On the half-yearly oscillations in the tropics

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ABSTRACT

The half-yearly component in the annual march of mean temperature and geostrophic zonal wind, below 100 mb and between 60° E and 120° E, is described by means of cross sections from pole to pole. We suggest that the second harmonics in the temperature, of opposite phase on the equator and in the subtropics, are linked with the position of the rising branch of the Hadley circulation twice a year near the equator.

1. Introduction

We have described earlier (van Loon & Jenne, 1969) a half-yearly component in the annual march of temperature, geopotential height, and zonal wind in the tropics of the Southern Hemisphere. Although it appears to be present and consistent in phase throughout the circumference, the half-yearly component proved to be far more conspicuous in the eastern hemisphere. Therefore we shall narrow the attention in this paper mostly to a sector between 60° E and 120° E, and extend the description there into the Northern Hemisphere. Furthermore, we shall try qualitatively to relate the half-yearly component to seasonal changes of the tropical meridional circulation.

2. An outline of the half-yearly oscillations

(a) *Temperature*

Fig. 1 recapitulates the character of the temperature oscillations. The vertical distribution of the phase[2] of the second harmonic in the annual march at Singapore (1° N, 104° E) is typical of the equatorial belt. The phase is constant in the troposphere where the harmonic's two maxima occur around the first of May and November. It reverses between 150 and 100 mb to one of maxima early in February and August, but a second reversal in the 70–50 mb layer brings it back to the phase of the troposphere. The other equatorial stations in Fig. 1: Fernando Noronha (4° S, 32° W) and Canton Island (3° S, 171° W), far from Singapore and from each other, show the same pattern.

The second harmonic on the border of the tropics, of which Alice Springs (24° S, 134° E) in Fig. 1 is an example, varies in opposite phase to that on the equator in most of the troposphere and in the lower stratosphere. However, a second abrupt phase reversal in the stratosphere does not take place; instead the harmonic slips gradually into the opposite phase from 150 to 40 mb after which the opposition seems to come to an end. The available evidence is that the second harmonic on the equator stays in the May/November phase at least as high as the 10-mb level (Reed, 1962, his Fig. 1 and Table 2).

The amplitude (Fig. 1) reaches a peak between 300 and 200 mb both at Singapore and Alice Springs; goes toward nought where the phase reverses near 150 mb; and has another peak in the reverse phase. At Singapore the amplitude grows with height after the second phase reversal, at Alice Springs it lessens as the phase changes.

(b) *Wind*

A second harmonic in the temperature is necessarily accompanied by a second harmonic in the latitudinal temperature *contrast* on either

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[2] The phase in Fig. 1 and in the following illustrations of phase has been so computed that 1 = 1 January, 2 = 1 February, etc.

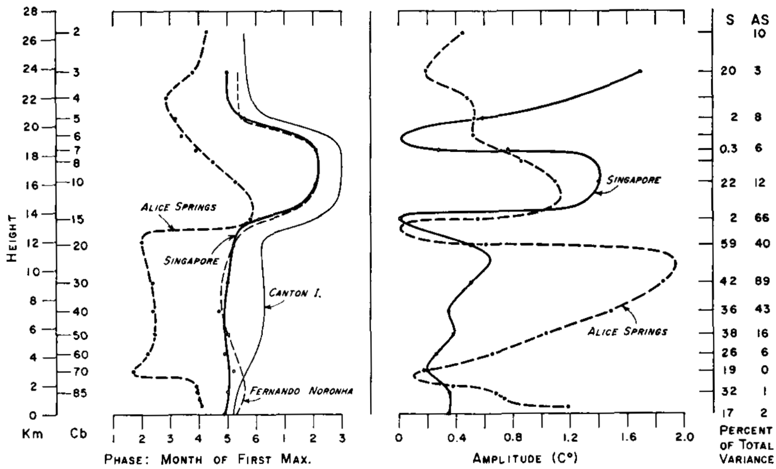
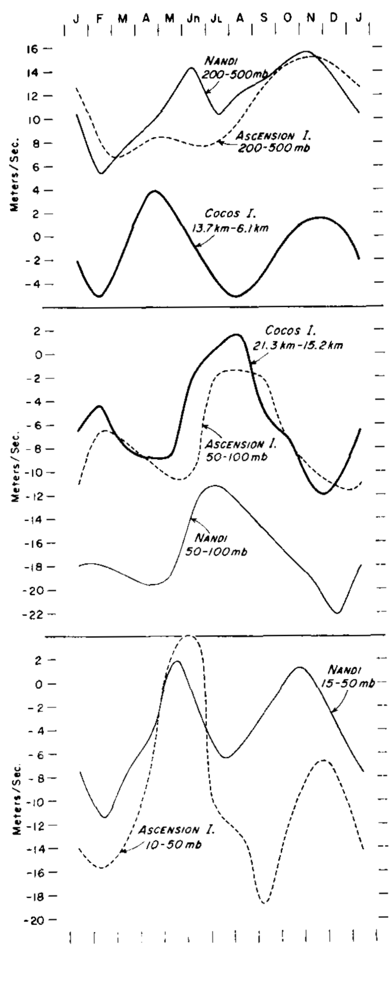


Fig. 1. The vertical distribution of the second harmonic in the temperature (C). The percentage of total variance is shown on the right-hand side.



side of its biggest amplitude—in this instance near the equator—and thus also in the thermal wind. Because the phase of the second harmonic in the temperature on the equator reverses twice with height (Fig. 1), the phase of the second harmonic in the tropical zonal thermal wind must reverse twice. Since, in addition, the phase of the second harmonic in the temperature reverses between the equator and another amplitude peak in the subtropics (see Figs. 3 and 4), the amplitude of the second harmonic in the tropical latitudinal temperature contrast—and therefore in the thermal wind—is enhanced beyond that which would be associated with the temperature at the equator only.

Fig. 2 shows the annual march of vertical differences in the observed zonal wind in the middle tropics near the longitudes of the equatorial stations in Fig. 1. Each zonal wind difference is approximately within a layer through most of which the phase of the second harmonic in the temperature is relatively constant. In all three layers the annual march of the wind shear contains a conspicuous half-yearly component whose phase plainly reverses from layer to layer. This is in accordance with the vertical phase reversals of the second harmonic in the temperature in equatorial and subtropical latitudes (Figs. 1 and 4), and thus

Fig. 2. The vertical distribution of observed zonal wind differences (m sec^{-1}) at Nandi (18° S), Cocos Island (12° S), and Ascension Island (8° S).

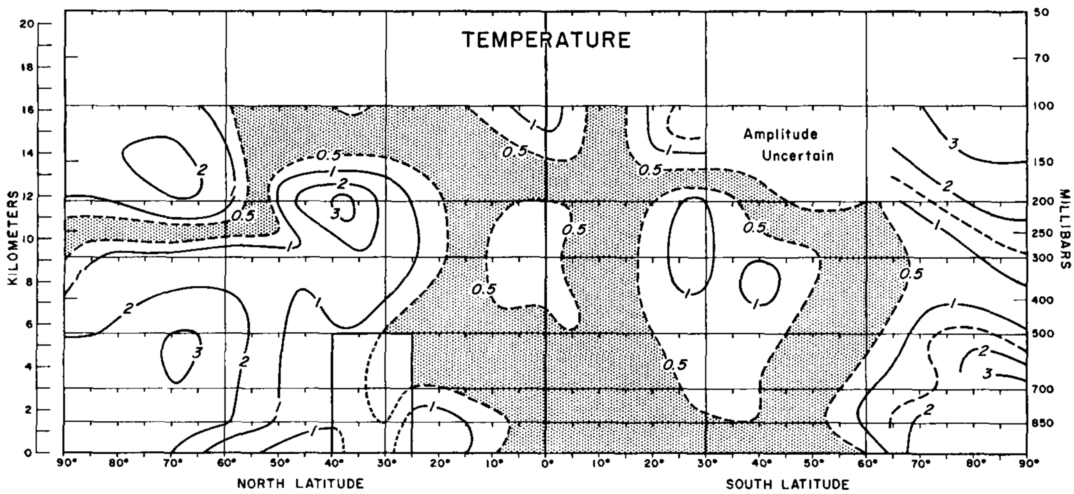


Fig. 3. Amplitude of the second harmonic in the annual march of the mean temperature (C) between 60° E and 120° E.

the vertical phase reversals of the second harmonic in the meridional temperature contrasts between these latitudes. The data from Cocos Island (12° S, 97° E) were too few to compute a zonal wind difference above the 50-mb level, but its similarity to Nandi (18° S, 177° E) and Ascension Island (8° S, 14° W) in the two lower layers, and the fact that the amplitude of the second harmonic in the temperature above 50 mb at Singapore grows fast (Fig. 1), make it reasonable to assume that above 50 mb the curve for Cocos Island will be shaped as those of Nandi and Ascension Island.

The reversal of the phase of the second harmonic in the vertical wind shear from the troposphere to the stratosphere dampens the amplitude of the second harmonic in the *wind* upward from the point of reversal. Above the second phase reversal of the vertical shear, the amplitude of the second harmonic in the wind will begin to grow. This is evident in Reed (1966, his Fig. 7).

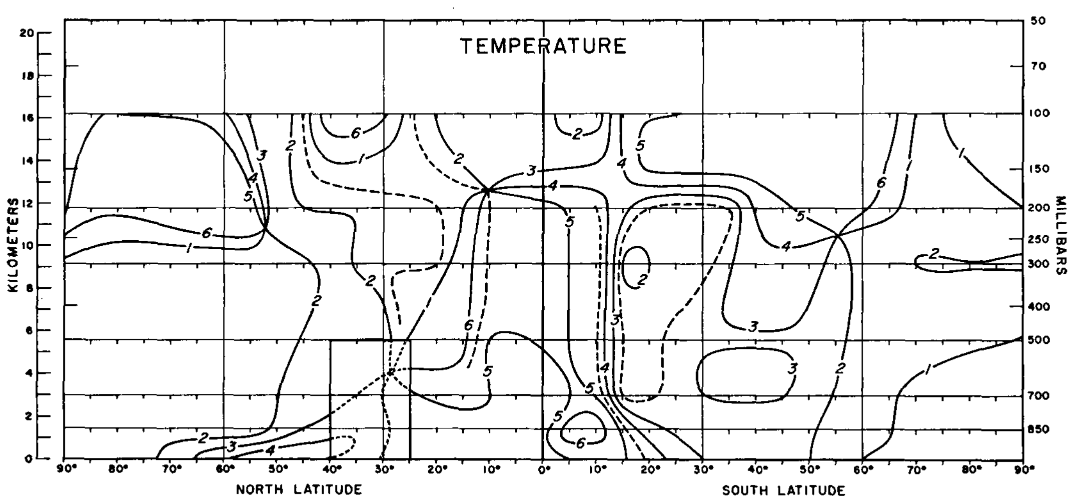


Fig. 4. Phase of the second harmonic in the mean temperature between 60° E and 120° E. The isopleths show the month of the first maximum, 1 = 1 January; 2 = 1 February, etc.

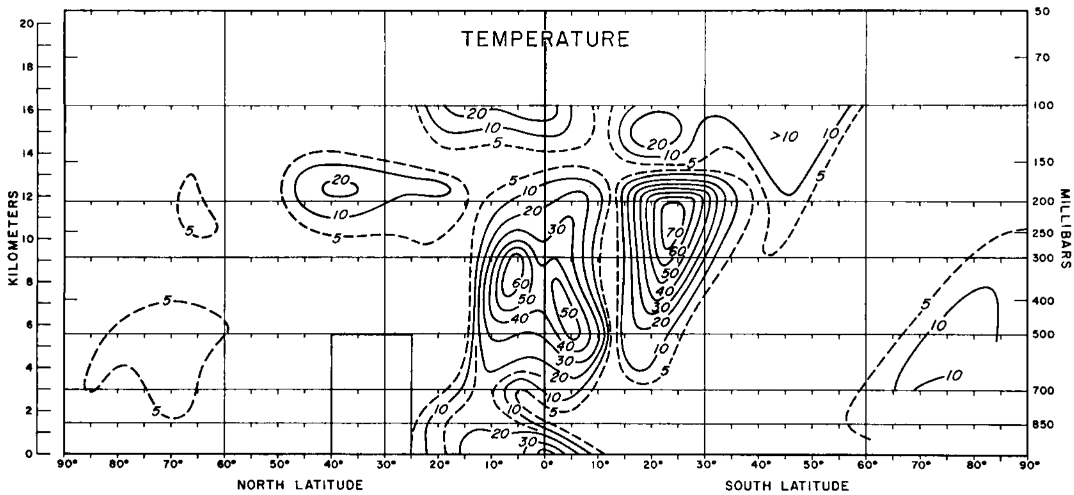


Fig. 5. Percentage of the total variance of the mean temperature between 60° E and 120° E which is explained by the second harmonic.

3. Description of the second harmonics between 60° E and 120° E

(*a*) *Temperature*

A section from pole to pole, and from the surface to 100 mb, of the amplitude of the second harmonic in the mean annual march of temperature averaged between 60° E and 120° E, is shown in Fig. 3. The material in this and in the following meridional sections stems from the hemispheric analyses by Taljaard *et al.* (1969) of temperature in the Southern Hemisphere; of geostrophic wind south of the equator by van Loon *et al.* (1970); and of the Northern Hemisphere by Crutcher & Meserve (1970). The amplitude (Fig. 3) and phase (Fig. 4) on the equator and in the tropics of the Southern Hemisphere agree with the observations at Singapore and Alice Springs. The latitudinal phase change in the southern tropics is abrupt, being contained within two data points (5 deg. lat.) everywhere above 700 mb. In the Northern Hemisphere the change occupies 15–20 deg. lat. Though the second

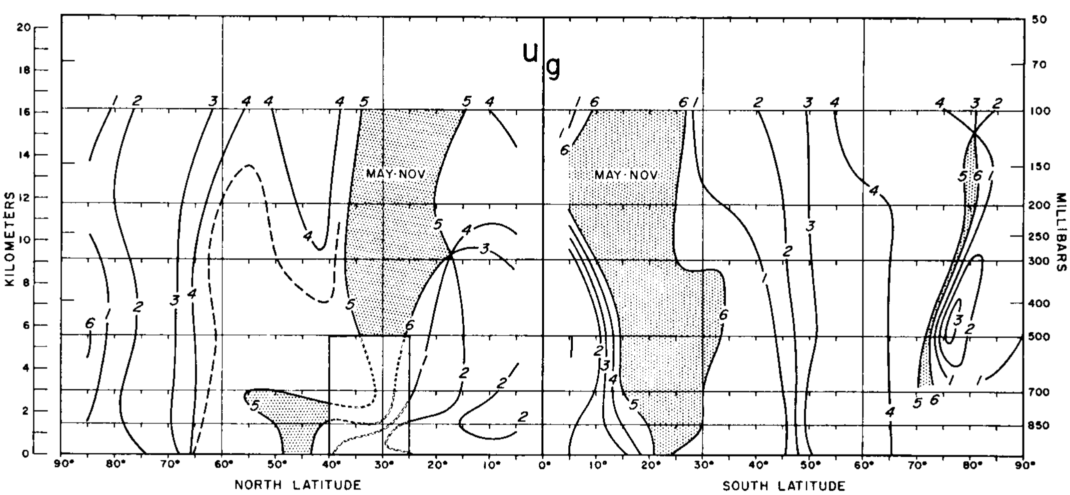


Fig. 6. Phase of the second harmonic in the zonal geostrophic wind between 60° E and 120° E.

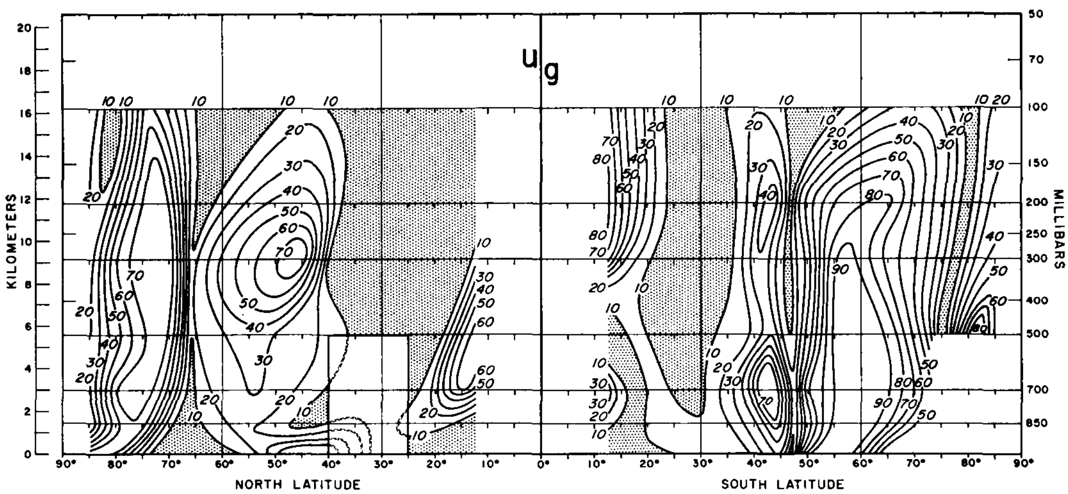


Fig. 7. Percentage of the total variance of the zonal geostrophic wind between 60° E and 120° E which is explained by the second harmonic.

harmonic has a bigger amplitude in the northern than in the southern subtropics, it accounts for much less of the total variance of temperature (Fig. 5). This is because the amplitude of the *first* harmonic in the northern subtropics is more than double that at the same latitude in the Southern Hemisphere.

(b) Zonal geostrophic wind

The phase of the second harmonic in the annual march of the mean zonal geostrophic wind between 60° E and 120° E, and the percentage of the total variance for which it accounts, are shown in Figs. 6 and 7. The percentage is not given between 12.5° N and 12.5° S, while the phase, which is not so sensitive to small errors in the contour analysis of constant pressure surfaces at low latitudes, is shown to the 5th parallels. The second harmonic of the wind observed at two equatorial stations, one within and the other close to the longitude sector, is given for orientation in Table 1. In the area with which we are concerned, the second harmonic in the zonal geostrophic wind reaches its maxima in May and November approximately between 15° S and 30° S, and between 20° N and 35° N (Fig. 6). In the Southern Hemisphere the harmonic in this phase dominates the annual march of the zonal wind in the upper tropical troposphere (Fig. 7), but in the Northern Hemisphere it holds only an insubstantial share of the total variance. This is in accordance with the large first harmonic in the annual march of temperature in the northern subtropical region mentioned above. In the lower half of the troposphere in low latitudes the harmonic is in the oposite phase: its maxima (i.e., minimum easterlies) are here arrived at in February and August (Fig. 6), hence the easterlies in the lower troposphere near the 10th parallels reach their maxima at about the time of the maximum westerlies (minimum easterlies) in the upper levels—*considering the second harmonics.* Fig. 7 indicates that the harmonic may explain a considerable part of the total variance also in this phase. It is worth noting that the second har-

Table 1. *The second harmonic of the observed zonal wind at two equatorial stations. The amplitude is in m sec^{-1} and the phase is given as the month of the first maximum. 1 = 1 January, 2 = 1 February, etc.*

	Nairobi (8 yrs)			Singapore (6 yrs)		
	Ampl.	Phase	Pct.	Ampl.	Phase	Pct.
850 mb	—	—	—	0.9	6.0	22
700 mb	2.0	1.8	29	0.9	6.4	27
500 mb	1.6	1.4	35	0.9	5.9	57
300 mb	1.5	5.3	21	1.9	4.9	31
200 mb	4.9	4.8	85	4.9	4.9	54
100 mb	1.2	5.2	10	1.0	2.3	10
50 mb	—	—	—	1.8	4.1	30

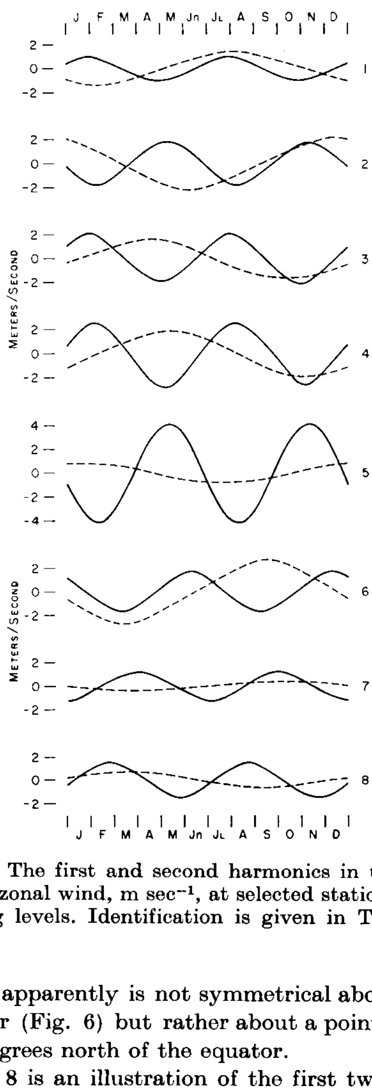


Fig. 8. The first and second harmonics in the observed zonal wind, $m\ sec^{-1}$, at selected stations and varying levels. Identification is given in Table 2.

monic apparently is not symmetrical about the equator (Fig. 6) but rather about a point some five degrees north of the equator.

Fig. 8 is an illustration of the first two harmonics in the zonal component of the *observed* wind near the latitudes and levels where the second harmonic of the geostrophic zonal wind in Fig. 7 accounts for a large share of the total variance. It is not possible to match perfectly positions and levels with the available data; and when comparing Figs. 6, 7 and 8 it must also be considered that the observed wind in general covers fewer years than the heights from which the geostrophic winds were computed, and that the geostrophic winds have been smoothed. Table 2 identifies the stations and provides information about periods and levels. The February/August phase in low latitudes is well illustrated by Bangkok (no. 3) and Dar es Salaam (no. 4). At both stations the variance of the second harmonic explains half of the total. The importance of the second harmonic in the upper tropical troposphere of the southern Indian Ocean is clearly shown by Cocos Island (no. 5).

4. On the nature of the oscillations in the temperature

The rising branch of the Hadley circulation[1] stays north of the equator during the southern summer in the Atlantic and most of the Pacific Ocean, while over South America and the stretch from Africa to the region north of New Zealand it moves into the Southern Hemisphere, see e.g., Hubert *et al.* (1969). Where the rising branch moves from one summer hemisphere to

[1] For brevity we use the words "Hadley circulation" in the following to denote the large-scale monsoonal circulation between hemispheres in the extreme seasons, and *not* the traditional, zonally-averaged meridional circulation.

Table 2. *Identification of stations in Fig. 9; the number of years used in the analysis; the level shown; and the percentage of the total variance accounted for by the first and second harmonics of the west-east component of the observed wind*

No.	Name	Lat.	Long.	Yrs.	Level	Pct. 1st harm.	Pct. 2nd harm.
1	Hatanga	72° N	102° E	7	700 mb	51	35
2	Podk. Tunguska	62° N	90° E	7	700 mb	51	25
3	Bangkok	14° N	101° E	5	500 mb	28	49
4	Dar es Salaam	7° S	39° E	4	700 mb	28	52
5	Cocos I.	12° S	97° E	4	13.7 km	3	91
6	New Amsterdam I.	38° S	78° E	7	700 mb	69	27
7	Wilkes Station	66° S	111° E	7	850 mb	8	72
8	McMurdo Sound	78° S	167° E	8	500 mb	10	48

the other it will be situated near the equator in the months between the summer in either hemisphere, and the half-yearly temperature oscillations on the equator may thus be interpreted in the following, somewhat schematic way:

The latent heat gathered by the trades is released in the troposphere in the rising branch. Above the column which receives the latent heat, the lifted, dry air cools adiabatically. This warming of the troposphere and simultaneous cooling of the low stratosphere happen in the transition periods twice a year in the equatorial belt where the rising branch moves to the summer hemisphere, and must introduce a second harmonic in the annual march of temperature. *In the troposphere the harmonic will reach its maxima during the periods when the latent heat is released, whereas in the lifted dry air above, the phase will be the reverse.* The reverse phase is observed to persist to about 19 km where, presumably, the mean vertical motion vanishes.[1]

The second harmonics in the temperature of the subtropics are not so immediately explicable. A clue to their nature may be found in the statistics of the monthly mean latitudes of the axis of the subtropical jet stream over Australia compiled by Weinert (1968). Fig. 9 shows the seasonal movement of the jet stream axis. It contains a strong half-yearly component which brings it nearest the equator in May and November, the time when the ascending branch is assumed to be on the equator. In the middle and upper troposphere below the subtropical jet stream the temperature gradient is steep with warm air on the side toward the equator. The temperature gradient in the lower stratosphere above the jet is equally steep but of the opposite sign, with warm air on the poleward side. It is logical that *a second harmonic in the latitudinal movement of the jet stream and the accompanying steep temperature gradients must be associated with a second harmonic in the temperature of a place within reach of the system* —and that *the phase of the second harmonic must reverse upwards at the axis of the jet stream where the latitudinal temperature gradient changes sign.* Thus the average lowest latitude of the

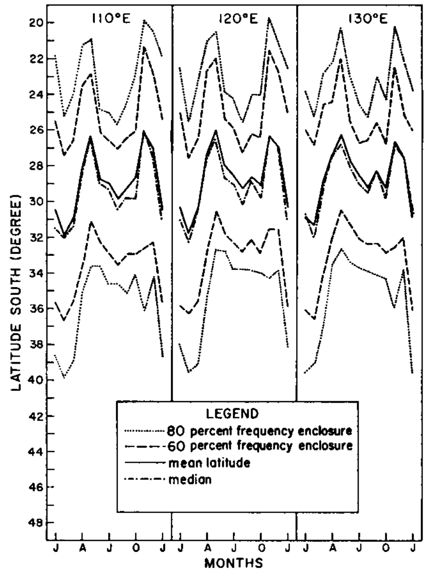


Fig. 9. Monthly mean latitudes of the axis of the subtropical jet stream at 200 mb over Australia —6 years (1956–1961). Reproduced from Weinert (1968).

subtropical jet stream in May and November (Fig. 9) is consistent with the second harmonics in the temperature of the middle and upper troposphere and low stratosphere over central Australia (Fig. 1). If the seasonal movement of the jet stream has a dominant half-yearly component, the second harmonic in the subtropical temperatures will be marked. If the first harmonic dominates the movement, a first harmonic must prevail in the annual march of the subtropical temperatures. The importance of the second harmonic in jet-stream latitude, evident in Fig. 9, in the eastern half of the Southern Hemisphere is well illustrated in Fig. 5.

Since the position of the subtropical jet stream is associated with the poleward side of the Hadley circulation, the second harmonics in the subtropical temperatures must ultimately be connected with the strength and latitudinal extent of the Hadley circulation.

The second harmonic in the zonal wind of the lower half of the equatorial troposphere—exemplified by Bangkok and Dar es Salaam (curves 3 and 4 in Fig. 8)—may also be related to the position of the rising branch. Where this is near the equator twice a year, as its position changes from one summer hemisphere to the

[1] The equatorial data above 19 km indicate a substantial second harmonic in the temperature in the reverse phase of that in the low stratosphere (Fig. 1). This distribution of phase suggests that the vertical motion changes sign at the level where the phase reverses.

other, a second harmonic must arise in the zonal component of the equatorward flow at low latitudes with easterly wind maxima in the transition periods.

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О ПОЛУГОДОВЫХ КОЛЕБАНИЯХ В ТРОПИКАХ

С помощью меридиальных сечений от полюса к полюсу описана полугодовая компонента в годичном ходе средней температуры и геострофического зонального ветра ниже поверхности 100 *мб* между 60° в. д. и 120°в. д. Мы полагаем, что вторая гармоника температуры, имеющая противоположные фазы на экваторе и в субтропиках, связана с положением восходящей ветви Хадлеевской циркуляции дважды в год вблизи экватора.