTIGUA	17	62	6/63- 5/72	509	491	464	371	66	38
14	SHERMAN	9	80	3/66-11/72	468	463	459	422	235	65
15	KWAJALEIN	8	167	3/63-12/72	307	303	309	305	184	28
16	ASCENSION	-8	15	10/62- 5/72	1004	959	951	937	598	167
17	WOOMERA	-31	-137	2/61- 8/72	860	780	15	75	76	76

STATION	MEAN(C) 20	30	40	50	60	64	ERROR OF THE MEAN (C) 20	30	40	50	60	64
1	-56.5	-47.1	-25.2	-9.6	-33.7	-46.9	4.7	3.8	2.4	2.1	4.6	6.1
2	-53.5	-46.2	-26.4	-5.1	-2.6	-4.2	3.2	2.8	1.8	1.0	1.0	1.5
3	-49.0	-43.7	-25.3	-5.4	-3.8	-7.1	2.1	1.9	1.2	.6	.9	1.2
4	-52.3	-45.8	-24.4	-4.8	-6.8	-9.2	1.8	1.7	1.1	.5	.5	1.2
5	-52.1	-45.1	-24.9	-5.8	-9.5	-12.4	3.0	2.6	1.6	.7	.8	1.5
6	-57.8	-44.2	-19.1	-7.3	-34.0	-53.2	5.5	4.3	2.1	1.2	3.6	5.6
7	-58.3	-43.2	-17.3	-2.4	-13.0	—	2.0	1.6	.7	.2	1.0	—
8	-59.6	-42.3	-18.2	-3.4	-11.1	-19.0	1.6	1.2	.5	.1	.5	2.4
9	-60.9	-42.7	-17.5	-2.8	-13.5	-18.0	1.7	1.3	.6	.2	.6	1.1
10	-62.5	-40.7	-17.0	-2.6	-12.2	-23.0	1.8	1.1	.5	.1	.6	2.8
11	-63.1	-40.5	-17.6	-3.6	-14.7	-23.8	1.9	1.3	.6	.2	.8	2.7
12	-64.6	-40.1	-16.1	.7	—	—	6.1	3.4	1.4	.3	—	—
13	-64.1	-39.1	-14.8	-.5	-7.2	—	2.9	1.8	.7	.2	2.9	—
14	-65.4	-40.1	-14.8	-.6	-10.6	-17.1	3.4	2.1	.9	.2	.9	2.9
15	-65.7	-40.7	-13.9	-.2	-11.5	—	4.1	2.5	.9	.2	1.1	—
16	-65.3	-39.5	-13.6	-.4	-10.6	-17.6	2.1	1.3	.5	.1	.5	1.9
17	-58.3	-38.0	—	-7.8	-22.3	-35.2						

B. AMPLITUDE (C) AND PHASE (DEGREES), WITH ERRORS, OF THE QBO (29 MONTH)

LEVEL (KM) STATION	AMPLITUDE 20	30	40	50	60	64	AMPLITUDE ERROR 20	30	40	50	60	64
1	.4	1.3	1.2	6.2	9.9	7.7	4.6	3.8	2.4	2.7	5.7	6.6
2	.7	1.4	1.1	.7	2.5	2.6	2.9	2.5	1.7	1.0	1.2	1.8
3	.5	1.1	1.1	1.1	2.1	2.3	1.9	1.7	1.2	.7	1.0	1.3
4	.2	.4	1.2	.7	1.5	3.9	1.6	1.5	1.1	.5	.6	1.6
5	.6	.7	1.6	1.7	2.5	2.2	2.7	2.3	1.6	.9	1.0	1.6
6	1.3	1.8	3.9	3.6	1.4	2.2	5.3	4.2	2.5	1.5	3.4	5.3
7	.3	.5	1.0	.3	.9	—	1.9	1.5	.8	.2	1.1	—
8	.1	.5	1.2	.1	.8	3.1	1.5	1.1	.6	.1	.6	2.7
9	.2	.8	2.1	1.3	1.1	1.6	1.6	1.3	.8	.2	.7	1.2
10	.4	.9	.4	.7	2.0	5.6	1.6	1.1	.5	.2	.8	3.3
11	.4	1.4	.9	.7	1.4	1.2	1.8	1.4	.7	.2	.9	2.6
12	.2	1.5	1.0	3.0	—	—	5.6	3.2	1.3	.4	—	—
13	.2	.5	.4	1.6	1.9	—	2.7	1.7	.7	.3	1.6	—
14	1.2	1.7	.5	.6	1.3	1.5	2.9	1.9	.7	.2	.9	2.8
15	1.2	1.8	.9	.5	1.4	—	3.8	2.5	.9	.3	1.1	—
16	.9	2.6	1.0	.5	1.1	1.6	2.0	1.6	.6	.1	.6	1.9
17	.6	1.3	—	1.4	2.9	2.8						

LEVEL (KM) STATION	PHASE 20	30	40	50	60	64	PHASE ERROR 20	30	40	50	60	64
1	23	-85	25	150	-175	-172	105	94	94	28	42	71
2	179	179	-135	-159	33	61	102	92	88	87	35	57
3	-164	-179	110	-16	-91	136	100	89	79	57	36	46
4	-5	-86	-117	-156	116	83	103	99	71	59	28	25
5	-43	59	84	63	64	80	101	98	77	35	26	60
6	-6	91	132	164		-38	100	94	53	30	94	94
7	4	-54	133	118	-138	—	101	96	62	64	80	—
8	-82	169	75	73	-167	144	104	94	42	86	64	69
9	2	82	70	6	13	65	102	87	23	11	50	63
10	14	-119	11	-95	-57	-28	99	83	81	15	26	47
11	-123	-146	54	-61	-154	34	100	75	63	17	54	94
12	-66	135	3	-102	—	—	105	92	85	8	—	—
13	-151	-127	-132	-130	-63	—	104	97	88	10	67	—
14	160	2	-141	59		54	94	79	87	30	58	90
15	-178	1	149	168	-20	—	98	85	75	33	65	—
16	-177	-0	-64	-83	-81	-73	93	49	43	17	47	81
17	92	-70	—	-165	147	150						

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Table 2. (Cont'd.)

C. AMPLITUDE(C) AND PHASE (DEGREES), WITH ERRORS, OF THE <u>ANNUAL</u> WAVE

	AMPLITUDE						AMPLITUDE ERROR						PHASE						PHASE ERROR					
LEVEL(KM)	20	30	40	50	60	64	20	30	40	50	60	64	20	30	40	50	60	64	20	30	40	50	60	64
STATION																								
1	16.9	16.2	18.2	13.1	3.1	8.6	6.2	5.2	3.3	2.7	4.2	6.3	-168	161	164	169	-19	-21	25	21	11	12	84	62
2	13.4	17.1	22.2	19.6	8.8	3.6	4.3	4.0	2.4	1.4	1.3	1.7	-173	170	176	-179	-159	-132	19	13	6	4	8	35
3	2.3	9.4	20.1	15.7	5.2	2.8	2.1	2.6	1.7	.9	1.2	1.4	179	-172	-174	-176	157	-175	74	16	4	3	13	39
4	4.4	11.0	17.6	13.9	5.6	3.0	2.2	2.3	1.5	.7	.7	1.5	-176	-174	177	176	162	134	38	12	4	2	7	36
5	2.1	9.8	18.1	12.7	4.1	2.9	3.0	3.6	2.3	1.1	1.1	1.7	-174	-170	178	177	144	54	87	22	6	4	16	49
6	6.8	7.1	10.2	8.4	2.9	3.3	5.8	4.9	2.7	1.6	3.6	5.5	179	-162	-175	-169	-165	12	69	58	17	11	80	87
7	2.1	4.7	4.9	2.8	.5	—	2.1	2.1	1.0	.3	1.0	—	-176	176	133	154	84	—	77	30	11	5	91	—
8	2.4	4.5	4.0	2.2	.7	2.5	1.8	1.6	.7	.2	.6	2.5	-170	177	148	-179	8	64	62	22	10	5	69	76
9	1.8	4.0	4.1	1.9	.8	2.2	1.7	1.7	.8	.2	.6	1.4	-158	179	133	167	-54	-7	75	28	11	7	66	53
10	3.0	1.9	2.0	.4	.7	3.0	2.0	1.3	.7	.2	.6	2.9	-150	163	111	-38	-13	157	56	59	21	26	72	73
11	2.6	1.6	1.5	.5	3.0	3.7	2.1	1.4	.8	.2	1.0	2.8	-153	136	106	-8	7	-13	67	71	35	27	22	62
12	3.4	2.6	2.0	1.4	—	—	5.4	3.2	1.4	.4	—	—	-144	161	78	91	—	—	88	83	60	19	—	—
13	2.7	.7	1.6	1.8	5.8	—	3.0	1.7	.9	.3	3.5	—	-138	138	43	36	-122	—	78	96	43	9	50	—
14	2.4	.5	2.8	3.3	2.0	3.4	3.4	2.0	1.2	.3	1.0	3.1	-146	141	64	45	19	62	84	99	27	5	40	72
15	2.7	.4	1.2	1.4	1.1	—	3.9	2.3	1.0	.3	1.1	—	-141	-163	89	20	16	—	86	102	65	11	73	—
16	3.0	.4	1.6	.6	4.8	6.9	2.3	1.2	.6	.2	.8	2.5	-133	45	52	18	15	24	64	98	25	13	8	23
17	2.0	3.3	—	5.3	4.2	2.9							-142	52	—	-7	-7	10						

D. AMPLITUDE(C) AND PHASE (DEGREES), WITH ERRORS, OF THE <u>SEMIANNUAL</u> WAVE

	AMPLITUDE						AMPLITUDE ERROR						PHASE						PHASE ERROR					
LEVEL(KM)	20	30	40	50	60	64	20	30	40	50	60	64	20	30	40	50	60	64	20	30	40	50	60	64
STATION																								
1	1.6	6.5	5.0	1.5	2.4	4.0	4.5	4.4	2.9	1.9	4.0	5.5	6	94	57	79	-6	-29	97	57	46	81	90	85
2	.4	6.2	5.5	1.9	3.4	3.2	2.9	3.3	2.3	1.2	1.2	1.6	150	90	68	47	-105	-125	103	42	28	55	23	39
3	1.7	3.2	.9	2.3	.7	3.5	2.0	2.1	1.2	.8	.8	1.5	32	39	23	-76	-97	-113	81	56	83	24	81	30
4	.7	3.1	2.1	1.7	3.2	3.2	1.7	1.9	1.3	.6	.7	1.5	73	62	59	-6	-37	-53	95	53	50	25	12	32
5	1.4	2.9	.5	.9	1.5	2.5	2.9	2.7	1.5	.7	.9	1.7	21	46	105	-96	-59	-90	94	72	94	65	53	57
6	1.0	3.6	3.1	.7	6.6	7.8	5.1	4.2	2.3	1.1	4.1	6.1	90	53	50	12	-67	-83	101	81	62	87	53	65
7	.8	.8	1.2	1.8	2.8	—	1.9	1.5	.8	.3	1.3	—	156	101	49	-63	-131	—	95	91	57	8	33	—
8	.8	.7	1.3	1.5	2.3	2.2	1.5	1.1	.7	.2	.7	2.4	-134	158	46	-53	-132	-151	90	88	35	8	19	79
9	.4	.8	1.5	1.7	1.7	1.7	1.6	1.3	.7	.2	.7	1.3	-153	164	37	-53	-126	-73	100	88	35	8	30	62
10	.4	.6	.9	1.6	1.4	.9	1.6	1.1	.6	.2	.7	2.6	-171	-151	15	-81	-159	108	100	90	54	6	37	98
11	.6	1.4	.3	1.2	.1	.5	1.8	1.4	.6	.2	.7	2.4	-117	-147	-86	-107	169	-145	97	76	90	10	104	102
12	.4	.9	1.4	.8	—	—	5.1	3.0	1.4	.4	—	—	-85	-122	-85	-112	—	—	105	98	75	36	—	—
13	.6	1.1	1.6	1.1	4.3	—	2.7	1.8	.9	.3	3.7	—	-100	-105	-98	-162	81	—	100	87	40	14	72	—
14	1.0	1.8	3.1	.8	1.4	4.5	3.2	2.1	1.1	.3	1.0	3.1	-173	-116	-142	-162	16	27	97	82	24	23	60	59
15	.3	1.8	3.9	1.7	.7	—	3.7	2.4	1.1	.3	1.0	—	-35	-122	-162	129	136	—	104	84	19	9	87	—
16	.4	1.1	3.1	.7	1.4	2.3	2.0	1.3	.6	.2	.7	2.0	94	-108	-142	168	54	51	100	80	12	12	33	69
17	.9	2.6	—	3.4	2.6	3.3							125	103	—	-32	-67	-150						

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E. AMPLITUDE(C) AND PHASE (DEGREES), WITH ERRORS, OF THE FOUR MONTH WAVE

	AMPLITUDE						AMPLITUDE ERROR					
LEVEL (KM)	20	30	40	50	60	64	20	30	40	50	60	64
STATION												
1	2.7	2.9	1.0	6.3	5.6	4.6	4.5	3.8	2.2	2.4	4.5	5.6
2	.7	1.8	2.1	1.1	2.9	3.4	2.9	2.7	1.9	1.1	1.2	1.7
3	.2	1.2	1.0	2.2	3.0	2.2	1.9	1.8	1.2	.8	1.1	1.4
4	.4	1.7	3.0	2.0	1.0	1.3	1.7	1.7	1.4	.6	.6	1.2
5	1.2	1.9	3.2	1.6	1.8	3.3	2.8	2.5	1.9	.8	1.0	1.8
6	1.8	4.2	4.2	.4	4.0	5.0	5.3	4.5	2.5	1.1	3.7	5.7
7	.3	1.0	1.4	1.1	1.0	—	1.9	1.5	.8	.3	1.1	—
8	.6	.1	1.9	.8	.2	2.2	1.5	1.1	.7	.2	.5	2.5
9	.2	.3	1.4	1.4	.9	.7	1.6	1.2	.7	.2	.6	1.1
10	.6	.2	.6	.6	.5	2.2	1.6	1.1	.5	.2	.6	2.7
11	.5	.2	.9	.9	1.0	.6	1.8	1.2	.7	.2	.8	2.3
12	.3	1.3	.8	1.3	—	—	4.9	3.0	1.3	.4	—	—
13	.3	.1	1.0	.6	3.2	—	2.7	1.7	.8	.3	2.8	—
14	.2	.6	1.0	.3	.8	3.2	3.2	2.0	.9	.2	.9	3.0
15	.5	1.2	.6	.8	1.5	—	3.7	2.3	.8	.3	1.2	—
16	.1	.7	.9	.6	.6	4.0	2.0	1.2	.5	.2	.6	2.3
17	.3	1.6	—	2.5	2.4	3.2						

	PHASE						PHASE ERROR					
LEVEL (KM)	20	30	40	50	60	64	20	30	40	50	60	64
STATION												
1	63	111	-26	-110	-124	-104	89	83	94	26	66	80
2	59	63	16	106	-138	-123	99	87	70	74	27	36
3	-140	143	52	-60	-135	150	103	86	81	24	24	53
4	-112	78	51	3	-74	169	100	76	32	20	48	73
5	-36	51	34	-42	-136	-143	94	84	48	41	42	43
6	65	59	45	136	-113	-110	96	77	48	97	72	79
7	171	102	72	53	95	—	103	87	50	15	78	—
8	9	-95	82	69	177	-163	95	105	24	14	94	79
9	122	-162	70	41	-5	-104	102	99	37	10	61	86
10	173	4	100	34	80	-159	97	102	68	15	80	83
11	-30	-149	99	61	-46	-4	98	101	64	14	68	98
12	-156	51	86	135	—	—	105	94	89	20	—	—
13	-89	-33	-95	148	-31	—	103	104	67	28	70	—
14	141	107	169	103	61	166	105	98	71	61	79	73
15	-31	179	111	154	15	—	102	92	85	22	64	—
16	-75	-145	-123	141	-40	-70	104	89	51	14	71	45
17	177	-176	—	-115	-114	-141						

Table 3

Solar Radiation Corrections

Reference	Basis	Sensor	KM 50	KM 55	KM 60
Hoxit and Henry (1973	Data Derived	Mostly Arcasonde 1A	2.2	1.2	7.2
Hoxit and Henry (1973)	Theoretical	Mostly Arcasonde 1A	1.7	3.1	5.4
Schmidlin (1974)	Data Derived	Datasonde	3.0	4.5	6.5
Ezemenari (1972)	Theoretical	Arcasonde 1A	2.5 $\pm$.4		5.8 $\pm$1.3

Table 4

Effect of solar corrections on amplitude of periodic components

(Corrected amplitude minus uncorrected amplitude)

KM	76	64	59	38	28	17	9	-8
A. LONG-TERM MEAN								
40	-.2	-.3	-.6	-.6	-.6	-.4	-.5	-.4
50	-.8	-1.3	-.4	-1.2	-.8	-.7	-.8	-.7
60	-2.1	-5.6	-4.8	-4.8	-4.9	-5.8	-4.2	-3.3
B. QBO								
40	.1	-.3	0	.1	0	0	.1	-.1
50	-.2	-.1	0	-.2	0	.2	-.3	-.3
60	-.2	.1	-.3	.4	-.1	-.1	-.4	-.4
C. ANNUAL								
40	-.6	-.1	0	0	0	-.1	0	0
50	-.2	-.1	-1.2	-.4	-.2	-.1	-.3	.1
60	-2.5	-1.0	-.6	-.3	-.5	-1.5	-.7	1.3
D. SEMIANNUAL								
40	-.1	-.1	-.1	-.1	0	0	.2	.1
50	-.4	.4	.1	0	-.1	.2	.1	.2
60	.6	.4	-.1	.3	-.1	-1.9	-.7	0
E. TERANNUAL								
40	.3	.1	.1	0	0	-.1	0	.2
50	.2	.3	0	-.1	0	-.3	0	.3
60	-.3	.4	.2	-.1	.1	-1.8	.6	0

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Table 5

Mean Yearly Diurnal Wave

Amplitude (C) and phase (local time) with errors (C, hours) in parentheses.

KM/LAT		76	64	59	55	38	34	32	28	22	17	9	8	-8
30	A	1.2(5.0)	1.7(8.1)	.3(2.0)	.4(8.7)	1.1(2.3)	1.5(3.2)	1.4(1.8)	1.8(2.2)	1.4(5.0)	1.4(3.9)	4.0(6.5)	2.7(6.2)	2.2(2.8)
	Ø	0630(6.4)	0645(6.6)	1100(6.6)	0730(6.9)	1220(6.4)	1240(6.1)	1350(5.4)	1200(5.7)	1200(6.5)	1050(6.4)	1550(5.9)	1800(6.6)	1715(5.4)
40	A	.4(3.3)	2.6(5.5)	1.7(1.5)	4.1(5.7)	1.5(1.1)	2.1(1.6)	1.6(1.0)	.7(1.0)	1.4(2.5)	2.5(2.0)	4.6(3.2)	1.9(2.2)	1.5(1.1)
	Ø	1530(7.0)	2115(6.0)	1350(4.6)	1945(5.6)	1600(4.2)	1410(3.7)	1700(3.8)	1430(5.7)	1440(6.0)	1445(4.4)	1415(3.9)	1220(4.8)	1310(4.3)
50	A	1.6(1.9)	2.5(3.6)	3.9(.9)	1.9(3.6)	2.0(.7)	2.6(.7)	3.5(.5)	1.4(.4)	3.9(1.5)	3.4(1.0)	2.0(1.2)	3.1(1.1)	1.6(.4)
	Ø	1730(5.2)	1415(5.9)	1250(1.0)	1845(2.1)	1330(1.1)	1340(1.3)	1400(.5)	1730(1.6)	1400(1.3)	1745(1.3)	1750(3.1)	1620(.9)	1910(1.0)
55	A	1.9(1.8)	3.8(4.2)	5.2(.8)	3.7(3.8)	.6(.6)	1.9(1.3)	3.9(.8)	2.5(1.1)	4.9(2.5)	6.9(2.8)	5.2(2.1)	2.7(1.5)	5.5(.9)
	Ø	1000(4.8)	1620(5.2)	1320(.7)	1100(5.4)	1315(4.8)	1245(3.5)	1340(1.0)	1230(2.0)	1450(2.3)	1300(1.5)	1700(1.8)	1430(2.7)	1930(.7)
60	A	5.4(2.5)	6.8(6.6)	5.9(1.1)	3.5(4.9)	3.2(2.4)	2.1(2.1)	3.1(2.9)	2.4(1.7)	5.4(4.4)	6.2(11.8)	9.5(6.2)	10.5(4.1)	8.1(1.7)
	Ø	1230(2.1)	1220(1.5)	1330(.8)	1215(5.8)	1030(4.1)	1150(5.1)	0945(4.0)	0440(3.8)	1740(4.5)	1150(6.0)	1530(3.6)	1615(5.0)	1915(.8)

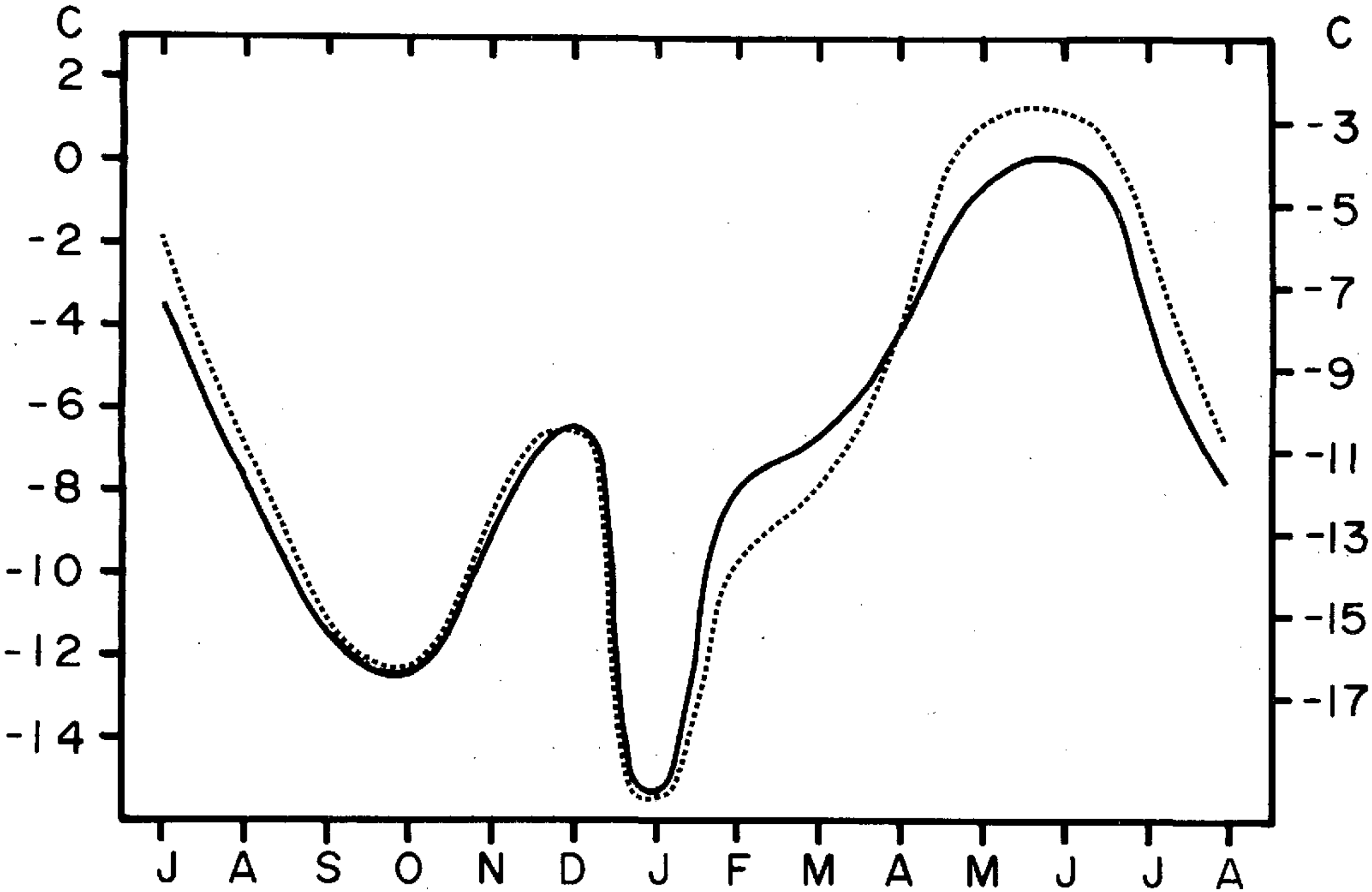

Figure 1. Consolidated monthly mean temperatures at Churchill at 60 km. Scale on left side is for temperatures not corrected for solar radiation (dotted line) and right scale is for temperatures corrected for solar radiation (solid line).

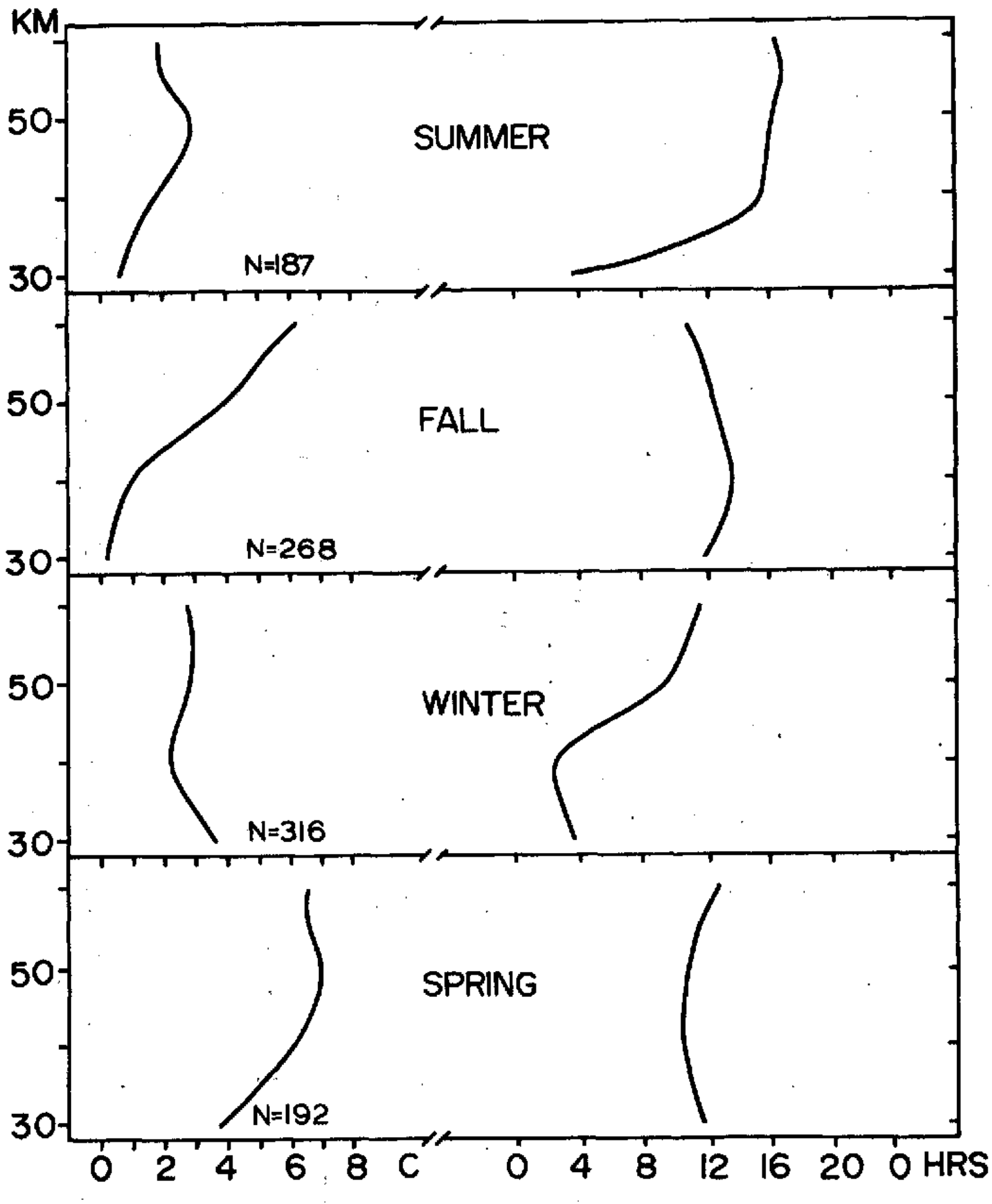

Figure 2. Amplitudes (C) and phases (local time) of the diurnal tide at Churchill by season (June, July, August is summer).

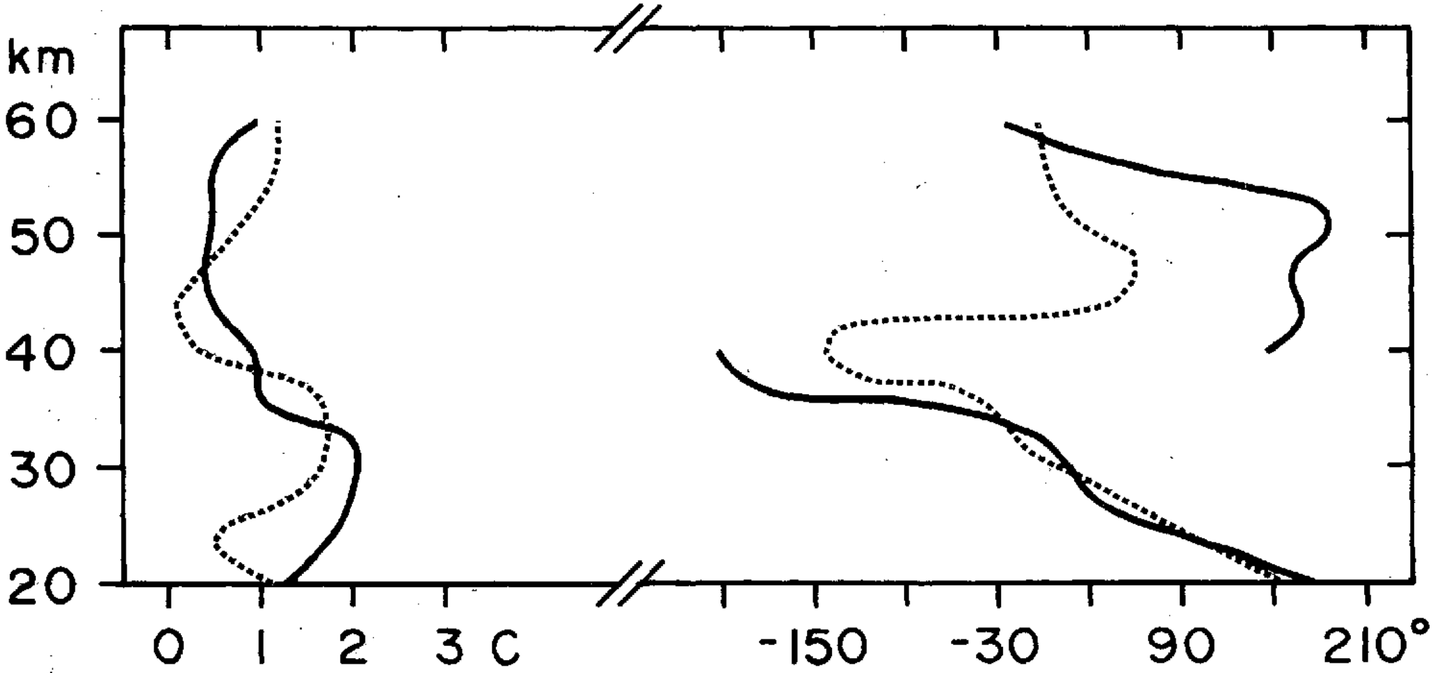

Figure 3. Amplitude (C) and phase of the QBO at Sherman (dotted line) and Kwajalein (solid line).

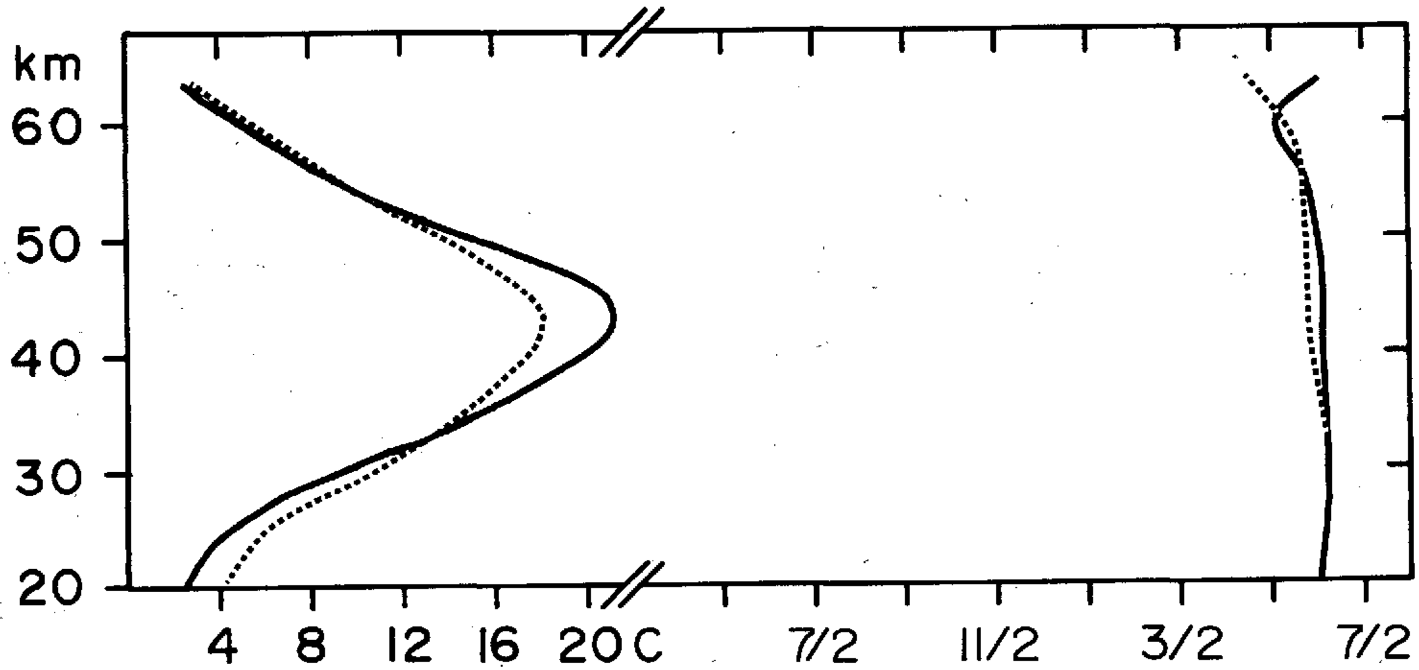

Figure 4. Amplitude (C) and phase of the annual wave at Churchill (dotted line) and Greely (solid line).

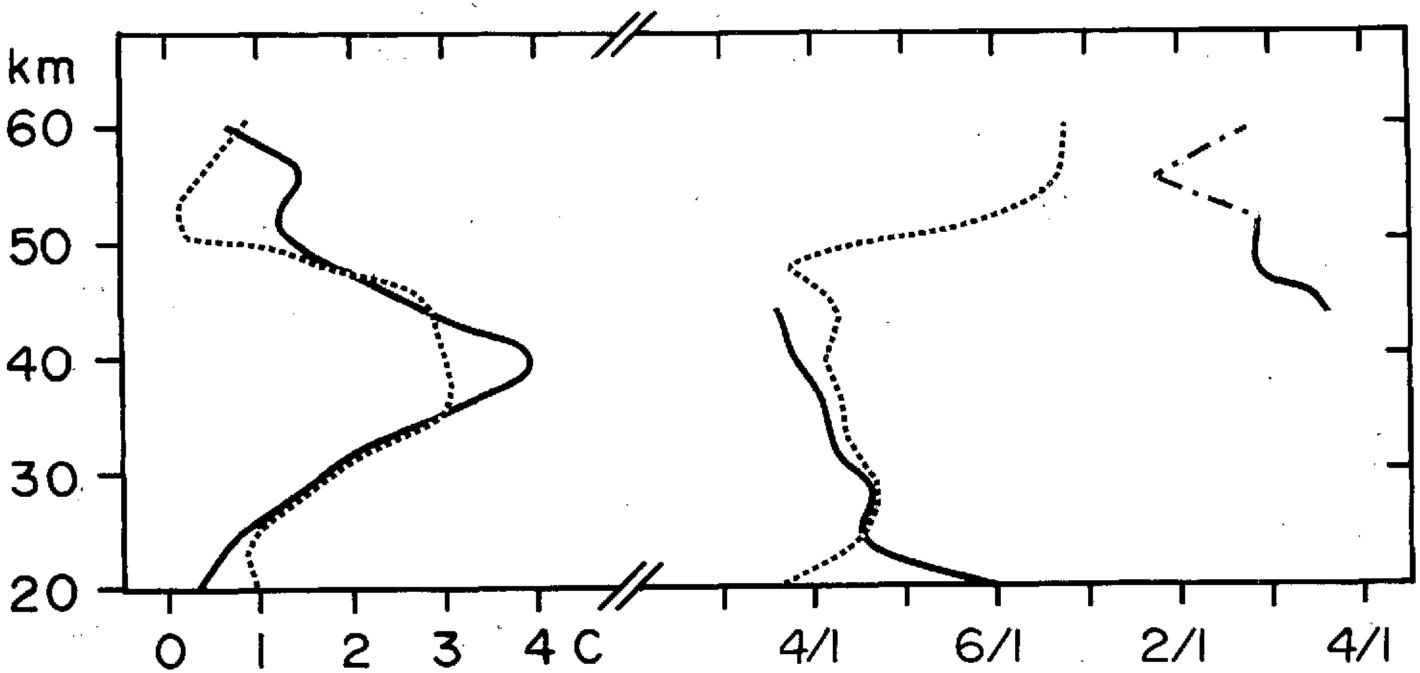

Figure 5. Amplitude (C) and phase of the semiannual wave at Sherman (dotted line) and Kwajalein (solid line).

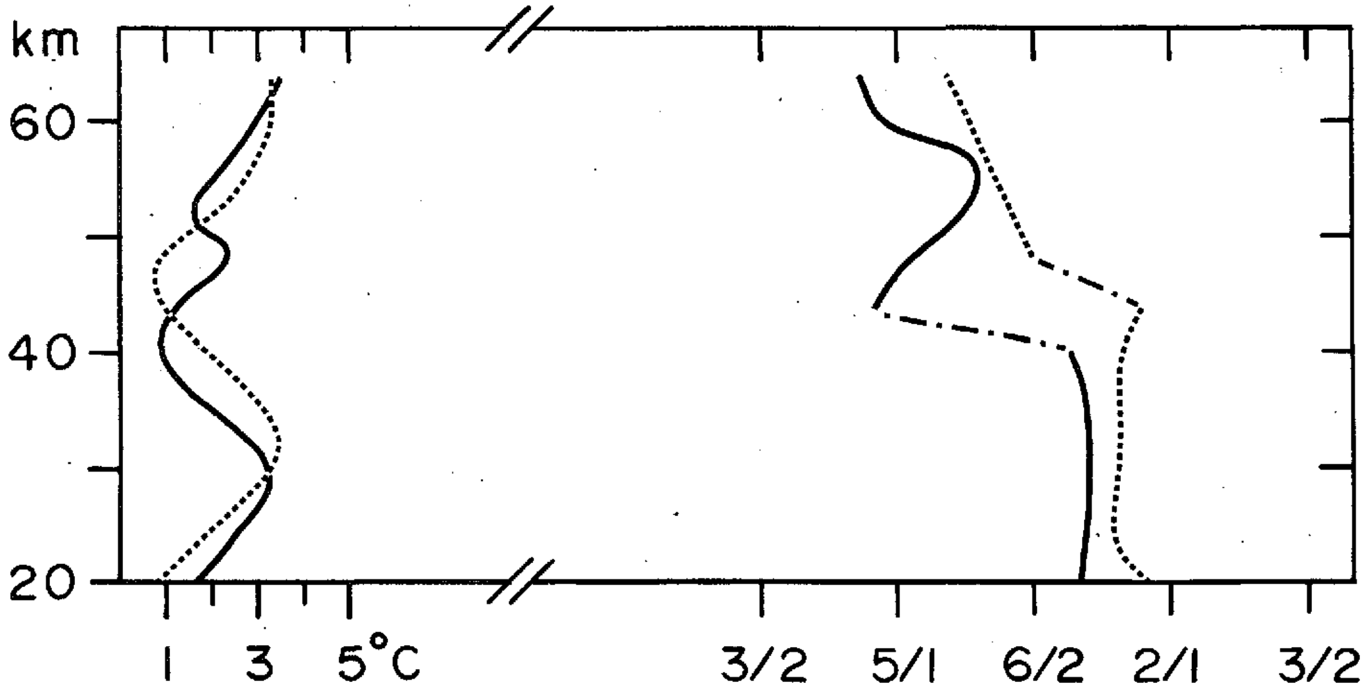

Figure 6. Amplitude (C) and phase of the semiannual wave at Churchill (solid line) and Greely (dotted line).

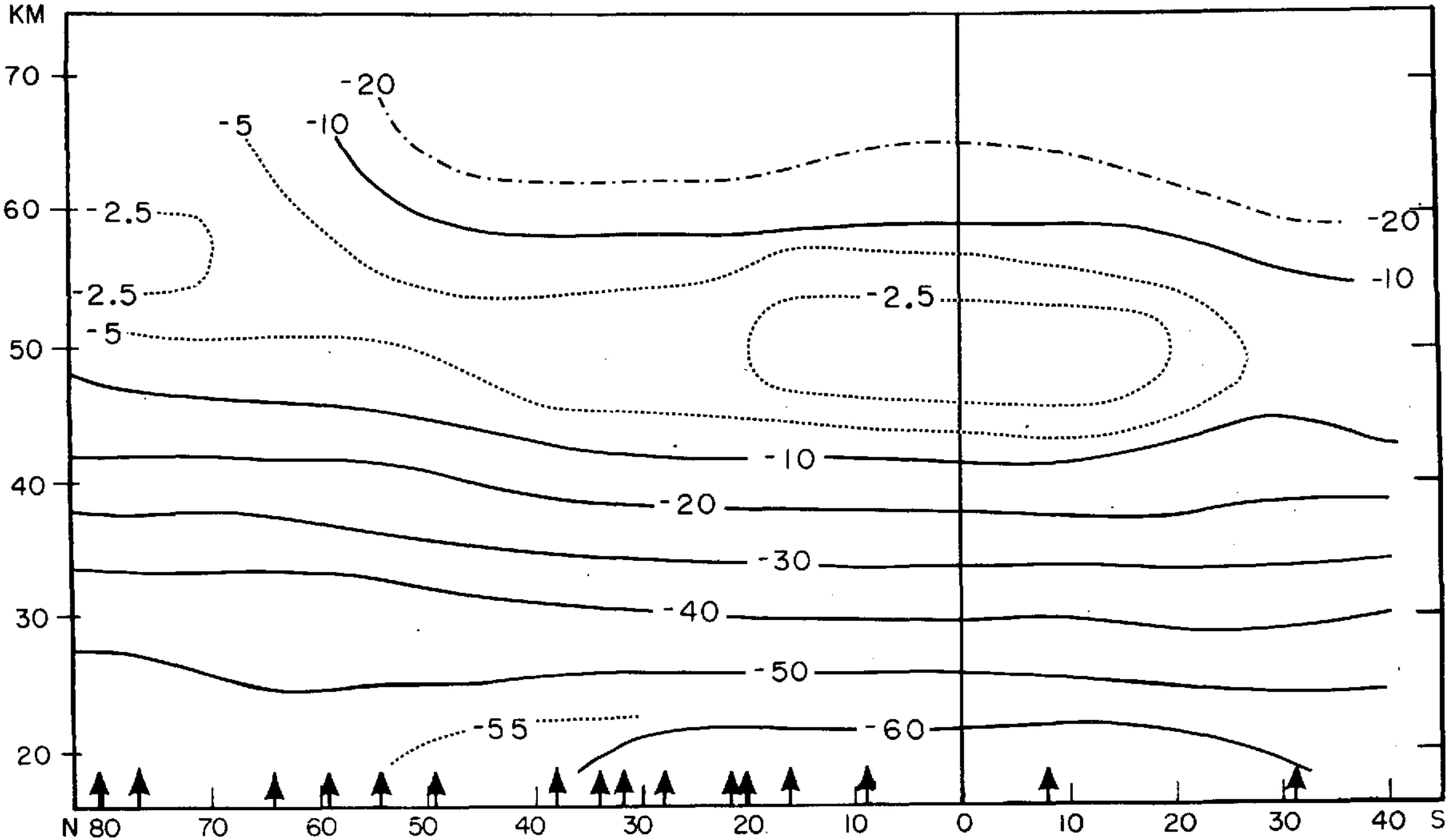

Figure 7. Amplitude (C) of twelve-year mean temperature.

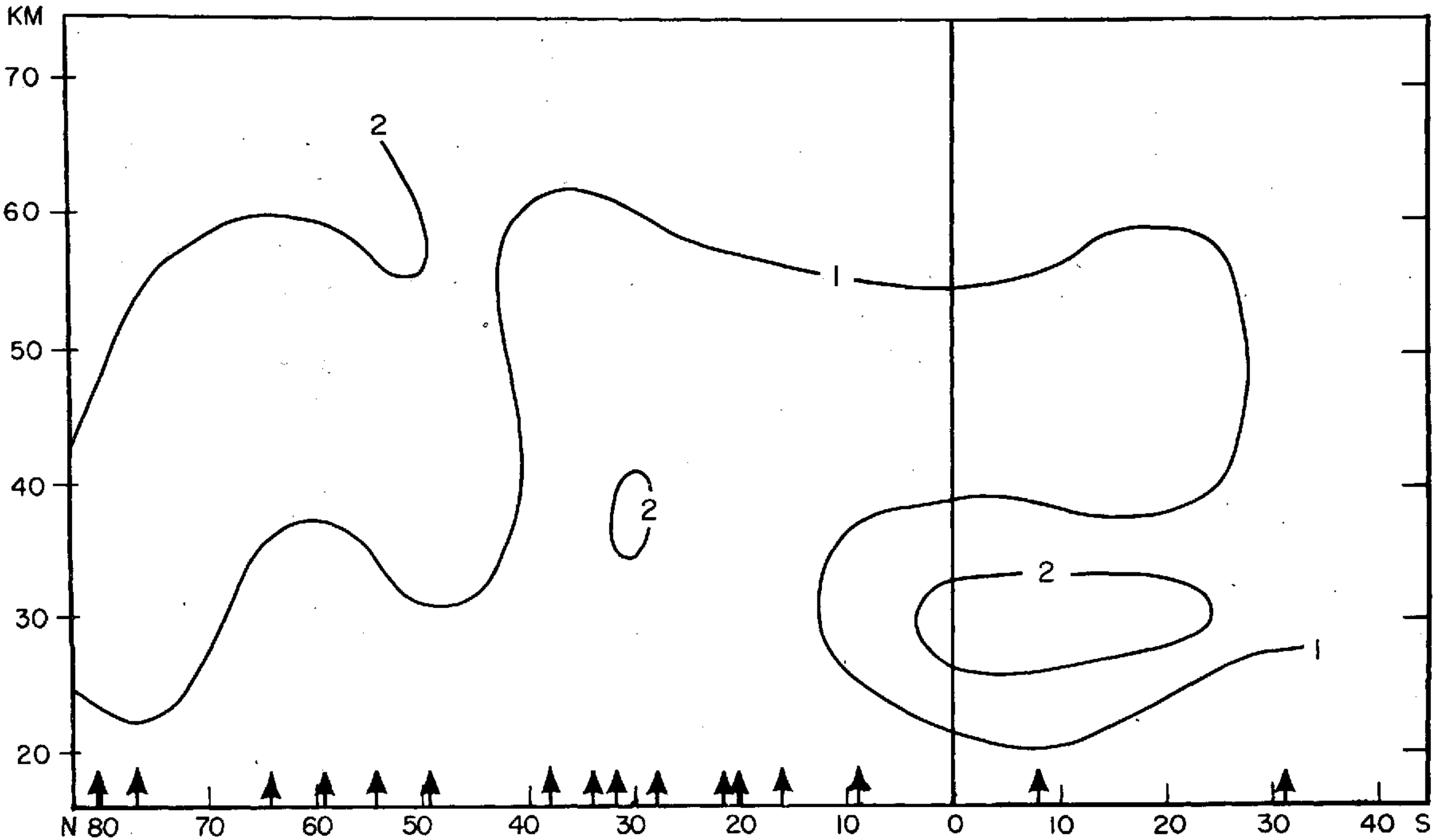

Figure 8. Amplitude (C) of quasi-biennial period in temperature.

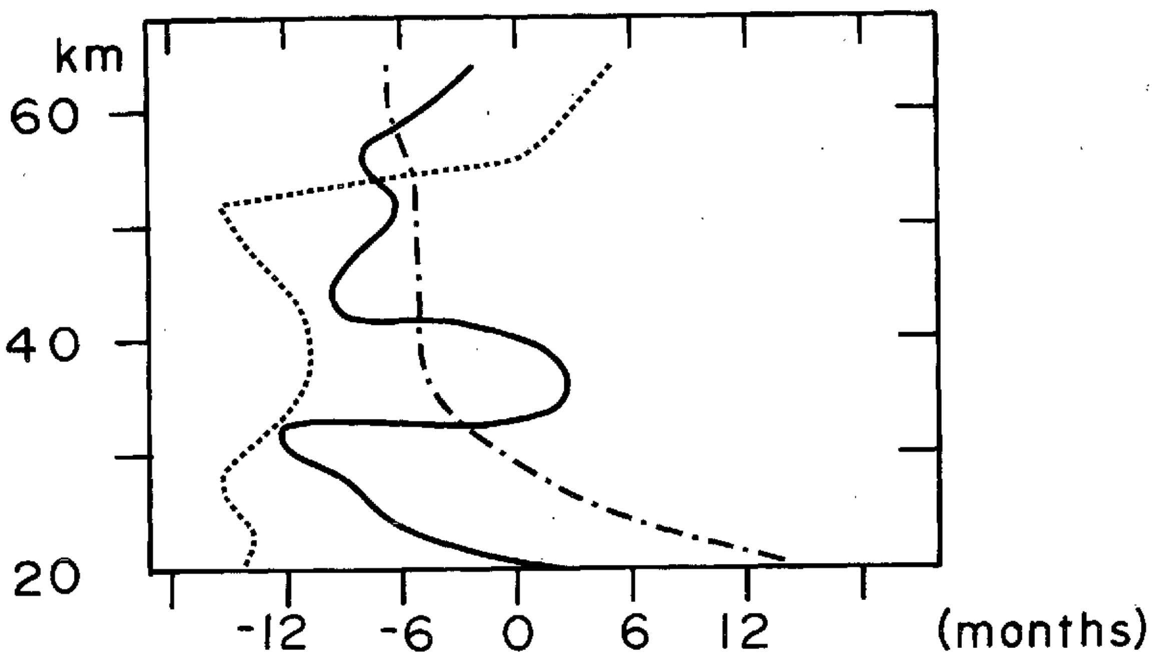

Figure 9. Relative phase progression of the QBO with altitude. Stations: Kennedy (solid), Thule (dotted), Ascension (dashed-dotted).

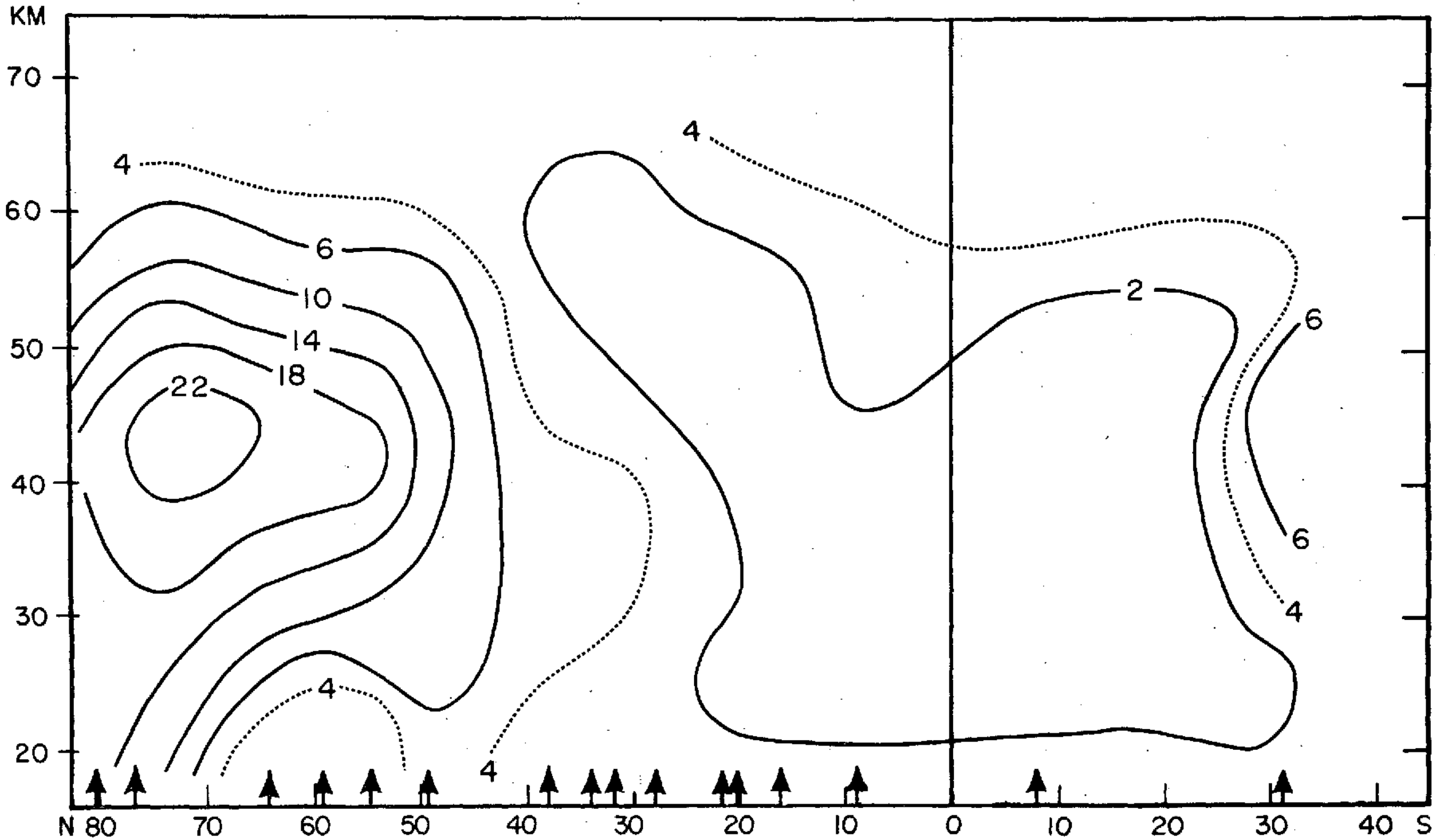

Figure 10. Amplitude (C) of annual period in temperature.

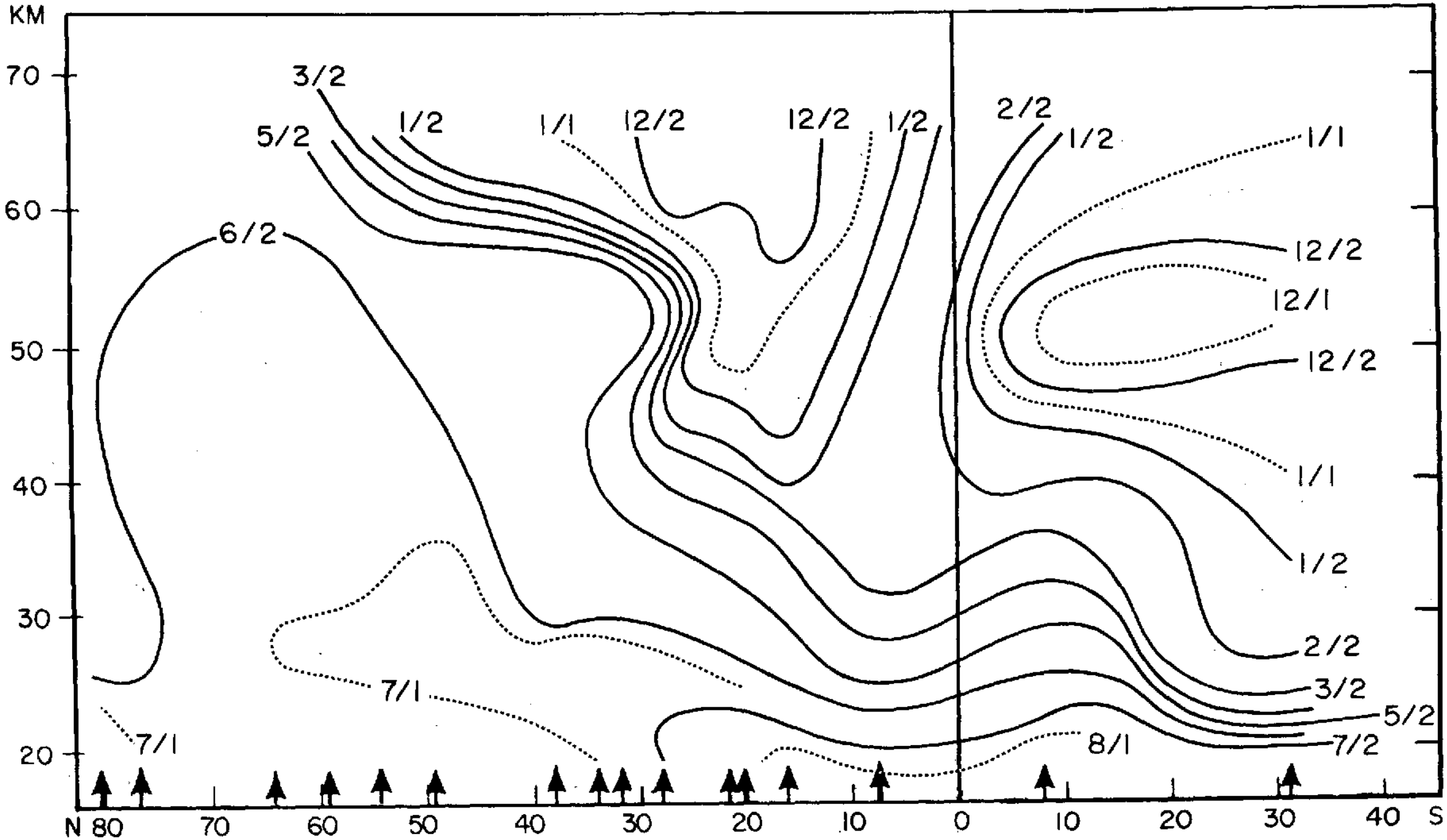

Figure 11. Phase of annual period in temperature in monthly periods (3/2 is the second half of March).

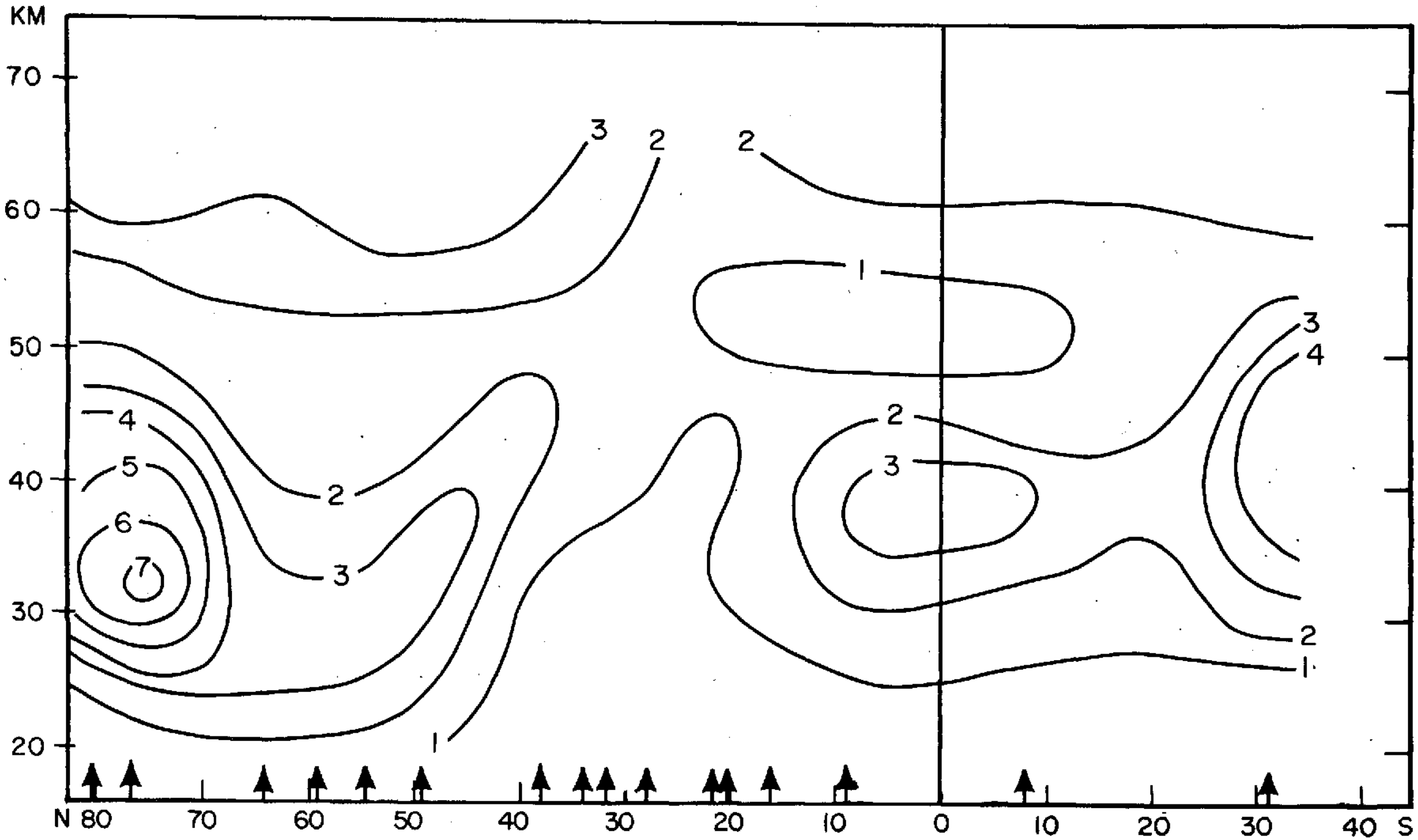

Figure 12. Amplitude (C) of semiannual period in temperature.

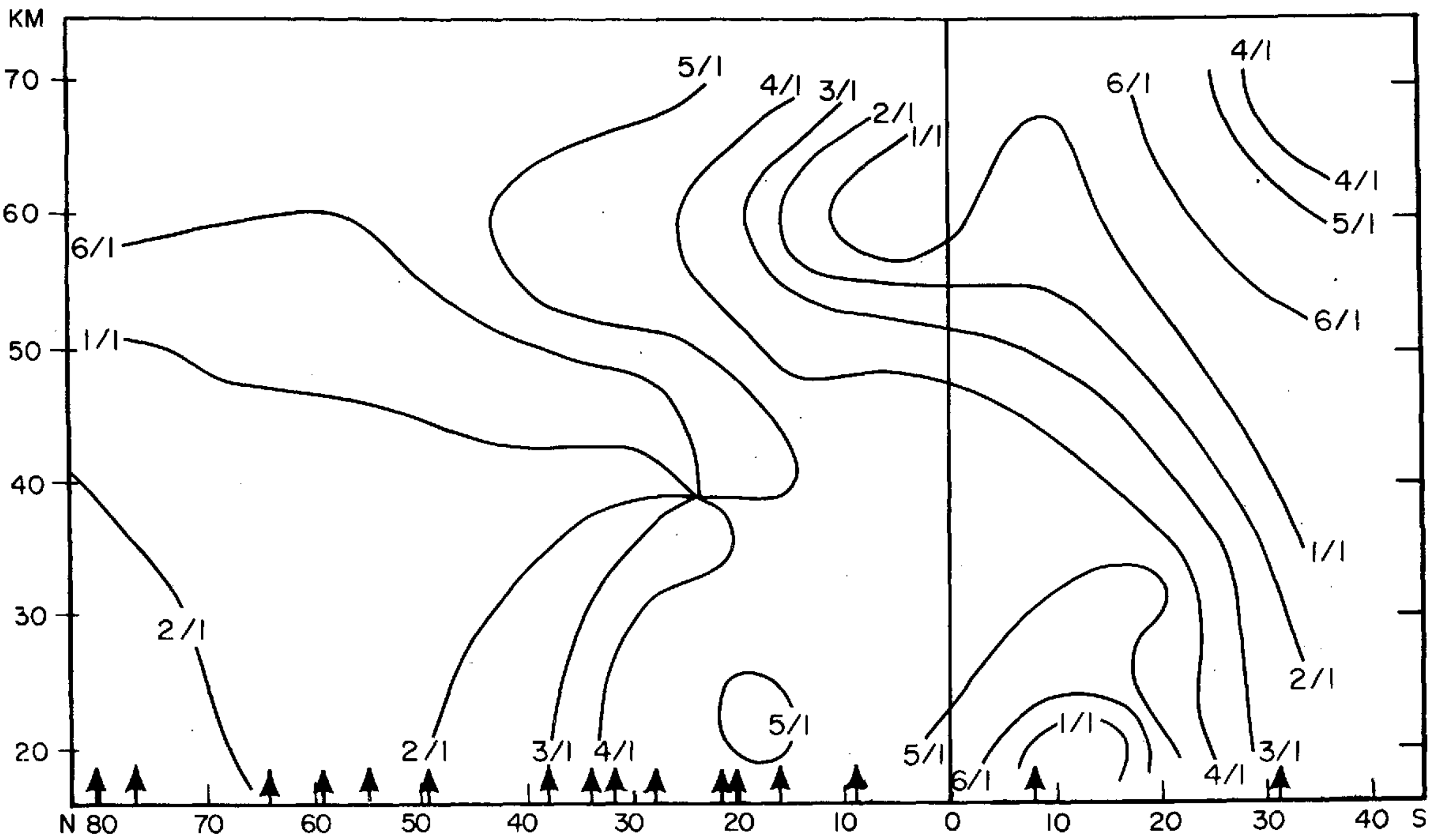

Figure 13. Phase of semiannual period in temperature in monthly periods (3/1 is the first half of March).

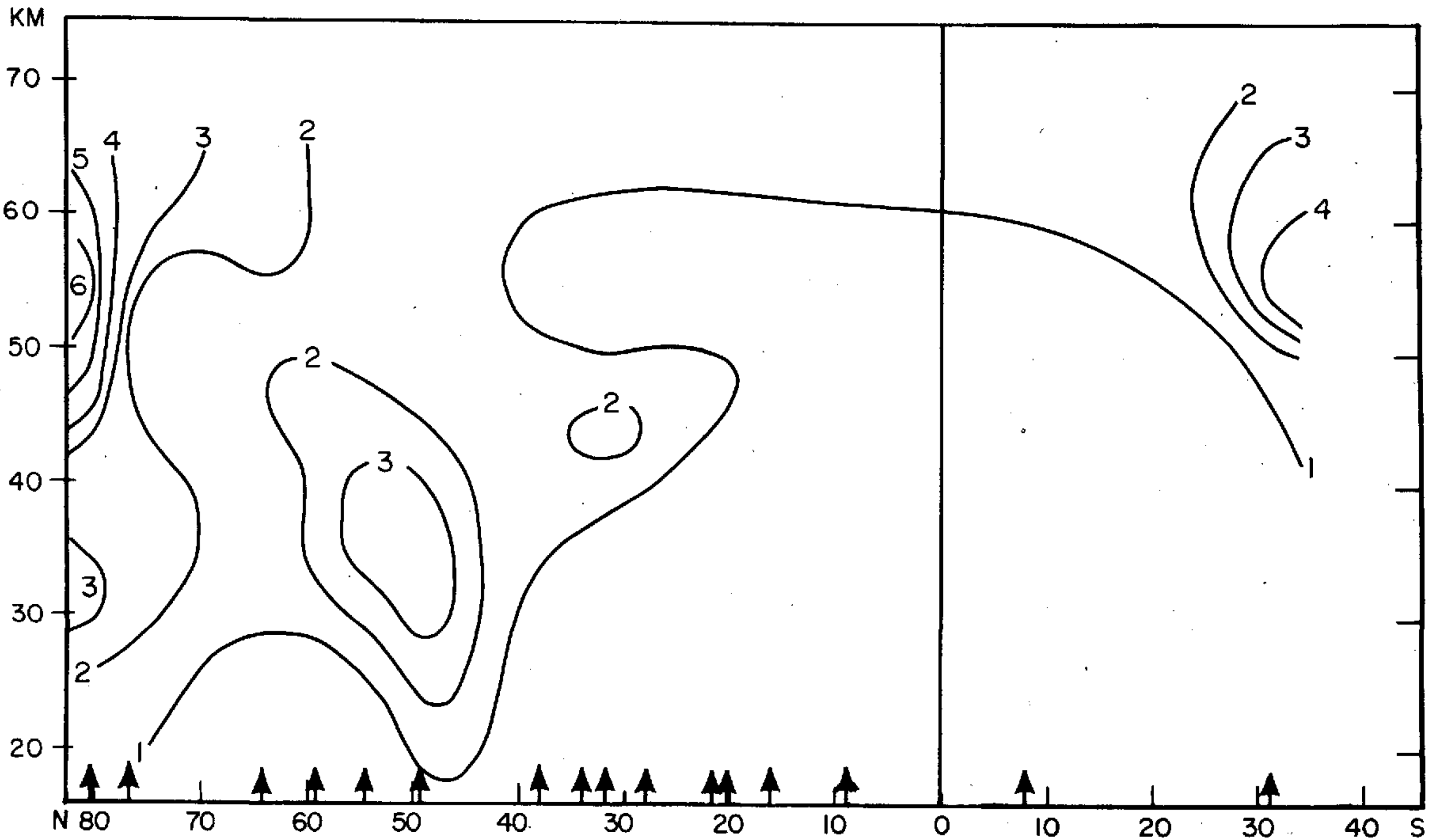

Figure 14. Amplitude (C) of terannual period in temperature.

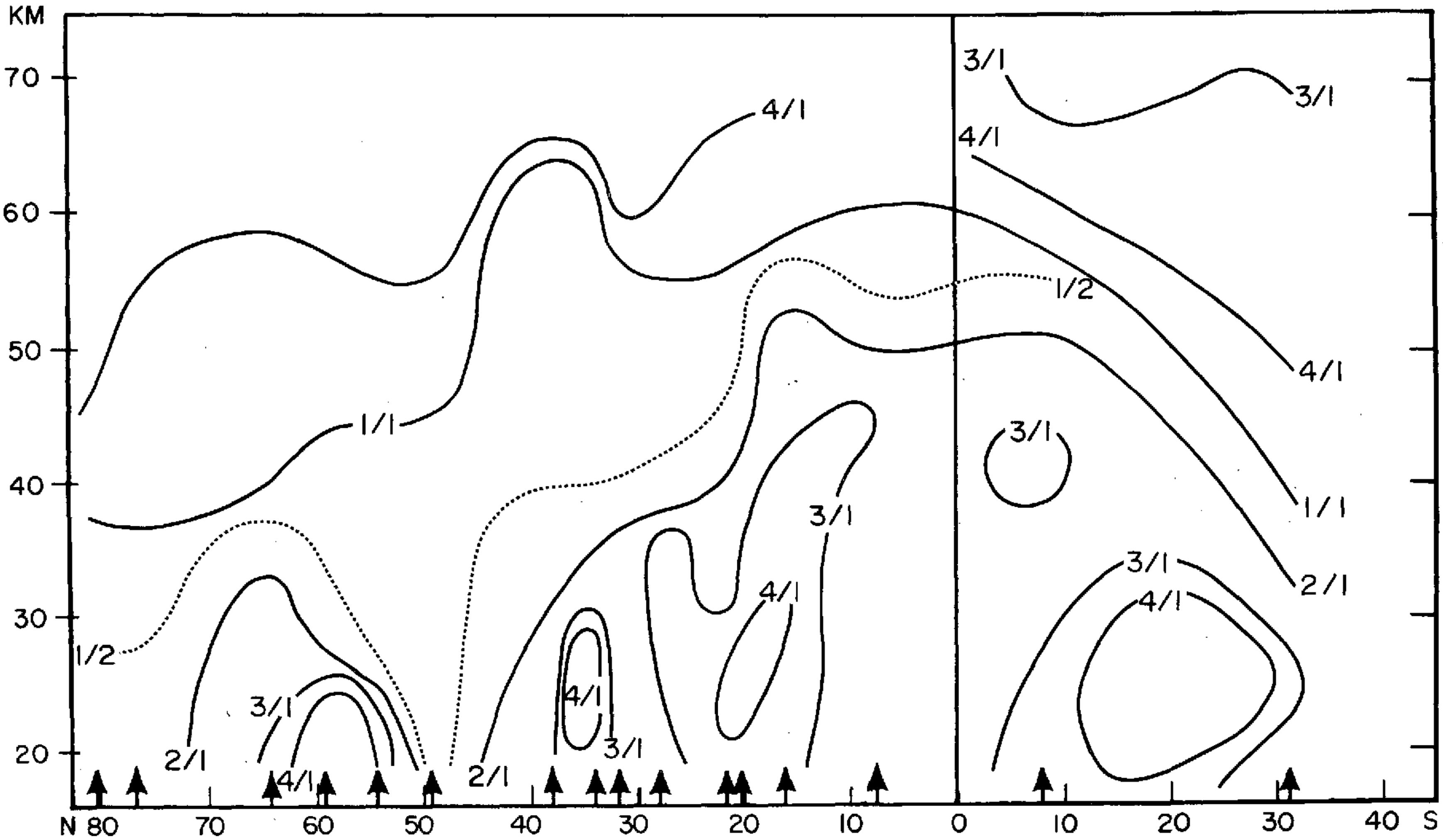

Figure 15. Phase of terannual period in temperature in monthly periods (3/1 is the first half of March).

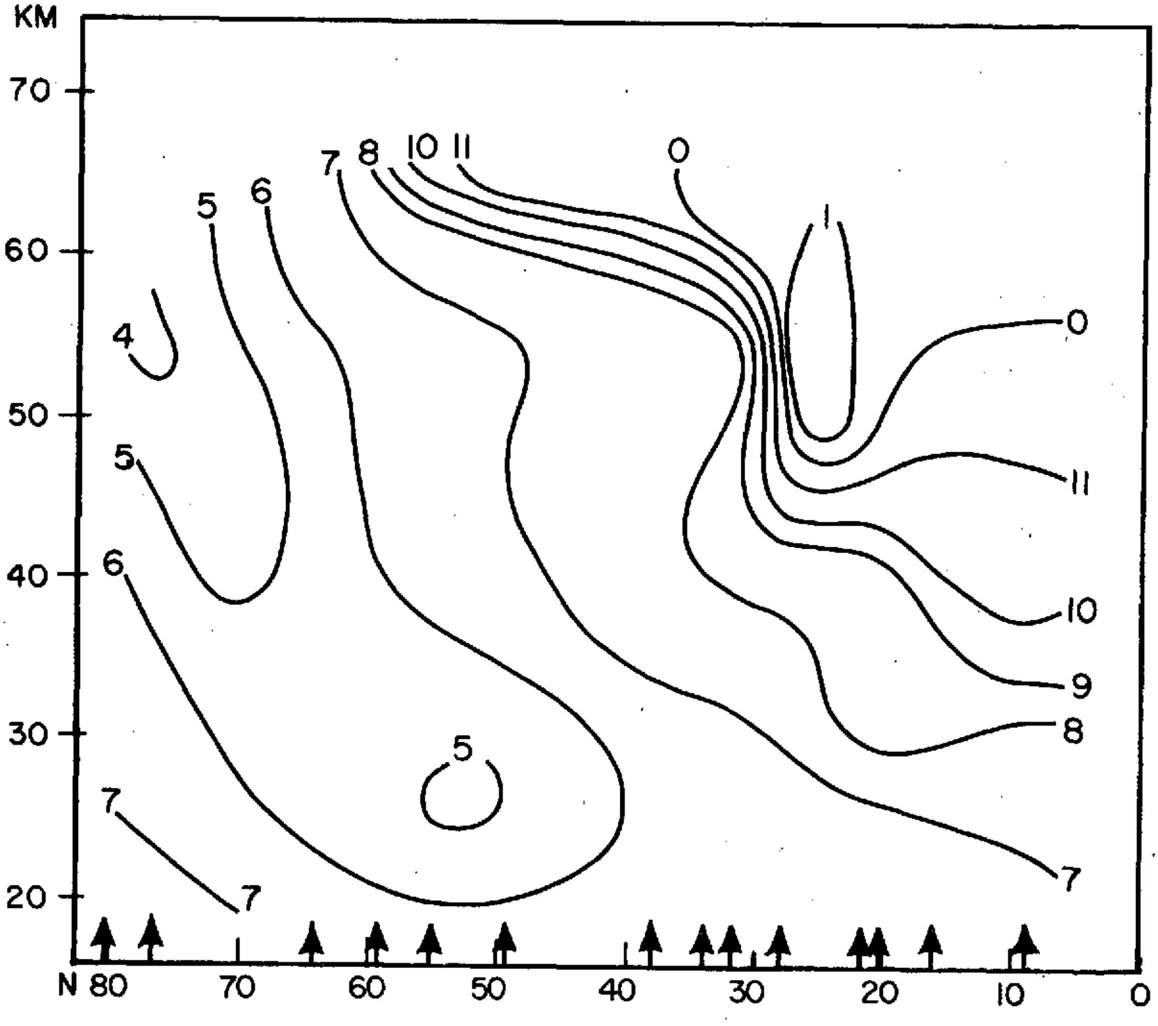

Figure 16. Lag of phase date of annual wave in zonal wind relative to annual wave in temperature in months. A value of 4 indicates wind wave is maximum 4 months later than temperature wave.

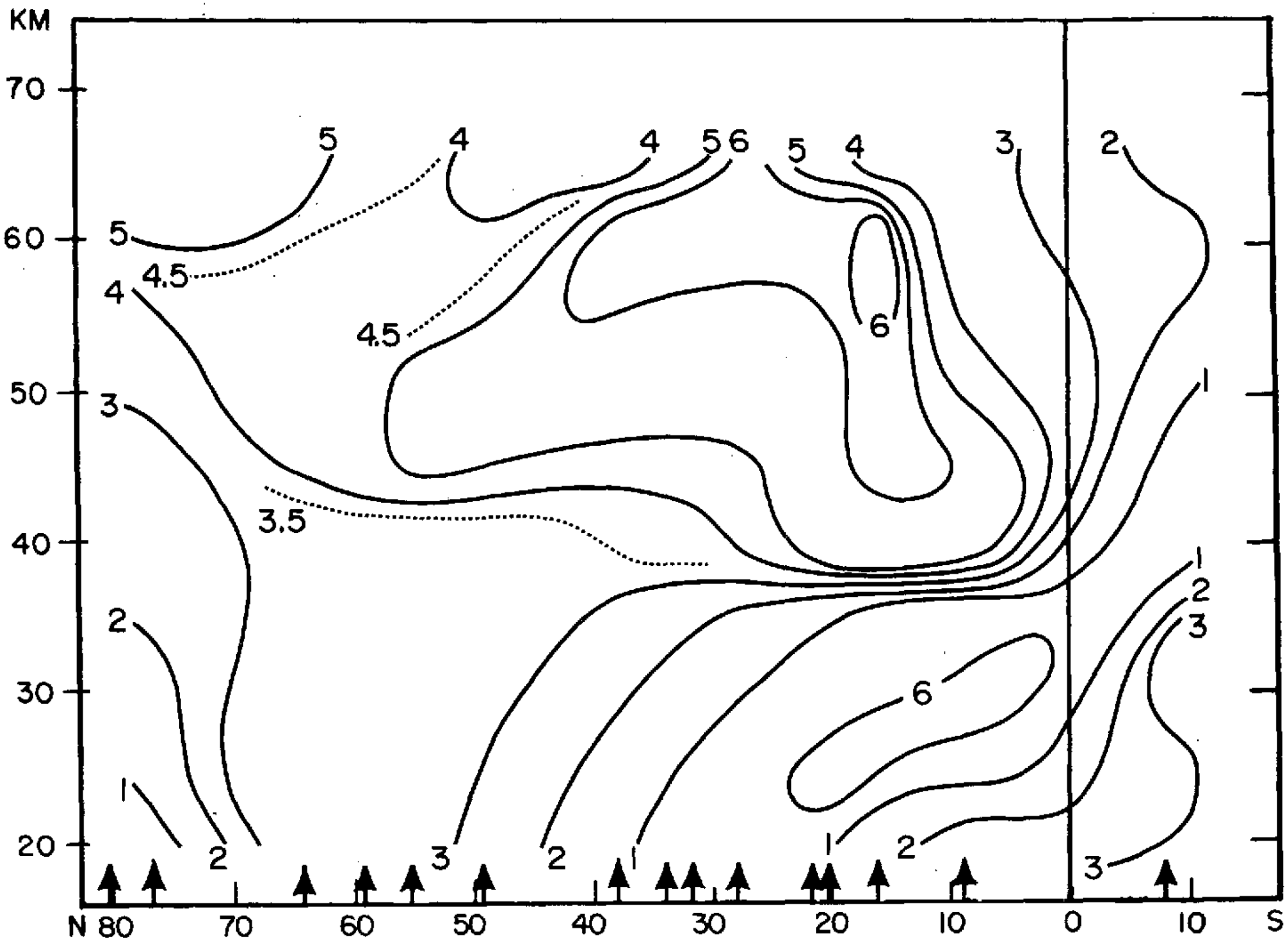

Figure 17. Same as Figure 16 for the semiannual wave.