The Half-Yearly Oscillations in the Tropics of the Southern Hemisphere

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(Manuscript received 14 June 1968, in revised form 2 November 1968)

ABSTRACT

In the tropics of the Southern Hemisphere the zonal wind in the troposphere above the 500-mb level has a well defined half-yearly oscillation with westerly maxima (easterly minima) in May and November. It is demonstrated that the oscillation is associated with second harmonics of opposite phase in the temperature above the equator and in the subtropics. The temperature oscillations are tentatively explained as being the result of an intensification of vertical motions from autumn to winter. The half-yearly temperature oscillations reverse phase near the tropopause, and again near the 50-mb level. Above this level they are thus in the same phase as in the upper troposphere. The phase reversals imply that the second harmonic of the zonal component of the thermal wind likewise changes phase twice.

A marked longitudinal asymmetry is observed with the oscillations being considerably stronger in the Eastern than in the Western Hemisphere.

1. Introduction

It has been established by Schwerdtfeger and Prohaska (1956), Schwerdtfeger (1963), and van Loon (1967a,b) that the annual march of pressures, meridional temperature gradients and winds in the troposphere in middle and high southern latitudes has subsubstantial half-yearly components. The spur to extend the search for half-yearly oscillations into the latitudes equatorward of 25–30S, where those referred to above come to an end, was provided by a remark by Wallace (1966). In the discussion of his Fig. 3.2, he traces a half-yearly oscillation in the zonal wind from the middle stratosphere, where it was found by Reed (1965) above Ascension Island, to the 70-mb level at 20S, and states, "Thus the results of the present study may be interpreted as indicating an extension of Reed's semiannual cycle to lower levels in the subtropics."

It is our aim to provide a further extension of the half-yearly oscillation into the troposphere of the southern tropical and subtropical regions.

2. Description of the half-yearly cycle in the zonal wind

In 1967 a series of climatological atlases of the Southern Hemisphere was prepared, in cooperation between NCAR and ESSA, which allows a description of the annual march of meteorological elements in all southern latitudes. In the present investigation, Volumes I (Taljaard, *et al.*, 1969) and II (van Loon *et al.*, 1969) of this series have provided most of the data.

The annual march of the zonal component of the geostrophic mean wind at 200 mb, averaged round the hemisphere, is shown in Fig. 1. Because the geostrophic wind in low latitudes is sensitive to variations of slope of the isobaric surface and owing to the difficulty in establishing the proper slope when using a grid of 5° latitude by 5° longitude, the magnitude of the wind appears to have been exaggerated. The sense of its month-to-month variation, however, seems little affected. The half-yearly component, which is the subject of this paper, causes the double peaks in the curves for 10S, 15S and 20S, and can still be discerned at 25S. The second harmonics of the mean zonal wind in the four latitudes are as follows:

$$10S\colon u=4.3 \text{ m sec}^{-1} \sin(2x+235°)$$
$$15S\colon u=4.7 \text{ m sec}^{-1} \sin(2x+226°)$$
$$20S\colon u=4.0 \text{ m sec}^{-1} \sin(2x+217°)$$
$$25S\colon u=2.2 \text{ m sec}^{-1} \sin(2x+197°)$$

The phase angles determine the value of x at which the extremes of u occur, x being defined for a series of 12 months by $x=iz$, where $z=360°/12$, and $i=0,1,2,\ldots$; 16 January is defined as $x=0$.

The functions reach maxima, i.e., maximum westerlies (minimum easterlies), in May and November. At 5S, which is not shown, the first maximum falls on 7 May; at 10S on 5 May; at 20S on 14 May; and at 25S on 24 May. The amplitude, phase and percentage of the total variance of the first two harmonics of the zonal wind are shown in Fig. 2. The peak of the amplitude of the second harmonic is near 15S, but the percentage of the total variance which is accounted for by the harmonic increases equatorward to 75% at 5S (not shown). At the 500-mb level (Fig. 3) the amplitude of the second harmonic is smaller, its share of the total variance considerably less, and its phase angle less firmly defined, the date of the first maximum moving from 12 May at 20S to 24 January at 5S.

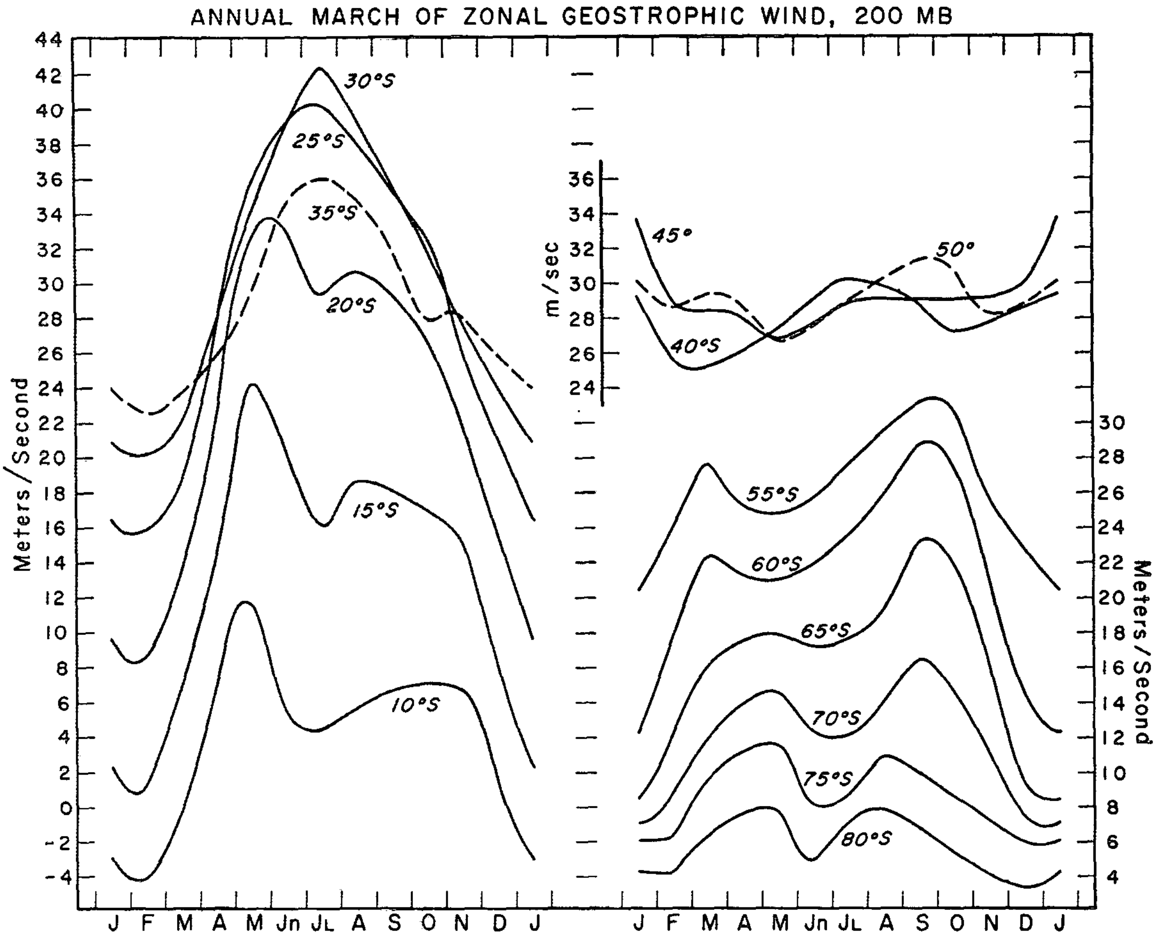

FIG. 1. Annual march of the zonal geostrophic wind (m sec^{-1}) at 200 mb averaged around the hemisphere.

A harmonic analysis of the zonal average, however, gives only limited information since there may be longitudinal differences in the oscillation. An areal distribution of the amplitude, percentage of the total variance, and phase angle at 200 mb is therefore shown in Figs. 4–6. It is immediately apparent that the amplitude (Fig. 4) is largest over the eastern half of the hemisphere with a well defined axis along 15S. In the western half, if there is such an axis of highest values, it must lie equatorward of 10S. The highest values on the map in the western half are less than half of those in the east. In the eastern half the oscillation's share of the total variance (Fig. 5) exceeds 50%, while in the west most values fall between 10 and 20%. The phase angle, on the other hand, is rather uniform in all longitudes on the equatorial side of 25S (Fig. 6) which suggests a common origin, but one of different intensity in either half of the hemisphere.

An examination of the second harmonic in the annual march of the 200-mb average height throws further light on the distribution of the oscillation in the zonal wind. The amplitude shown in Fig. 7 is at a maximum near the equator over the eastern half, but not over most of the western half of the hemisphere. A minimum encircles the hemisphere in the tropics—well defined over the eastern half, where it lies close to 15S, but rather diffuse over the western half and with its axis close to the equator in most of the Pacific Ocean. The next feature important to the oscillation in the wind is the circumpolar maximum amplitude of the height in middle latitudes.

The phase angle of the second harmonic of the 200-mb height (Fig. 8) reverses where the amplitude is at a minimum in the tropics. In the eastern half this phase change is abrupt, but it is not well marked over much of the western half.

Although the amplitude of the second harmonic of the 200-mb height is not large on either side of the tropical minimum over the eastern half of the hemisphere, the fact that the phase change is very marked creates a comparatively large second harmonic in the meridional height difference, and thus in the zonal wind. And although the harmonic in the height does not account for a striking amount of the total variance (see inset on Fig. 7), the first harmonic in the 200-mb height does not vary much in amplitude and phase angle in

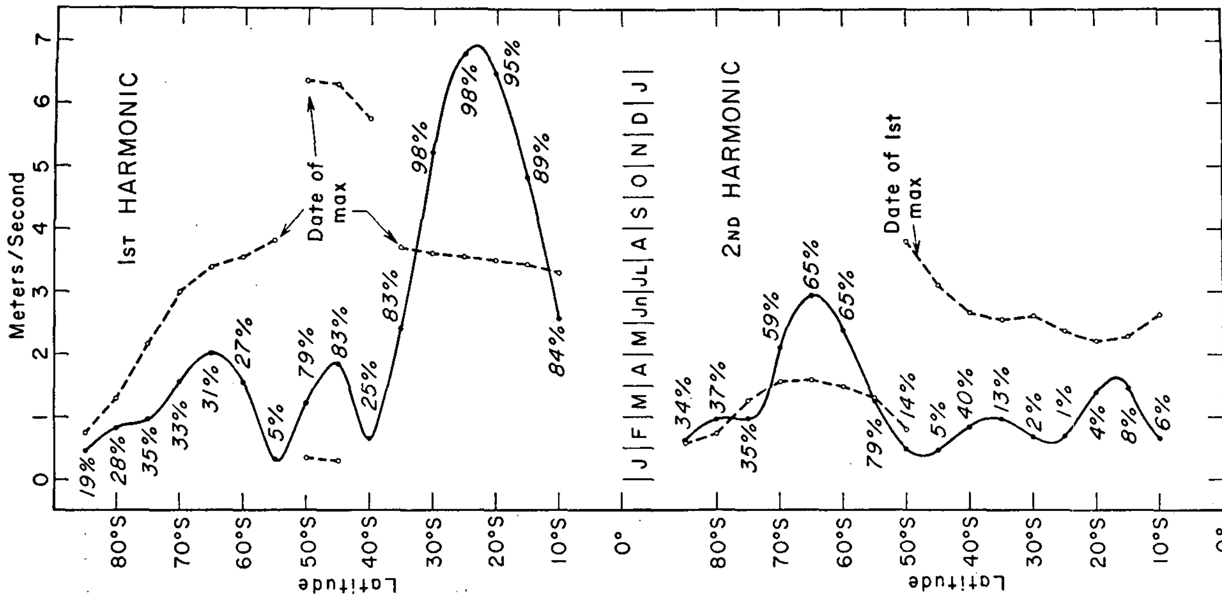

FIG. 3. Same as Fig. 2 except for 500 mb.

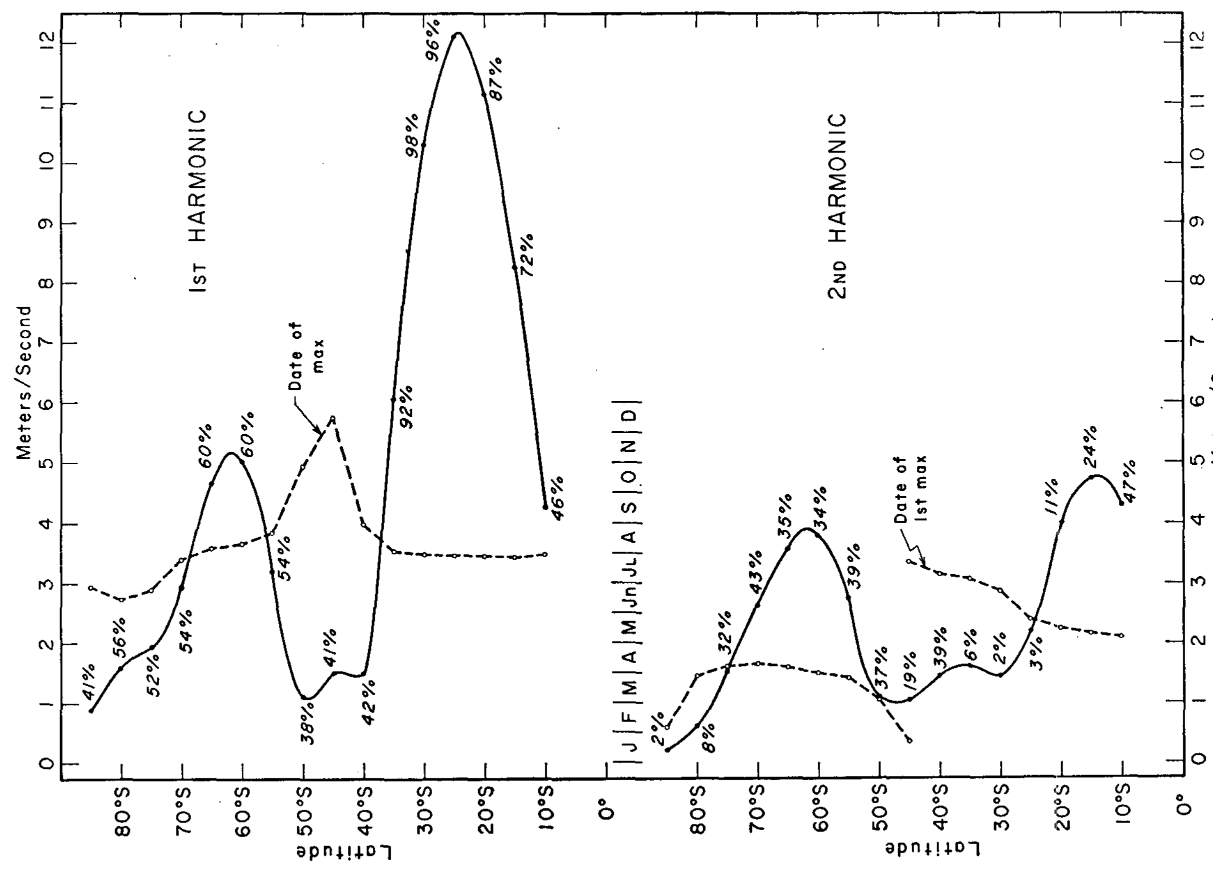

FIG. 2. Amplitude (m sec^{-1}), date of maxima, and percentage of the total variance of the first and second harmonics of the zonally averaged geostrophic wind at 200 mb.

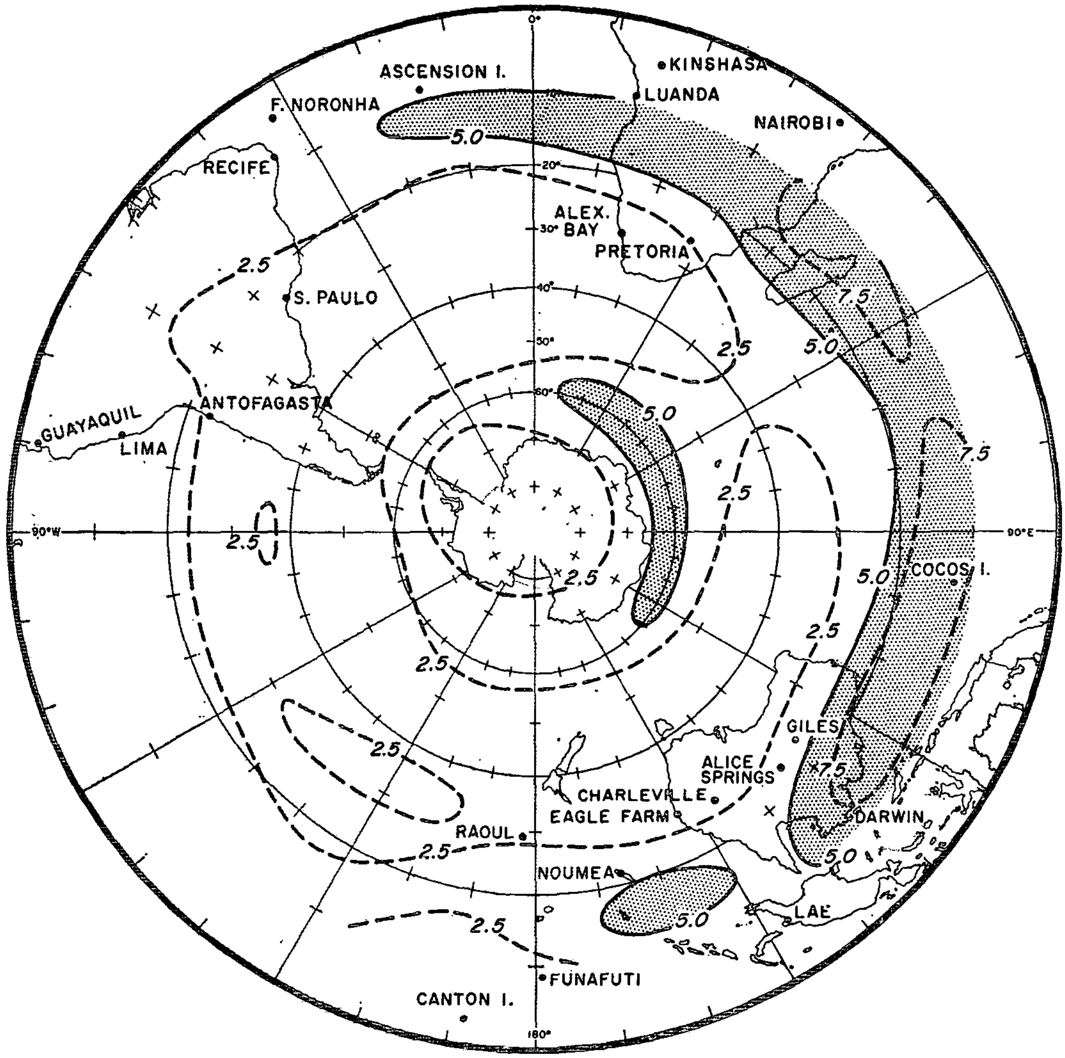

FIG. 4. Amplitude (m sec^{-1}) of the second harmonic of the zonal geostrophic wind at 200 mb. Note that the amplitude in the tropics is exaggerated owing to the use of the geostrophic relationship.

low latitudes (Fig. 9), thus tending to cancel or diminish in the meridional height difference across these latitudes. This leaves the second harmonic a large share of the total variance in the height gradients, and therefore also in the zonal wind. In the region between 20 and 40S the opposite is the case. Here the amplitude of the first harmonic in the height increases fourfold with latitude, but the second harmonic remains in nearly the same phase across the latitude belt. As a consequence, the second harmonic in the height gradient becomes of small significance for the wind field (Fig. 5).

The variations of the observed wind

Thus far we have dealt only with zonal winds computed from height gradients. Because the aerological network is meager in the southern tropics, it is desirable to corroborate the computed winds by reference to observed winds. Fig. 10 contains the zonal component of the observed wind at and near the 200-mb level at 8 stations in the tropics (see Fig. 4 for locations). At Lima, Recife, Ascension Island and Funafuti, the data were smoothed by applying the formula

$$b_s = (a+2b+c)/4,$$

to the successive monthly means a, b and c. This does not materially affect the shape of the curves, but makes it easier to identify the half-yearly oscillation. The latter is unmistakably visible in the curves, though obviously not of equal proportion everywhere. Even the large annual range at Lima does not obscure the half-yearly variation. Recife at 200 mb is an exception, but the variation becomes evident there at 100 mb. It

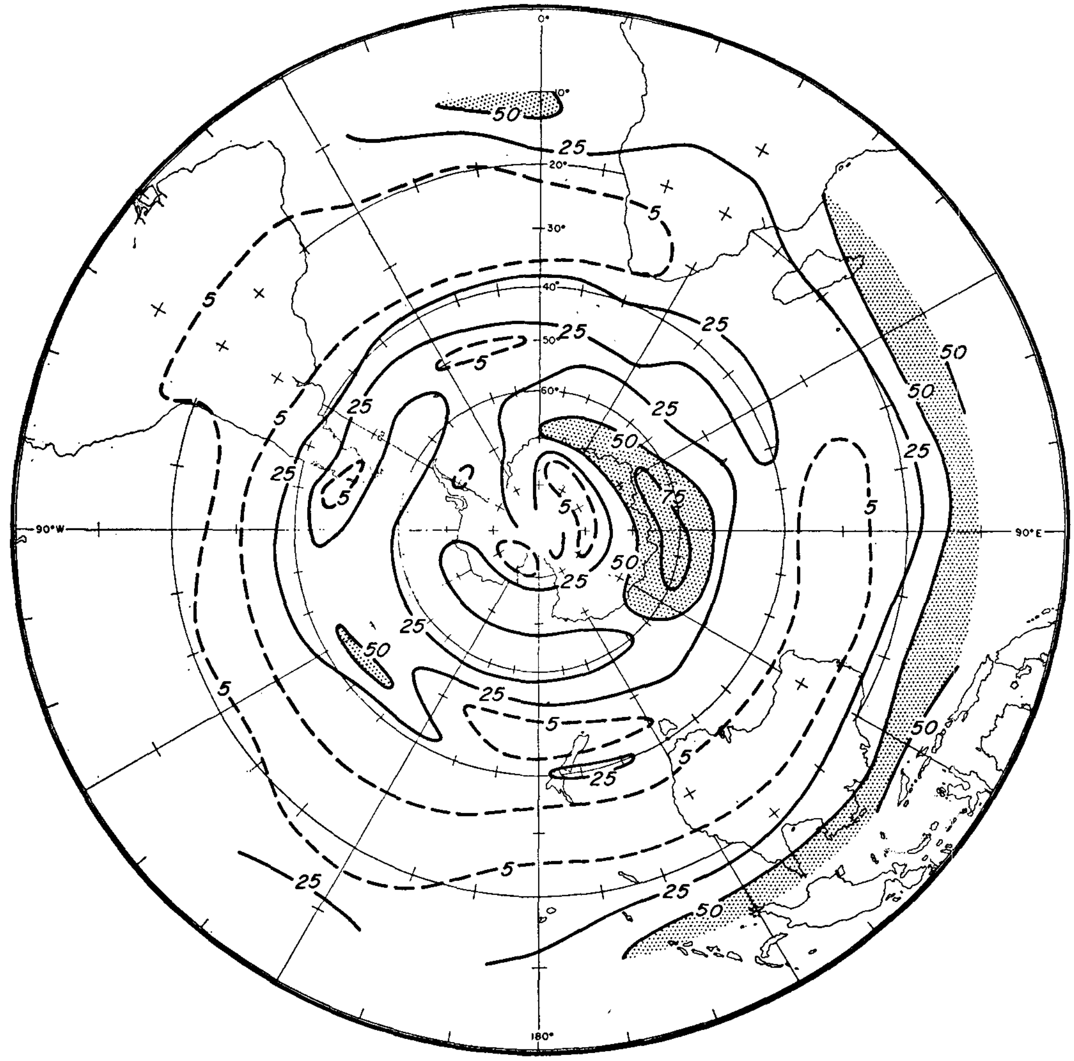

FIG. 5. Percentage of the total variance accounted for by the second harmonic of the zonal geostrophic wind at 200 mb.

is also clear that the phase of the half-yearly cycle must be nearly the same in all 8 stations with maximum westerlies or minimum easterlies in May and November. Furthermore, the regional differences found in Figs. 4 and 5 are reflected in the annual march of the observed wind; the semiannual oscillation is most pronounced at Lae, Darwin, Cocos Island and Luanda.

Figs. 4, 5, 7 and 10 indicate that Cocos Island is in a position where the half-yearly variation is intense. It is thus of interest to examine the annual march of the wind at such a station in more detail. Fig. 11 is a time section of the mean zonal and meridional components of its observed wind for the period June 1957–May 1961, based on data published by Maher and McRae (1964). The cycle is apparent in the alternation of westerly and easterly zonal components in the upper troposphere, and it is noteworthy that the easterly maximum in winter coincides with a strengthening of the northerly (poleward) component of the meridional wind aloft, and with a comparatively strong southerly component near the surface. The vertical distribution of the second harmonic of the zonal wind is given in Fig. 12. The amplitude is small below 20,000 ft, where the harmonic also accounts for little of the total variance. Above 25,000 ft the second harmonic explains more than 50% of the total variance; at its highest the percentage rises to just above 90% at 45,000 ft. The phase distribution is such that the maxima of the harmonic are reached in January and July below 20,000 ft. Above this level the phase is constant with maxima in May and November; the variation with height comprises only the 5 days between 9–14 May and 9–14 November.

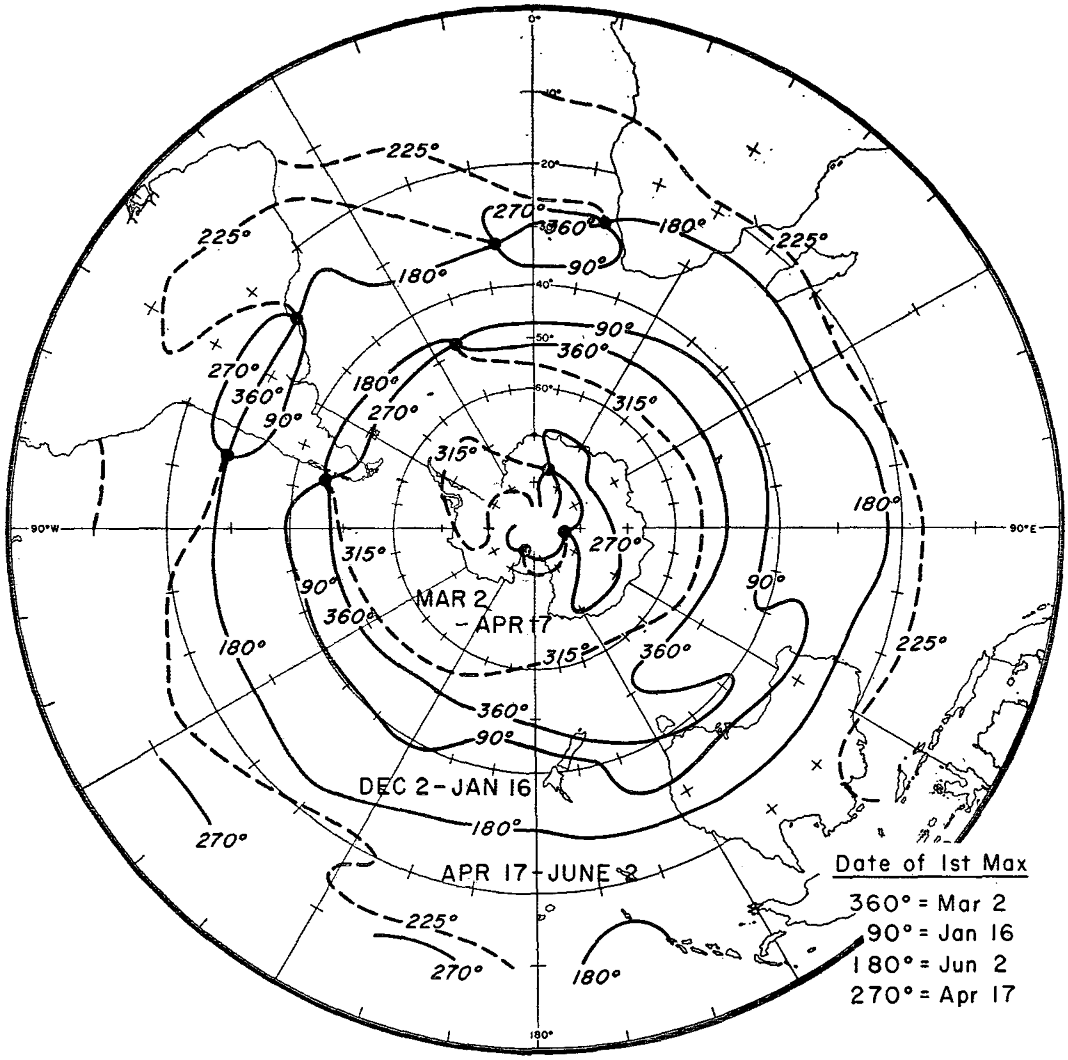

Fig. 6. Phase angle of the second harmonic of the zonal geostrophic wind at 200 mb.

3. Description of the annual march of temperature

In the hemispheric average (Fig. 2) the half-yearly oscillation in the zonal wind reaches its highest amplitude in the latitudes between 10 and 15S. It is therefore natural to look for an immediate cause of the oscillation in the temperature contrast across these latitudes; that is, to search for the second harmonic in the temperature gradient which is indicated by the thermal wind relationship. Fig. 13a shows the zonally averaged, annual march of the 300-mb temperature at 25S and on the equator, and of the temperature contrast between the two parallels. It is clear that the contrast has the required half-yearly oscillation, and that it is produced by half-yearly oscillations of opposite phase in the temperature curves for the two parallels. Fig. 13b shows the same three curves for two stations situated on the same meridian in the Australian region. The oscillation in the temperature contrast is more marked than in the zonal mean, and is strongly influenced by the dominant second harmonic in the higher-latitude station. Over Africa (Fig. 13c) the half-yearly oscillation in the temperature contrast at the 300-mb level is apparent too, but shows up more clearly at 200 mb (Fig. 13d) where the two temperature curves have only small annual variations.

Further information can be gained from Table 1, which shows the amplitude, phase angle, and percentage of the total variance of the second harmonic of the temperatures and temperature contrasts at five levels. Here two stations in South America have been added to provide information from a region where the half-yearly oscillation in the wind is less conspicuous. An examination of the percentage of the total variance given in the table reveals that the oscillation in the

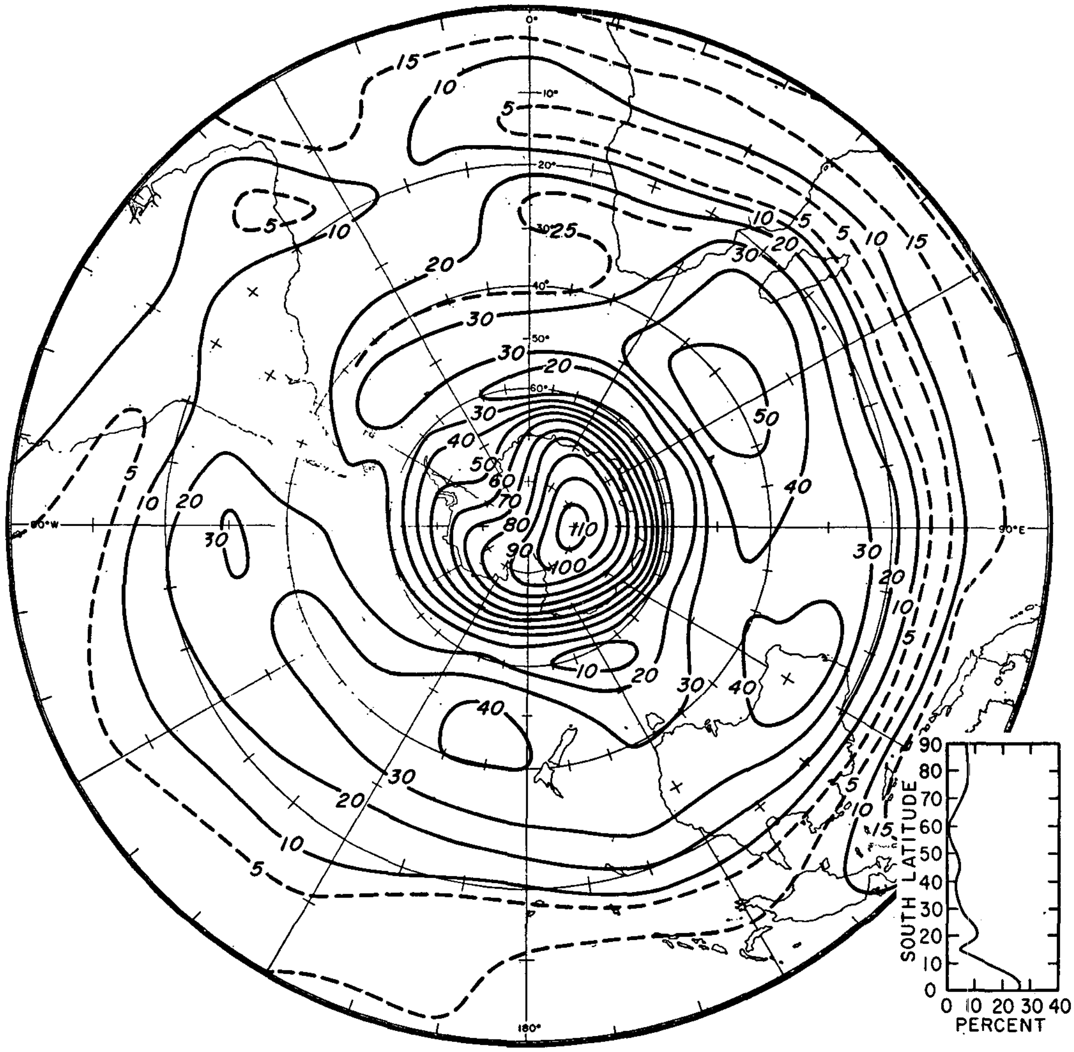

FIG. 7. Amplitude (m) of the second harmonic of the height of the 200-mb surface. Inset shows a meridional profile of the zonally averaged percentage of the total variance.

temperature contrast gains significance only above the 500-mb level and that, as the wind showed, it is stronger in the Eastern than in the Western Hemisphere. At the eastern stations, the amplitude is highest at 300 mb, in South America at 200 mb. The phase angles lie between 219° (Singapore-Giles) and 242° (Nairobi-Pretoria), i.e., with the first maximum between 2 and 13 May.

For comparison, the second harmonic of the temperature contrast between three pairs of stations in the Northern Hemisphere is listed in Table 2. Although the amplitudes are of the same magnitude as in the Southern Hemisphere at 300 and 200 mb, the percentages of the total variance indicate that the half-yearly cycle is overshadowed by the annual cycle. The phase angles show a slightly wider scattering with the day of the first maximum occurring between 25 April (221°) and 12 May (275°).

A year-to-year variation of the annual march of temperature at 300 mb can be seen in Fig. 14. Alice Springs in Australia was selected partly because it is in a region where the half-yearly oscillation is strong enough to be visible in the temperature, partly because the station provides a nearly unbroken record for 15 years. It is evident that the characteristic of the annual march which creates the second harmonic is the general, unexpected trend towards a warming from autumn to winter. If the temperature trend at this level were controlled mainly by radiation, the annual minimum would be in winter. Instead, the monthly mean winter temperatures frequently reach the summer level. The amplitude, phase angle, and percentage of the total variance of the second harmonic for each of the 15 years are shown in Table 3. The phase is rather consistent, the first maximum of the harmonic falling between 24

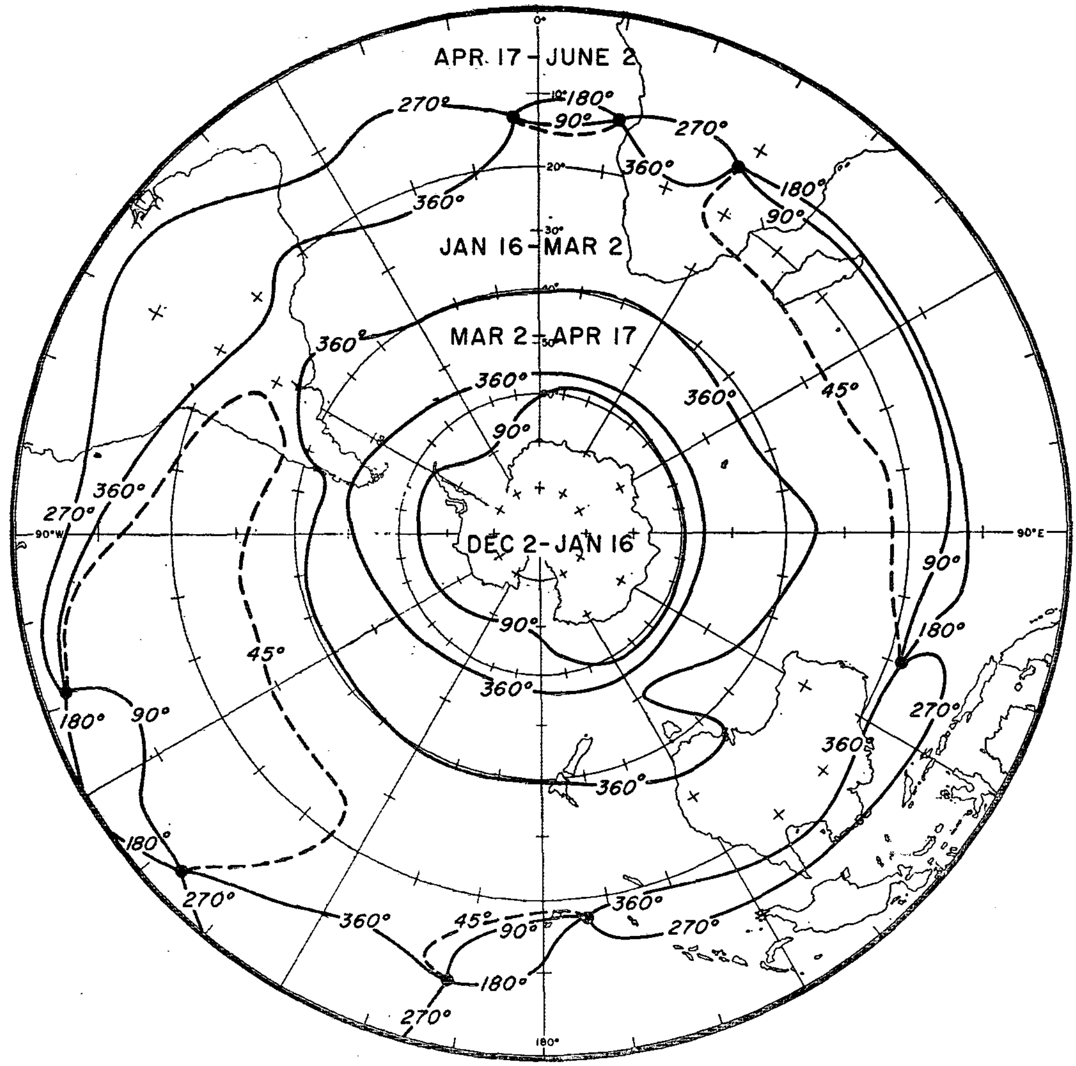

FIG. 8. Phase angle of the second harmonic of the 200-mb height.

January (1952) and 24 February (1964). In nearly all years the second harmonic explains a substantial portion of the annual march. A harmonic analysis of the 15-year mean gives the result

$$y = -34.1\text{C} + 0.5\text{C}\,\sin(x+68°) + 1.5\text{C}\,\sin(2x+41°).$$

The first harmonic accounts for 12% of the total variance, the second for 87%, so no higher terms are important. The reason why the half-yearly component in the long-term average shows such a large share of the total variance is that the phase angle of the first harmonic ranges between 151° and 317°, or nearly half a year centered on February, while *the phase angle of the second harmonic varies little from one year to another.*

Tables 1 and 2 show that the second harmonics of the temperatures at the equatorial and subtropical stations and of the temperature contrast between them reverse phase from 200 to 100 mb. At the latter level it is colder at the equator than in the subtropics. This means that the second harmonic in the latitudinal temperature contrast will now cause a maximum easterly (minimum westerly) vertical shear in May and November in the second harmonic of the zonal wind, in contrast to the levels below.

The annual range of the 100-mb temperature is large at the four stations in Fig. 15, and the highest temperatures of the year are reached during the *southern winter* (see Appendix 1), which is characteristic of the southern tropics and subtropics as far south as 35 to 40S, and apparently up to the 50-mb level.

4. Synthesis and conclusion

Not unexpectedly, the half-yearly oscillations in the zonal wind of the upper troposphere proved to be asso-

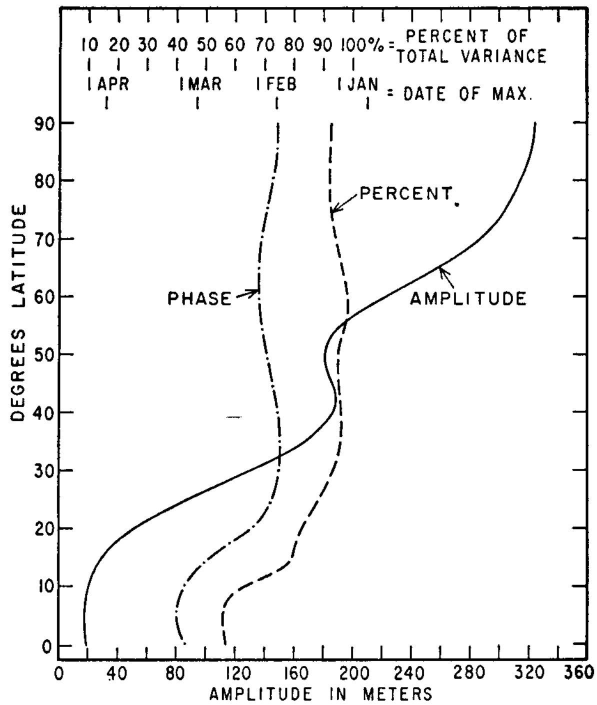

FIG. 9. Meridional profile of the zonally averaged amplitude, phase, and percentage of total variance of the first harmonic in the 200-mb height.

ciated with second harmonics of opposite phase in the temperature in equatorial and subtropical latitudes. It is tempting to rationalize that a second harmonic in the temperature on the equator is caused by the sun's crossing twice a year, but as will be pointed out below, this is not necessarily so. The second harmonic at 25S, however, can hardly be a direct outcome of the sun's double crossing. As is evident from Figs. 13 and 14, the half-yearly temperature cycle in this latitude depends on the temperature rise from autumn to winter, or to the lack of a further temperature drop during this period when this would be expected. The second harmonic with maxima in February and August in the upper half of the subtropical troposphere is observed at a latitude which is in a region of net subsidence. A warming, or lack of cooling, from autumn to winter *could* be the result of an intensification of the downward motion as part of a general intensification of the circulation in the meridional plane. In the same way the minimum of the second harmonic near the equator in August could stem from an intensification of upward motion from May to August.

We have no way of proving such a hypothesis, but two factors hint that it may not be entirely unfounded. The first is the strengthening of the meridional circulation indicated by the meridional component of the wind at Cocos Island (Fig. 11), which culminates in August. This is, naturally, evidence from only one spot where conditions likely are favorable, and such a conspicuous increase in the meridional wind would *not* be found everywhere. The other factor which points to the meridional circulation as a possible agent is that the half-yearly cycle in wind and temperature is more pronounced over the eastern than over the western half of the hemisphere. The strength of the tropical easterlies

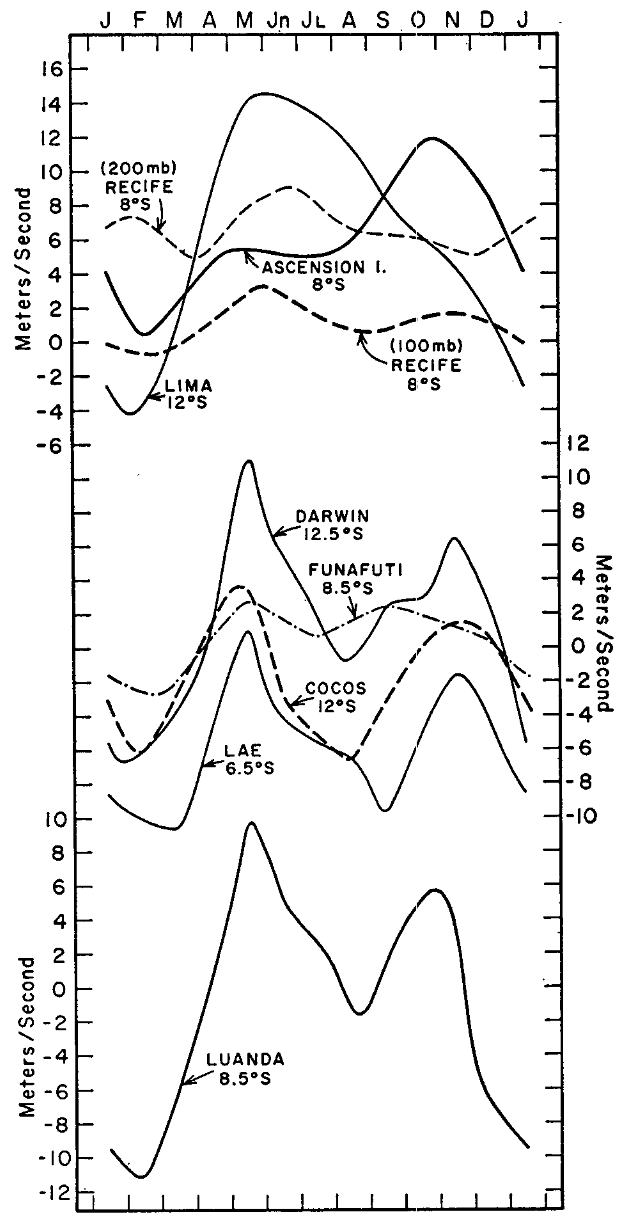

FIG. 10 Observed zonal wind (m sec^{-1}) at or near 200 mb as well as values for Recife at 100 mb.

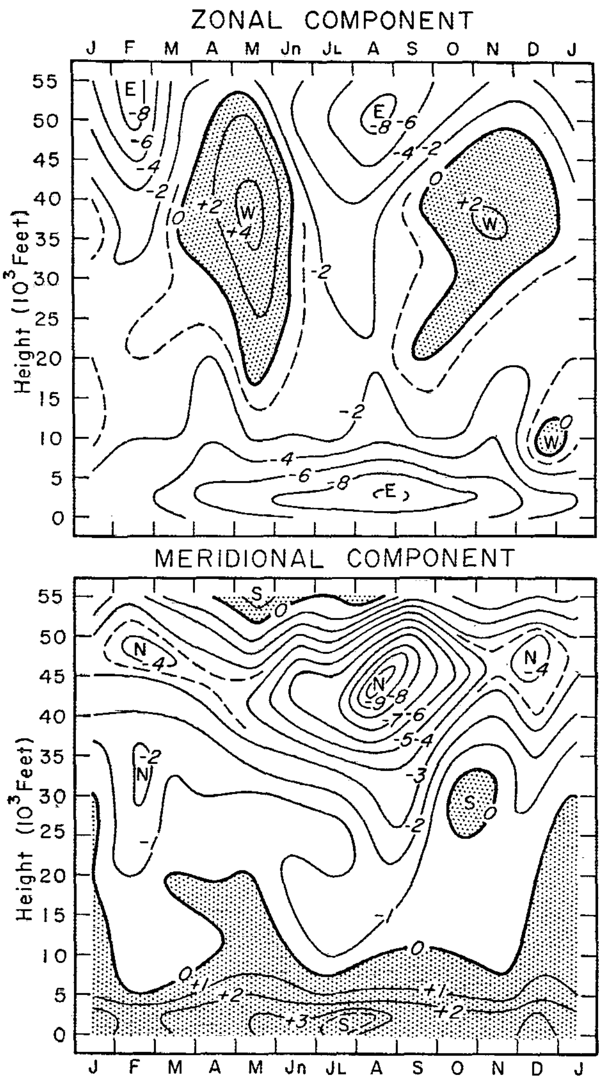

FIG. 11. Time section of the zonal and meridional components of the observed wind (m sec^{-1}) at Cocos Island.

at sea level may be used as an indirect and relative measure of the intensity of the meridional circulation, since a more intense circulation implies a stronger return flow in the lowest levels, and because of the deflection due to the earth's rotation there is also a stronger zonal easterly component. Over the eastern half of the hemisphere, between the Greenwich meridian and 180°, the average zonal component of the sea-level geostrophic wind at 20S in August measures 7.8 m sec^{-1}, but over the western half, only 4.8 m sec^{-1}. This suggests a stronger tropical meridional circulation over the eastern half.

The average phase angle of the second harmonic in the 200-mb temperature at six equatorial stations (Singapore, Nairobi, Kinshasa, Fernando Noronha, Guayaquil and Canton Island) is 226° with maxima on 10 May and 10 November. These stations are so distributed as to give a fair average for the equatorial regions. At 100 mb the average phase angle for the same six stations is 50° with maxima on 5 February and 5 August. An examination of the temperatures between the two levels shows that this complete phase reversal takes place near a height of 15 km.

The average phase angle for six subtropical stations (Giles, Pretoria, Alexander Bay, Sao Paulo, Antofagasta and Noumea) is 34° at 200 mb with maxima on 13 February and 13 August. At 100 mb it is 235° and the maxima fall on 6 May and 6 November. The phase appears to reverse at a slightly lower level than at the equator.

The second harmonic of the latitudinal temperature contrast accordingly changes phase at a height between 14 and 15 km, and so, consequently, does the second harmonic of the thermal wind. At Cocos Island, for example, this happens at the level where the amplitude of the second harmonic in the zonal wind in Fig. 12 begins to decrease which is at 14.6 km.

The second harmonic does not remain in the reversed

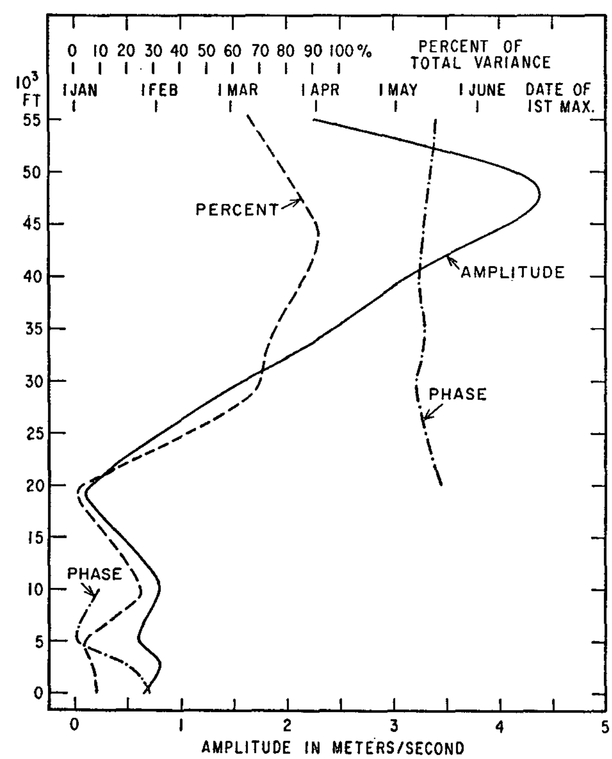

FIG. 12. Vertical distribution of the amplitude (m sec^{-1}), phase, and percentage of total variance of the second harmonic of the zonal component of the wind at Cocos Island.

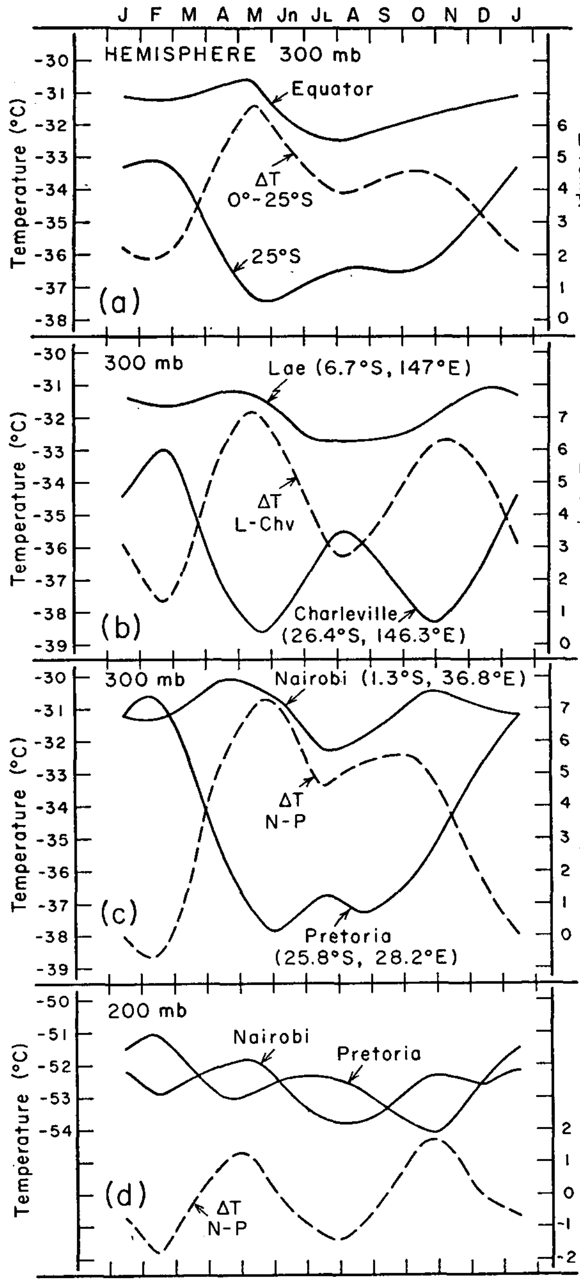

FIG. 13. Annual march of 300- and 200-mb temperatures (°C), zonally averaged and at equatorial and subtropical stations, and of the temperature difference.

phase through a very deep layer. On the equator (Table 4) the phase changes again in the vicinity of the 50-mb level to the same phase as in the upper troposphere. The average phase angle at 30 mb (24 km) for the four equatorial stations (Singapore, Canton Island, Guayaquil, and Fernando Noronha) is 210° with maxima on 18 May and 18 November. In the subtropics the phase also reverses to about the same as in the upper troposphere, but as far as the meager data (1–3 years) can be trusted, only over the part of the hemisphere where the oscillations at lower levels are strong. Antofagasta is in nearly the same phase as the equatorial stations in contrast with the three subtropical stations in Australasia. The second harmonic of the meridional temperature difference thus also acquires maxima in May and November in Australasia, as in the upper troposphere. How far upward this last phase reversal extends is uncertain, but Reed's (1965) wind data from Ascension Island indicate that it may continue to 40 km.

A *schematic* vertical distribution of the second harmonics in the temperatures is given in Fig. 16. The curve on the upper right is not valid for the western half of the hemisphere, but should be representative of the eastern half. The curves imply nothing about the size of the amplitude nor the exact phase; such information can be gained, though incompletely, from the tables. An indication of the second harmonic in the vertical wind shear, which follows from the second harmonic in the latitudinal temperature differences, is shown in the middle of the figure.

There seems no reason not to believe that the half-yearly oscillations in the lowest 20–22 km are connected, and presumably through vertical motions. Above this level in the *equatorial* region, absorption of insolation may become a factor in creating a second harmonic in the annual march of temperature. *However, the fact that the second harmonic at 30 mb at 25–30S in Australasia is in opposite phase to that at the equator, and that the same longitudinal asymmetry seems to exist as at lower levels, suggests that the half-yearly oscillations, as high as we have been able to follow them, may be linked by a chain of vertical motions.*

APPENDIX 1

Annual Range of Temperature at 100–200 mb

In the uppermost troposphere and in the lower stratosphere of the Southern Hemisphere the highest temperatures of the year in the tropics and subtropics are reached during the southern winter. This is partially illustrated in Fig. 17, which could not be extended beyond the 100-mb level because of insufficient data for zonal means. Individual station data, however, show it to continue to at least 50 mb. Since the northern tropics have their highest temperatures at the same levels during the *northern summer*, the entire area between some 20N and 40S is warmest in July–August. Fig. 17 shows that there is also an area in the Northern

TABLE 1. Amplitude (°C), phase angle (=90° on 16 January), and percentage of total variance of the second harmonic of temperatures for various levels at equatorial and subtropical stations and of temperature differences between station pairs.

	Equatorial stations						Subtropical stations		
	Amplitude	Phase angle	Percentage	Amplitude	Phase angle	Percentage	Amplitude	Phase angle	Percentage
	Singapore			Singapore-Giles			Giles		
700 mb	0.2	243	14	0.3	252	0.7	0.1	84	0.1
500 mb	0.3	235	25	1.1	213	27	0.9	25	12
300 mb	0.5	229	40	2.1	219	87	1.7	37	81
200 mb	0.4	222	47	1.0	228	50	0.6	51	34
100 mb	1.4	61	23	2.6	50	76	1.3	217	11
	Nairobi			Nairobi-Pretoria			Pretoria		
700 mb	0.2	288	3	0.8	137	7	1.0	311	7
500 mb	0.3	199	41	0.8	195	6	0.5	12	2
300 mb	0.7	239	74	1.8	236	26	1.0	53	9
200 mb	0.6	228	44	1.4	242	91	0.8	71	55
100 mb	1.1	69	27	1.7	57	38	0.6	211	3
	Guayaquil			Guayaquil-Antofagasta			Antofagasta		
700 mb	0.3	260	58	0.1	37	0.6	0.4	246	5
500 mb	0.1	199	5	0.2	235	0.6	0.2	73	0.3
300 mb	0.1	282	4	0.7	236	8	0.6	47	4
200 mb	0.1	229	11	0.9	229	43	0.8	49	26
100 mb	0.3	54	1	0.7	92	9	0.5	289	1

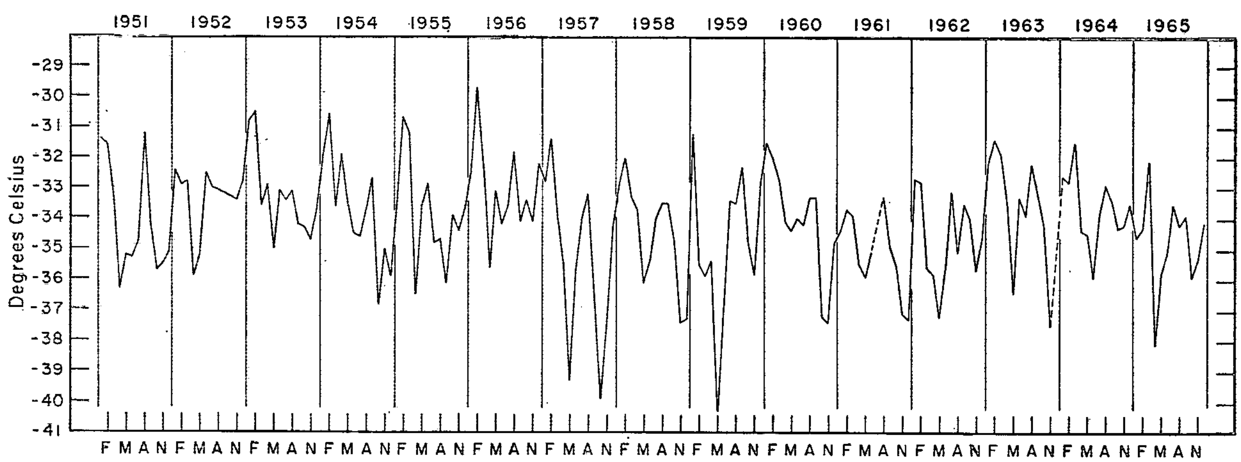

FIG. 14. Time section, 1951–1965, of 300-mb temperature (°C), at Alice Springs.

TABLE 2. Amplitude (°C), phase angle (=90° on 16 January), and percentage of total variance of the second harmonic of the temperature difference between station pairs.

	Singapore-Calcutta			Nairobi-Aswan			Canton I.-Lihue		
	Amplitude	Phase angle	Percentage	Amplitude	Phase angle	Percentage	Amplitude	Phase angle	Percentage
700 mb	0.5	25	2	0.3	273	0.3	0.1	284	0.4
500 mb	0.6	285	2	1.1	218	6	0.1	305	0.2
300 mb	1.0	275	3	2.4	241	20	0.5	238	9
200 mb	1.0	236	10	2.0	234	29	1.1	221	57
100 mb	1.5	37	22	1.6	44	16	0.3	73	5

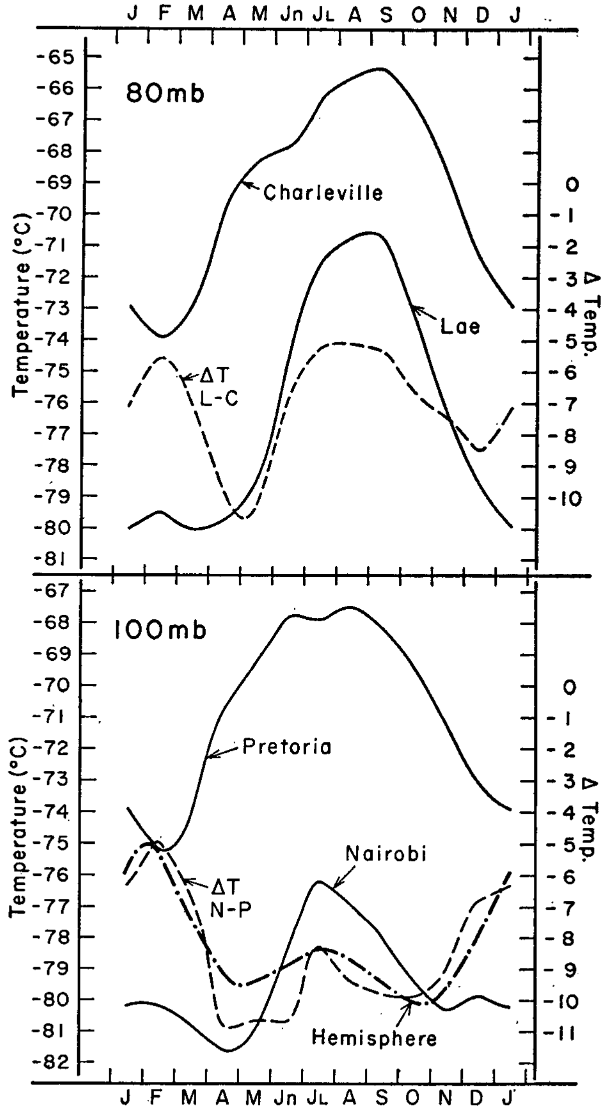

FIG. 15. Same as Fig. 13, except for 100 and 80 mb.

Hemisphere between 24 and 46N, where the temperature is higher in winter, corresponding apparently to the region centered on 30S. The higher winter temperatures in the subtropics occur when the radiation balance would be expected to produce the lowest temperatures of the year. They are therefore necessarily an outcome of effects other than radiational.

It is also worth noting that the warming in winter strengthens the poleward temperature contrast in middle and high latitudes, which causes the stratospheric polar night jet stream, and which is produced by the unequal loss of radiation with latitude. Without the added effect, the polar night westerlies would be weaker and less concentrated latitudinally.

APPENDIX 2

The Oscillations in Middle and High Latitudes

Although they do not fall under the topic of this paper, the illustrations give much new information about the half-yearly oscillations in middle and high latitudes so that a brief description will be of value.

Two out-of-phase oscillations are observed in the zonal wind, one with equinox maxima on the poleward side of 50S, and one with solstice maxima on the equatorward side. The highest amplitude of the oscillation south of 50S is reached near 60S at both sea level at 500 and 200 mb (compare Figs. 2, 3 and 18). The sine functions and the corresponding variances for the three levels at 60S are as follows:

$$\text{Sea level}: u=2.0 \text{ m sec}^{-1} \sin(2x+312°), \quad 87\%$$
$$500 \text{ mb}: u=2.4 \text{ m sec}^{-1} \sin(2x+305°), \quad 65\%$$
$$200 \text{ mb}: u=3.8 \text{ m sec}^{-1} \sin(2x+305°), \quad 34\%$$

The phase angle is remarkably constant with height, the date of the first maximum falling on 27 March at sea level and on 31 March at the 500- and 200-mb levels. The amplitude increases with height, but the share of the total variance drops from 87% at the surface to 34% at 200 mb. Since the annual component increases at even higher elevations at 60S, the percentage of the total variance accounted for by the second harmonic must go on decreasing upward (van Loon, 1967a).

The solstice maxima in the wind occur at latitudes between 30 and 45S. From there the phase changes gradually to the May and November maxima at higher levels in the tropics. The largest amplitude is at 35–40S. The sine functions and the corresponding variances for the three levels at 35S are as follows:

TABLE 3. Amplitude (°C), phase angle (=90° on 16 January), and percentage of total variance of the second harmonic of the 300-mb temperature at Alice Springs for the years 1951–1965.

Year	Amplitude	Phase angle	Percentage
1951	2.1	42	72
1952	0.9	75	41
1953	1.3	56	49
1954	1.3	17	27
1955	0.7	67	9
1956	1.3	49	39
1957	3.0	56	74
1958	2.1	13	76
1959	1.9	48	32
1960	1.8	43	57
1961	1.5	24	77
1962	1.3	48	47
1963	2.1	28	70
1964	1.1	13	52
1965	1.2	49	37
Std. dev.	0.35	17.4	19.7

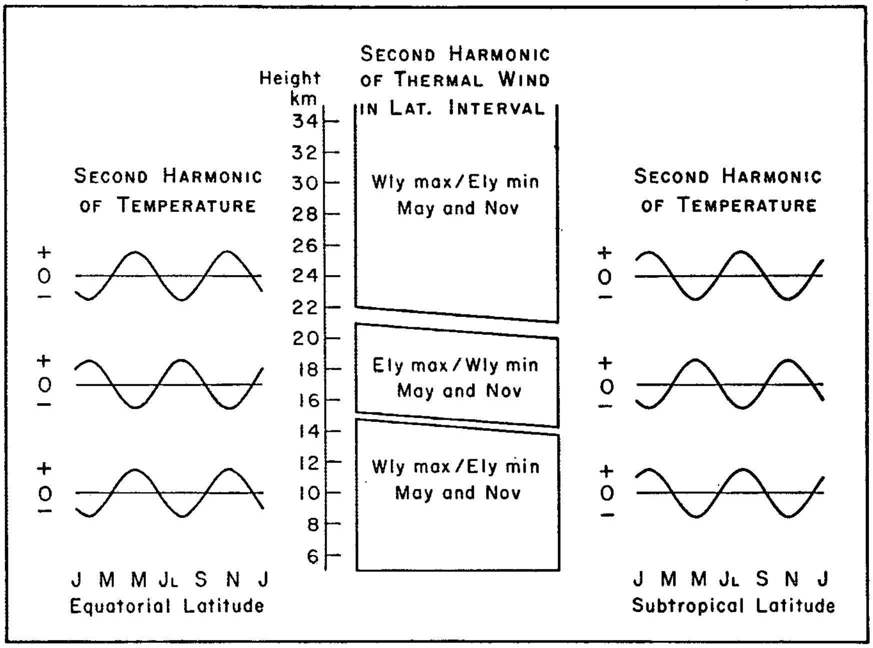

FIG. 16. Schematic representation of the vertical distribution of second harmonics in the temperature on the equator and in the subtropics, and of the time of maxima in the second harmonic of the thermal wind in the tropics.

TABLE 4. Amplitude (°C), phase angle (=90° on 16 January), and percentage of total variance of the second harmonic of temperatures at the 30-mb level at equatorial and subtropical stations and of differences between station pairs.

Equatorial stations						Subtropical stations		
Amplitude	Phase angle	Percentage	Amplitude	Phase angle	Percentage	Amplitude	Phase angle	Percentage
	Guayaquil			Guayaquil-Antofagasta			Antofagasta	
0.8	205	15	0.7	171	26	0.5	258	15
	Canton I.			Canton-Raoul			Raoul	
0.8	199	36	1.9	205	69	1.0	30	50
	Singapore			Singapore-Eagle Farm			Eagle Farm	
1.7	241	20	2.2	219	32	0.9	352	72
	Singapore			Singapore-Charleville			Charleville	
1.7	241	20	1.8	223	25	0.5	335	28

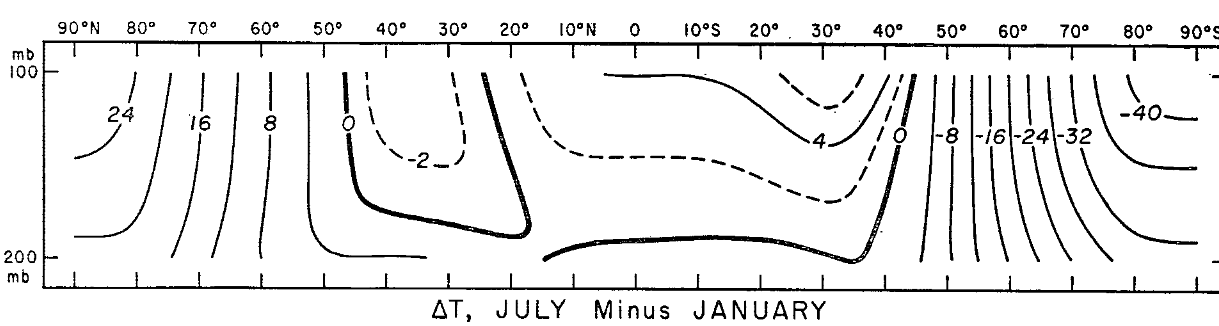

FIG. 17. Zonally averaged temperature difference, July minus January, in the layer between 200 and 100 mb.

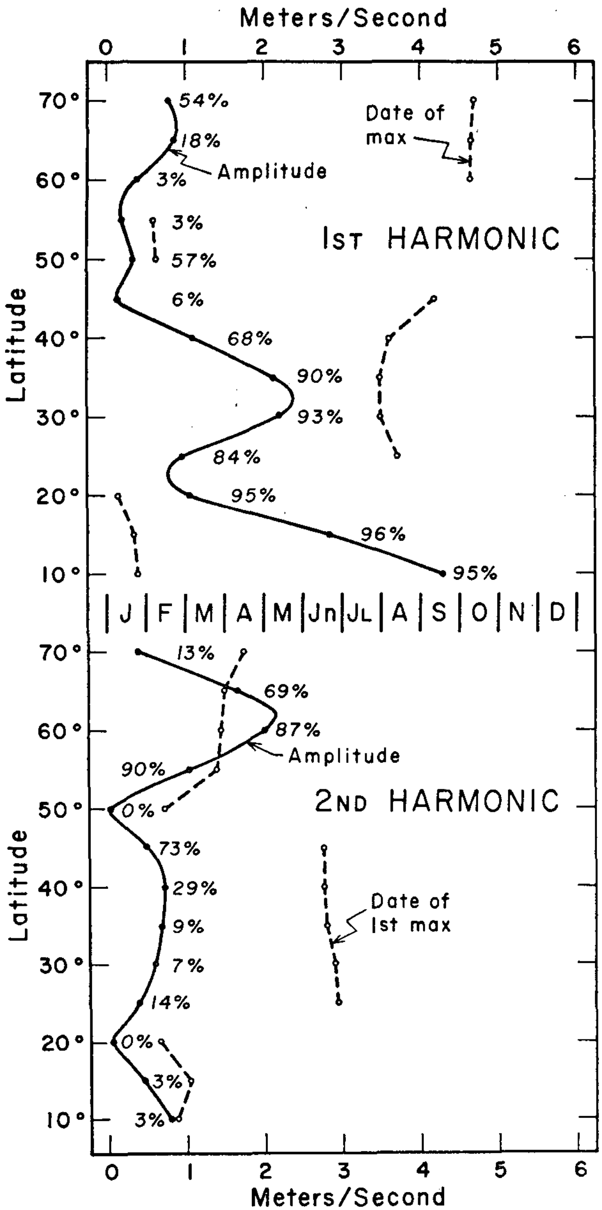

FIG. 18. Same as Fig. 2, except for sea level.

$$\text{Sea level}: u = 0.7 \text{ m sec}^{-1} \sin(2x+150°), \quad 9\%$$

$$500 \text{ mb}: u = 1.0 \text{ m sec}^{-1} \sin(2x+178°), \quad 13\%$$

$$200 \text{ mb}: u = 1.6 \text{ m sec}^{-1} \sin(2x+117°), \quad 6\%$$

The amplitude increases with height as at 60S, but the phase is not so constant. The date of the first maximum is 17 June at sea level, 3 June at 500 mb, and 4 January at 200 mb. The percentages of the total variance are small since the *annual* variation is comparatively large at all three levels at 35S. At 40S, where there is little annual variation, the second harmonic accounts for substantially higher percentages.

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