Evidence of the 5-day period oscillations in the geopotential field

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ABSTRACT

The geopotential height data for the standard isobaric levels for seventeen stations in the tropics are analysed cross-spectrally to trace the propagation of the planetary scale pressure waves. A spectral peak at the 4.6-day periodicity is available at most of the stations in the 850 mb and 700 mb levels and the associated phases correspond to the wavenumber one progression. At the higher levels, the spectral peak is not very prominent—most likely due to the poor signal to noise ratio, the phase progression is also not clearly seen. The inter-level cross-spectra show strong barotropy of the geopotential height fluctuations, the amplitude of which in terms of pressure is nearly constant up to 300 mb and works out to be about 1.5 mb.

1. Introduction

1.1. As early as 1895, Eliot discovered the existence of pressure oscillations over the Asian monsoon region, with a mean period of about 5 days, which he presumed were stationary in character. Without being aware of Eliot's work, these pressure oscillations were also studied by Frolow (1942) and Palmer & Ohmstede (1956). Wallace & Chang (1969) showed that these pressure oscillations in the tropics arise from a westward propagating pressure wave of zonal wavenumber one. Using IGY surface pressure data of about 200 stations, Misra (1971) extended this study and showed that these 5-day pressure oscillations are global in character. He confirmed the westward propagation in the tropical belt 20° N to 20° S and showed that the wave axis is oriented along longitude lines. Madden & Julian (1972) further examined the IGY data and demonstrated that the wavenumber one anomaly propagates over the globe in 5 days time, and that the maximum amplitude of the pressure oscillations occurs in the middle latitudes. The latitudinal dependence of the amplitude of these oscillations and the westward propagation are in qualitative agreement with Longuet Higgins's (1968) result for $m=1$, $n=2$ planetary wave mode, computed for the Lamb's parameter ($\varepsilon = 4\Omega^2 R^2/gh$) equal to 10.

1.2. These global pressure oscillations are more persistent than the 5-day wind oscillations discovered in the tropical Pacific (Yanai & Maruyama, 1966; Wallace, 1971; Criticism by Julian, 1971), which are highly dependent on the seasonal changes in the mean flow. On account of their small amplitude, these pressure oscillations do not appear to be directly associated with weather phenomena. It has also been found that the period of these oscillations is independent of latitude and longitude and do not have any seasonal variation (Ananthakrishnan & Misra, 1970). Hence they are in the nature of an atmospheric tide (Alaka, 1963). Since no forcing of such periodicity is yet known, they may be regarded as atmospheric free oscillations. For a 5-day period and wavenumber one, with one node between poles, this will correspond to a depth of 8.8 km in the case of homogeneous atmosphere.

1.3. Due to the complex thermal structure of the earth's atmosphere, the problem of finding an equivalent depth has aroused considerable controversy in the literature. In general, it is possible to show that the long waves in the atmosphere can have a spectrum of velocities. For given distributions of temperature with altitude, oscillations of the atmosphere appropriate to a spectrum of equivalent depth oceans are possible. In the case of the atmosphere the amplitude of the oscillations may vary

Table 1. *Stations used in the study*

Figures in brackets indicate new WMO index numbers

Sl. no.	Station index	Name	Latitude	Longitude	Height above sea level (m)	Observation time for maximum record GMT
1	61052	Niamey Aero	13°29′ N	2°10′ E	234	06
2	94120	Darwin Airport	12°26′ S	130°52′ E	29	00
3	40309 (91334)	Koror	7°20′ N	134°29′ E	30	12
4	94294	Townsville	19°16′ S	146°40′ E	6	00
5	40505 (91408)	Truk.	7°27′ N	151°50′ E	2	12
6	40504 (91348)	Ponape	6°58′ N	158°13′ E	34	12
7	41601 (91250)	Eniwetok	12°21′ N	162°21′ E	5	12
8	41606 (91245)	Wake Island	19°17′ N	166°39′ E	9	12
9	91680	Nandi	17°45′ S	177°27′ E	18	00
10	21504 (91285)	Hilo	19°43′ N	155°03′ W	0	12
11	11807 (78501)	Swan Island	17°24′ N	83°56′ W	11	00
12	11813 (78383)	Grand Cayman	19°18′ N	81°22′ W	3	12
13	11715 (78397)	Kingston	17°56′ N	76°47′ W	7	12
14	11643 (78988)	Willemstad	12°11′ N	68°58′ W	8	00
15	11641 (78526)	San Juan	18°26′ N	66°00′ W	22	00
16	11647 (78862)	St. John	17°07′ N	61°47′ W	4	12
17	50101	Ascension Island	7°58′ S	14°24′ W	79	12

with height. The latter result was proved by Taylor (1936). In an atmosphere in convective equilibrium, adiabatic oscillations are possible, which however will correspond to a unique equivalent depth (Lamb, 1932; Eckart, 1960). In the analytical studies on the atmospheric oscillations, the boundary conditions used are: (i) the vertical component of velocity must vanish at the surface of the earth and (ii) no wave component may propagate energy downward at infinity. The latter condition is imposed because of the assumption that the oscillation producing potential is mostly introduced at the lowest levels, where the air density is greatest. But the free periods of the atmosphere are determined from an additional condition that the pressure variation at the surface of the earth vanishes in the absence of an exciting force. It can be shown that for any equivalent depth of the atmosphere, there will be a doubly infinite set of free periods (Wilkes, 1949). When resonance occurs, a specified mode is amplified and the free period is displayed.

1.4. As discussed in the previous paragraph, any perturbation shown in the surface pressure has to have an external forcing associated with it. The nature of the forcing can be decided only after one examines the vertical structure of the pressure oscillations. Eliasen & Machenhauer (1965, 1969), Deland (1964, 1965) have examined the 500 mb geopotential height field by harmonic analysis and have shown evidence of wavenumber one progression round the globe in about 5 days' time in the middle troposphere. Examining the data of 500 mb heights and the surface pressure for the IGY period, Madden & Julian (1972) have shown that the oscillations are barotropic.

1.5. During his stay at the NCAR in the summer of 1972, the present writer undertook a study of the vertical structure of the 5-day pressure oscillations utilising the aerological

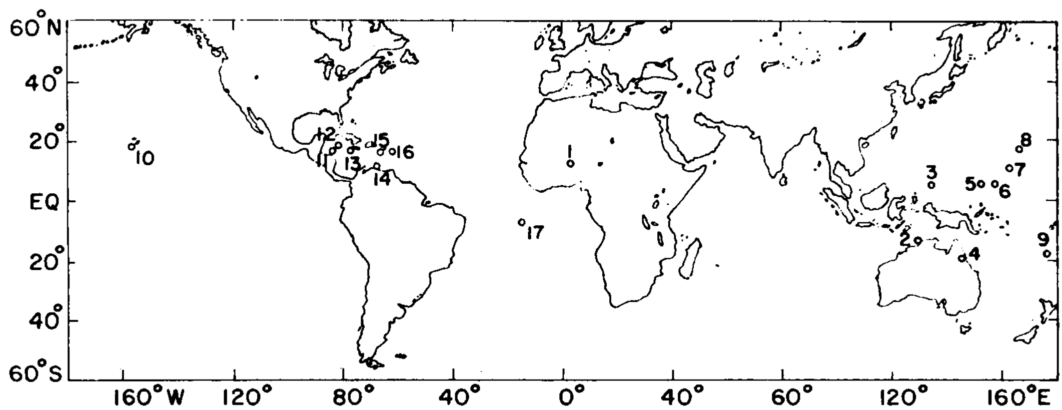


Fig. 1. Geographical locations of stations used in the study.

data of tropical stations. The results reported below are based on this study.

2. Data for study

The data utilised in this study consist of once-daily geopotential height values of 850, 700, 500, 300 and 200 mb levels, extracted from NCAR's data acquisition facility. 43 radiosonde stations in the tropics more or less uniformly distributed in longitude were selected. The period chosen for the study was January 1961 to December 1962. Data with some breaks in the records were available for all the stations for this period. After screening the data, the stations which had a break in record for more than three consecutive days were rejected. Gaps at three days or less were filled in by linear interpolation. After effecting this elimination, 17 stations were available for study.[1] Particulars of these stations are listed in Table 1, and their geographical distribution is shown in Fig. 1. It will be seen that the station density is larger in the west Pacific and the west Atlantic areas whereas data void areas exist elsewhere. A more comprehensive study may be possible with the recent upper air network in the tropics.

3. Computations

3.1. The computational procedure followed in the earlier study (Misra, 1971) has been adopted in the present work also. The method consists of extending the bivariate spectral analysis to the multivariate case. A first difference filter is applied to the daily observed data series, thus essentially reducing the data to a 24-hour tendency field, the spectral estimates have been smoothed by the Tukey window (Jenkins & Watts, 1968), giving the weights by

$$W(K) = 0.5\left(1 + \cos\frac{\pi K}{M}\right) \quad K = 0, M$$

where M is the maximum lag used. The covariance function is calculated as a three-dimensional array and the 'even' and 'odd' function as

$$\mathrm{EV}(K, I, J) = \tfrac{1}{2}(\mathrm{COV}(K, I, J) + \mathrm{COV}(K, J, I))$$

$$\mathrm{OD}(K, I, J) = \tfrac{1}{2}(\mathrm{COV}(K, I, J) - \mathrm{COV}(K, J, I))$$

$$K = 0, M;\ I = 1, \mathrm{NS};\ J = 1, \mathrm{NS}$$

where NS is the number of stations employed in the study. The co- and quadrature spectra are computed by

$$\mathrm{COSPEC}(L, I, J,) = 2\mathrm{EV}(0, I, J) + 2\sum_{K=1}^{M-1} \mathrm{EV}(K, I, J)\cdot W(K)\cdot\cos\frac{\pi KL}{M}$$

$$\mathrm{QSPEC}(L, I, J) = 4\sum_{K=1}^{M=1} \mathrm{OD}(K, I, J)\cdot W(K) \times \sin\frac{\pi KL}{M}$$

$$L = 0, M;\ I = 1, \mathrm{NS};\ J = 1, \mathrm{NS}$$

[1] The latitude separation between the stations is unimportant because the earlier analysis shows that the wave epoch reaches any meridian line at constant phase.

It is simple to calculate the phase and coherence squares as three dimensional arrays with the following relations

$$\mathrm{PHASE}(K, I, J) = \mathrm{ARCTAN}(-\mathrm{QSPEC}(K, I, J) / \mathrm{COSPEC}(K, I, J))$$

$$\mathrm{COHSQ}(K, I, J) = (\mathrm{COSPEC}^2(K, I, J) + \mathrm{QSPEC}^2 (K, I, J))/(\mathrm{SPEC}(K, I) \times \mathrm{SPEC}(K, J))$$

$$K = 0, \mathrm{M};\ L = 1, \mathrm{NS};\ J = 1, \mathrm{NS}$$

3.2. The detection of large scale waves in this method is made by following the coherence and the phase matrices. In certain seasons, the tropical atmosphere shows preference to short period waves which are coherent for a synoptic scale area and are forced by the latent heat release. When there is a cumulative effect of various wave scales around a particular frequency, decomposition of the variance by orthogonal functions have been suggested (Wallace & Dickinson, 1972). The particular case that we are investigating is concerned with the largest scale waves (wavenumber one) and is also independent of the season. We have taken data for a two-year period and so, the non-stationary waves are not expected to present themselves. As we shall see later the coherence fields are significant on a global scale.

4. 24-hour tendency filter

The characteristics of the first difference filter with the associated gain function are enumerated in Jenkins & Watts (1968). The successive difference applied on to a daily recorded series has a great advantage as it works as a low frequency cut off in the estimation of spectra without causing any loss in the generality of the results. Since most meteorological data necessarily possess the low frequency trend, because of their causal relationship with the movement of the sun and because of the fact that the spectral peaks are not tuned harmonics, but have the property of leaking their power to the neighbouring frequencies (for a good consideration see Granger & Hatanaka, 1964), it seems essential that the low frequency trend has to be removed in order to make it fit for any empirical study. To achieve this goal, construction and use of high pass filters have been explained by Holloway (1960) and Blackman & Tukey (1958). However, the application of a filter to the series has got the obvious disadvantage of creating spurious 'spectral peaks'. An example on the generation of such 'spurious peaks' with the use of high pass filter developed by Maruyama (1968) has been shown in a recent communication by Jones (1972). If for any reason one wishes to suppress the effect of the dominant annual cycle or the synoptic scale local disturbances, it seems best to work with the 24-hour tendency field rather than using any artificial filter. In the event of data availability in 6 hour- or 12-hour intervals, the 24-hour tendency filter eliminates the dominant diurnal and semidiurnal tides, which become conspicuous when one works with the pressure or the geopotential height fields.

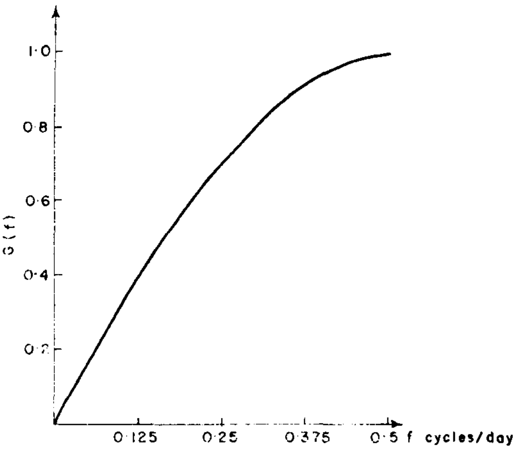


Fig. 2. Gain-function of the first difference filter.

4.2. The gain function of the first difference filter is reproduced from Jenkins & Watts in Fig. 2. The gain is gradual from 0.0 to 0.5 cycle/day frequency and is maximum at the high frequency end. In certain cases, there may be a possibility of a weak signal at the high frequency end to be marked, because of the power gain. In the analysis of the yearly data, this may give rise to an evidence of a 'quasi-biennial' oscillation. For an evidence of a signal at the high frequency end, the first difference filter is definitely unsuitable. But for the middle frequency range, the first difference filter is undoubtedly superior to the raw data. The 24-hour difference series can be considered to be as physical as the observed one and hence,

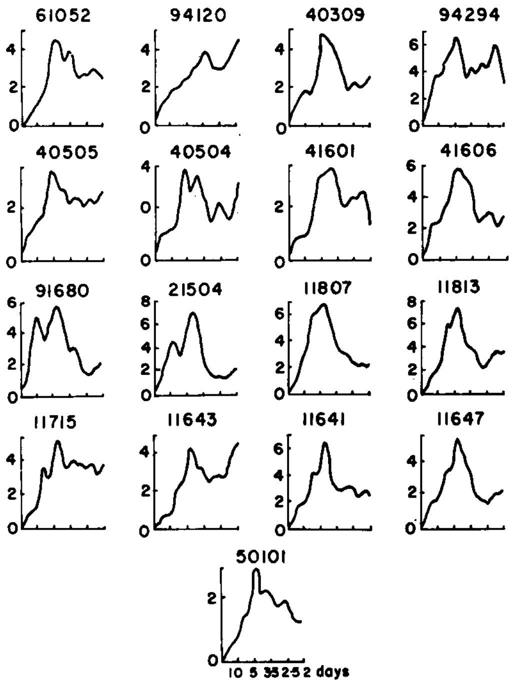


Fig. 3. Spectral estimates for the 850 mb height tendency field.

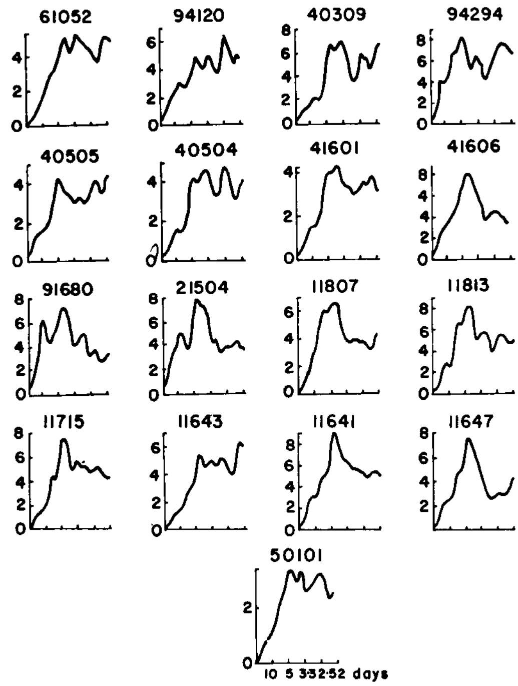


Fig. 4. Spectral estimates for the 700 mb height tendency field.

statistical significance of the results can be physically interpreted. In the following calculations, we have used the first difference filter in the geopotential height fields. Before operating the filter, it is suggested that the spectra of the observed series be first obtained. Only if there is a preferred variance in the middle frequency region, the difference filter can be used and the middle frequency band can be explored further.

5. Results

5.1. *Auto-spectra for height tendency fields*

Fig. 3 through Fig. 7 give the autospectra plots for the height tendency fields for the 850 mb, 700 mb, 500 mb, 300 mb and 200 mb respectively. The ordinates for the first three figures are in units of 100 m^2 and those for Figs. 6 and 7 are in 1000 m^2. Since we are interested only in the power contribution around the 5-day period, no significance intervals have been shown in the diagrams. The statistical tests show that the high frequency

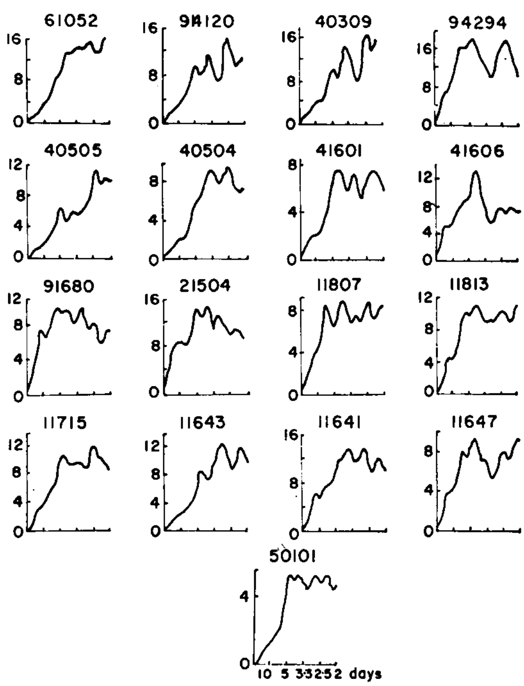


Fig. 5. Spectral estimates for the 500 mb height tendency field.

Table 2(i): *Coherence estimates for the 24-hour tendency field in 850 mb heights for the 4.6-day periodicity*

	61052	94120	40309	94294	40505	40504	41601	41606	91680	21504	11807
61052	1.0	0.1	0.2	0.0	0.1	0.0	0.0	0.1	0.2	0.3	0.2
94120	0.1	1.0	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2
40309	0.2	0.2	1.0	0.4	0.4	0.5	0.4	0.3	0.2	0.2	0.2
94294	0.0	0.2	0.4	1.0	0.4	0.5	0.4	0.3	0.3	0.1	0.2
40505	0.1	0.2	0.4	0.4	1.0	0.6	0.5	0.3	0.3	0.2	0.1
40504	0.0	0.1	0.5	0.5	0.6	1.0	0.5	0.3	0.3	0.2	0.2
41601	0.0	0.1	0.4	0.4	0.5	0.5	1.0	0.6	0.2	0.1	0.1
41606	0.1	0.1	0.3	0.3	0.3	0.3	0.6	1.0	0.3	0.1	0.0
91680	0.2	0.1	0.2	0.3	0.3	0.3	0.2	0.3	1.0	0.3	0.0
21504	0.3	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.3	1.0	0.2
11807	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.0	0.0	0.2	1.0
11813	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.6
11715	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.5
11643	0.1	0.3	0.2	0.1	0.3	0.2	0.3	0.2	0.2	0.2	0.5
11641	0.1	0.2	0.3	0.2	0.4	0.4	0.4	0.3	0.2	0.1	0.4
11647	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.3	0.2	0.2	0.4
50101	0.3	0.2	0.3	0.2	0.3	0.3	0.2	0.2	0.1	0.2	0.2

Table 2(ii): *Coherence estimates for the 24-hour tendency field in 700 mb heights for the 4.6-day periodicity*

	61052	94120	40309	94294	40505	40504	41601	41606	91680	21504	11807
61052	1.0	0.1	0.2	0.0	0.1	0.1	0.0	0.0	0.2	0.3	0.1
94120	0.1	1.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1
40309	0.2	0.1	1.0	0.2	0.4	0.4	0.3	0.3	0.1	0.1	0.1
94294	0.0	0.1	0.2	1.0	0.4	0.2	0.3	0.3	0.2	0.1	0.1
40505	0.1	0.1	0.4	0.4	1.0	0.3	0.3	0.3	0.2	0.2	0.0
40504	0.1	0.1	0.4	0.2	0.3	1.0	0.3	0.2	0.2	0.1	0.1
41601	0.0	0.1	0.3	0.3	0.3	0.3	1.0	0.5	0.3	0.1	0.1
41606	0.0	0.1	0.3	0.3	0.3	0.2	0.5	1.0	0.3	0.1	0.1
91680	0.2	0.1	0.1	0.2	0.2	0.2	0.3	0.3	1.0	0.3	0.0
21504	0.3	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.3	1.0	0.1
11807	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.1	1.0
11813	0.1	0.0	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.1	0.6
11715	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.5
11643	0.0	0.2	0.2	0.1	0.2	0.2	0.3	0.2	0.1	0.1	0.3
11641	0.1	0.2	0.3	0.2	0.2	0.4	0.3	0.3	0.1	0.0	0.3
11647	0.0	0.2	0.3	0.2	0.2	0.3	0.3	0.2	0.1	0.1	0.3
50101	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1

components having periods less than 5 days are all significant at the five percent confidence limit. But the 5-day characteristic, wherever it is prominent, stands out also at the one percent confidence limit. The peaking around 5 days is most consistent in the 850 mb level (Fig. 3) where it is shown at all stations. At the 700 mb level, the peaks are prominently found in the west Pacific and the Atlantic region. Components other than the 5 days gain strength at many stations. At the 500 mb level, only one station, Wake Is (41606, 19°17′ N, 166°39′ E) shows a peak around 5 days periodicity. At other stations, the power contributions have no 5-day preference. A similar situation exists at the 300 mb level (Fig. 6) except for two stations, Hilo (21504, 19°43′ N, 155°03′ W) and St. John Is. (11647, 17°07′ N, 61°47′ W). The 5-day mode is hardly preferred at the 200 mb level (Fig. 7)—only one station—St. John showing same indication.

5.2. *Interstation coherence study*

Since our object is to study the characteristics of the spectral band between 4–5 days and because of the fact that the power spectra give

11813	11715	11643	11641	11647	50101
0.2	0.1	0.1	0.1	0.1	0.3
0.2	0.2	0.3	0.2	0.2	0.2
0.2	0.2	0.2	0.3	0.3	0.3
0.2	0.2	0.1	0.2	0.3	0.2
0.2	0.2	0.3	0.4	0.4	0.3
0.2	0.1	0.2	0.4	0.4	0.3
0.2	0.1	0.3	0.4	0.4	0.2
0.1	0.1	0.2	0.3	0.3	0.2
0.1	0.1	0.2	0.2	0.2	0.1
0.2	0.2	0.2	0.1	0.2	0.2
0.6	0.5	0.5	0.4	0.4	0.2
1.0	0.6	0.5	0.5	0.5	0.2
0.6	1.0	0.5	0.5	0.4	0.1
0.5	0.5	1.0	0.7	0.6	0.1
0.5	0.5	0.7	1.0	0.8	0.2
0.5	0.4	0.5	0.8	1.0	0.3
0.2	0.1	0.1	0.2	0.3	1.0

11813	11715	11643	11641	11647	50101
0.1	0.1	0.0	0.1	0.2	0.2
0.0	0.1	0.2	0.2	0.2	0.2
0.2	0.1	0.2	0.3	0.3	0.1
0.2	0.1	0.1	0.2	0.2	0.1
0.2	0.1	0.2	0.2	0.2	0.1
0.2	0.0	0.2	0.4	0.3	0.2
0.2	0.1	0.3	0.3	0.3	0.2
0.1	0.1	0.2	0.3	0.2	0.1
0.0	0.0	0.1	0.1	0.1	0.1
0.1	0.1	0.1	0.0	0.1	0.1
0.6	0.5	0.3	0.3	0.3	0.1
1.0	0.5	0.4	0.4	0.4	0.1
0.5	1.0	0.4	0.3	0.3	0.0
0.4	0.4	1.0	0.5	0.5	0.0
0.4	0.3	0.5	1.0	0.7	0.1
0.4	0.3	0.5	0.7	1.0	0.2
0.1	0.0	0.0	0.1	0.2	1.0

a significant peak in the periodicity of 4.6 days, we present here the coherence matrices for the 4.6-day periodicity computed among the stations considered. Table 2 (i) to 2 (v) give such matrices for the 850 mb, 700 mb, 500 mb, 300 mb and 200 mb height tendency fields respectively. It can immediately be seen that the coherence estimates weaken as one goes higher up in the troposphere. At 300 mb and 200 mb levels, *the coherence estimates are insignificant*, except for the west Atlantic (San Juan 11641, 18°26′ N, 66°00′ W; St. John Is 11647, 17°07′N, 61°47′ W). The significant coherence extends westward at the lower levels for the west Atlantic stations. At lower levels, 700 mb and 850 mb, the west Pacific stations are significantly coherent. The pockets of coherence in the

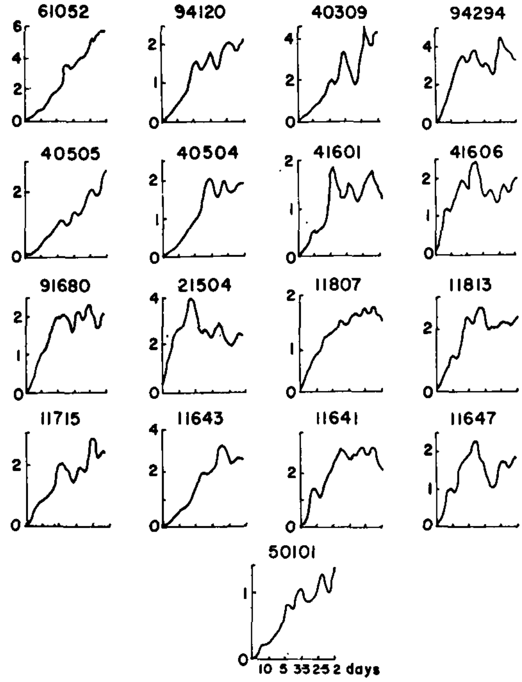


Fig. 6. Spectral estimates for the 300 mb height tendency field.

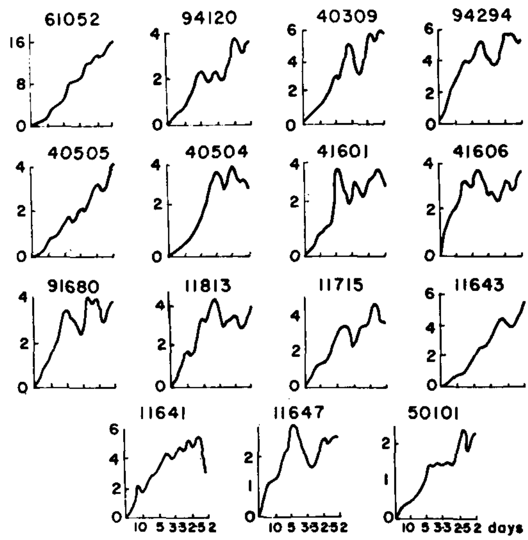


Fig. 7. Spectral estimates for the 200 mb height tendency field.

Table 2(iii): *Coherence estimates for the 24-hour tendency field in 500 mb heights for the 4.6-day periodicity*

	61052	94120	40309	94294	40505	40504	41601	41606	91680	21504	11807
61052	1.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.0
94120	0.0	1.0	0.2	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0
40309	0.1	0.2	1.0	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.0
94294	0.1	0.1	0.1	1.0	0.2	0.2	0.1	0.1	0.1	0.0	0.0
40505	0.0	0.0	0.2	0.2	1.0	0.1	0.2	0.2	0.2	0.1	0.1
40504	0.0	0.1	0.2	0.2	0.1	1.0	0.1	0.1	0.1	0.0	0.0
41601	0.0	0.1	0.1	0.1	0.2	0.1	1.0	0.2	0.2	0.0	0.0
41606	0.0	0.1	0.1	0.1	0.2	0.1	0.2	1.0	0.1	0.0	0.0
91680	0.0	0.0	0.1	0.1	0.2	0.1	0.2	0.1	1.0	0.1	0.0
21504	0.2	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	1.0	0.1
11807	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	1.0
11813	0.0	0.0	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.0	0.3
11715	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.3
11643	0.0	0.2	0.1	0.0	0.2	0.1	0.2	0.2	0.1	0.0	0.1
11641	0.0	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.0	0.1
11647	0.0	0.1	0.2	0.0	0.2	0.1	0.2	0.1	0.1	0.0	0.1
50101	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.0

Table 2(iv): *Coherence estimates for the 24-hour tendency field in 300 mb heights for the 4.6-day periodicity*

	61052	94120	40309	94294	40505	40504	41601	41606	91680	21504	11807
61052	1.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1
94120	0.0	1.0	0.2	0.0	0.1	0.1	0.1	0.1	0.0	0.1	0.0
40309	0.1	0.2	1.0	0.0	0.1	0.2	0.0	0.0	0.1	0.1	0.0
94294	0.1	0.0	0.0	1.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0
40505	0.0	0.1	0.1	0.0	1.0	0.0	0.1	0.1	0.3	0.1	0.1
40504	0.1	0.1	0.2	0.1	0.0	1.0	0.0	0.1	0.0	0.0	0.0
41601	0.0	0.1	0.0	0.1	0.1	0.0	1.0	0.1	0.2	0.0	0.0
41606	0.0	0.1	0.0	0.0	0.1	0.1	0.1	1.0	0.1	0.0	0.1
91680	0.0	0.0	0.1	0.1	0.3	0.0	0.2	0.1	1.0	0.0	0.0
21504	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	1.0	0.1
11807	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1	1.0
11813	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.2
11715	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.2
11643	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.1
11641	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1
11647	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0
50101	0.0	0.1	0.1	0.1	0.0	0.2	0.1	0.0	0.1	0.0	0.0

Atlantic and Pacific may invoke that the oscillations in the geopotential fields are localised phenomena. But it is important to note that the coherence estimates between the Pacific and Atlantic stations are significantly higher in the 850 mb and 700 mb levels. This will mean that the large scale fluctuations do occur in the lower levels and on that is superposed the smaller scale fluctuations. From the coherence matrices, it can be seen that the local scale fluctuations are deeper than the larger scale fluctuations. In the next section, we shall see that the largest scale fluctuations attain in the lowest levels.

5.3. *Interstation phase study*

Figs. 8, 9, 10 and 11 give plots of the phase estimates for the 4.6-day wave periodicity as a function of longitude separation among stations, for the 850 mb, 700 mb, 500 mb and 300 mb height fields respectively. In each figure, we have eight sets of phase lines, corresponding to eight reference stations, i.e. (i) Niamey Aero, (ii) Darwin Airport, (iii) Truk, (iv) Nandi, (v)

11813	11715	11643	11641	11647	50101
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.2	0.2	0.1	0.0
0.1	0.0	0.1	0.2	0.2	0.1
0.2	0.1	0.0	0.1	0.0	0.1
0.1	0.1	0.2	0.2	0.2	0.1
0.2	0.0	0.1	0.2	0.1	0.1
0.2	0.0	0.2	0.2	0.2	0.1
0.1	0.1	0.2	0.2	0.1	0.0
0.1	0.0	0.2	0.1	0.1	0.1
0.0	0.0	0.0	0.0	0.0	0.0
0.3	0.3	0.1	0.1	0.1	0.0
1.0	0.3	0.1	0.2	0.4	0.1
0.3	1.0	0.1	0.2	0.2	0.0
0.1	0.1	1.0	0.4	0.4	0.0
0.2	0.2	0.4	1.0	0.5	0.1
0.4	0.2	0.4	0.5	1.0	0.2
0.1	0.0	0.0	0.1	0.2	1.0

11813	11715	11643	11641	11647	50101
0.0	0.0	0.1	0.1	0.1	0.0
0.1	0.0	0.1	0.1	0.0	0.1
0.1	0.0	0.0	0.0	0.0	0.1
0.0	0.0	0.0	0.0	0.0	0.1
0.1	0.1	0.1	0.1	0.1	0.0
0.1	0.0	0.1	0.0	0.0	0.2
0.1	0.1	0.0	0.0	0.1	0.1
0.1	0.1	0.0	0.0	0.0	0.0
0.0	0.1	0.1	0.0	0.1	0.1
0.0	0.0	0.0	0.0	0.0	0.0
0.2	0.2	0.1	0.1	0.0	0.0
1.0	0.1	0.0	0.1	0.1	0.1
0.1	1.0	0.1	0.1	0.0	0.0
0.0	0.1	1.0	0.4	0.3	0.0
0.1	0.1	0.4	1.0	0.4	0.1
0.1	0.0	0.3	0.4	1.0	0.1
0.1	0.0	0.0	0.1	0.1	1.0

Hilo, (vi) Swan Is, (vii) St. John Is and (viii) Ascension Is. The phase progression in each case shows that the 4.6-day period corresponds to wavenumber one. This is a reflection of the surface wave. At the 500 mb level (Fig. 10), the wave progression is not as systematic as in the lower levels, but the wavenumber one progression is traceable to some extent. At the 300 mb level, the phase function does not respond to wavenumber one progression.

5.4. *Inter-level coherence study*

We have next undertaken a cross-spectral study among the 24-hour height fluctuation series for the isobaric levels at the individual stations. The 200 mb level, which does not give good coherence for the 4.6-day wave periodicity, has been omitted from this study. Instead, the 1 000 mb height fluctuations have been added to the sample. The coherence estimates between various levels with 1 000 mb, 850 mb, 700 mb, 500 mb and 300 mb height series being taken as references respectively are shown in Fig. 12. In general, the height fluctuations in the vertical show good coherence for the 4.6-day periodicity. In fact, a study of the coherence matrices for the entire frequency domain shows that the coherence is generally high for oscillations of periodicity greater than about 4 days. In some of the cases, however, the coherence estimates assume lower values when we recede from the reference level.

5.5. *Inter-level phase study*

Estimated phase differences between the height fluctuations at various levels for the 4.6-day periodicity are all small and fall within the 95% confidence interval except for the stations—Swan Is, Niamey Aero and Ascension Is. For the first two stations, the 300 mb height fluctuation has a phase lead of about 30° to 1 000 mb and 850 mb level; whereas the 300 mb fluctuations at Ascension lag the 1 000 mb fluctuations by a similar amount. But in most other cases, the inter-level phase difference lies within a maximum of 10 degrees.

5.6. *Calculation of the amplitude of the pressure fluctuation from hydrostatic consideration*

Two main findings stand out from the inter-level cross-spectrum: (i) the 4.6-day periodicity has a significant coherence in the vertical plane, and (ii) there is little phase tilt in the vertical for the fluctuations of the heights of the isobaric surfaces. From the spectral plots given in section 5.1, we have taken the power contribution at the 4.6-day periodicity; the square root of this gives the height fluctuations Δz corresponding to this period. The values of Δz thus obtained for the various isobaric levels averaged over the entire area is given in Table 3. The mean values of temperature at these isobaric levels are also given in the table. The

Table 2(v): *Coherence estimates for the 24-hour tendency field in 200 mb heights for the 4.6-day periodicity*

	61052	94120	40309	94294	40505	40504	41601	41606	91680
61052	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94120	0.0	1.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0
40309	0.0	0.1	1.0	0.1	0.1	0.1	0.0	0.0	0.0
94294	0.0	0.0	0.1	1.0	0.0	0.0	0.1	0.1	0.1
40505	0.0	0.0	0.1	0.0	1.0	0.0	0.1	0.1	0.3
40504	0.0	0.0	0.1	0.0	0.0	1.0	0.1	0.1	0.0
41601	0.0	0.1	0.0	0.1	0.1	0.1	1.0	0.1	0.2
41606	0.0	0.1	0.0	0.1	0.1	0.1	0.1	1.0	0.2
91680	0.0	0.0	0.0	0.1	0.3	0.0	0.2	0.2	1.0
11813	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.0
11715	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.2
11643	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1
11641	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
11647	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50101	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1

values of Δp corresponding to the values of Δz calculated from the relation $|\Delta p| = |\lg \Delta z|$ are given in the last column of the table. It will be seen that Δp has nearly constant value of about 1.5 mb from 850 mb up to 300 mb level. This is practically the same as the pressure fluctuation at the surface.

6. Discussion

6.1. The present study shows that the amplitude of 5-day pressure oscillation is nearly constant from the surface up to about 300 mb level and its magnitude is about 1.5 mb in the tropical belt. This means that the proportionate pressure variation $\Delta p/p$ due to this

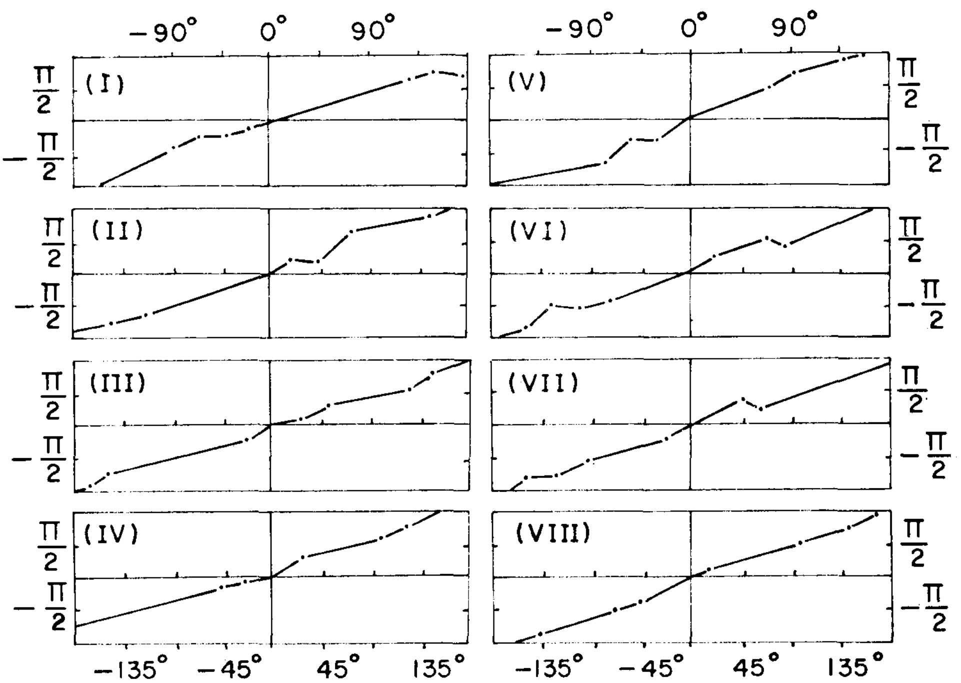


Fig. 8. Phase difference against longitude difference plot for the 850 mb height data for the 4.6-day periodicity.

11813	11715	11643	11641	11647	50101
0.0	0.0	0.1	0.2	0.1	0.1
0.0	0.0	0.1	0.0	0.0	0.0
0.1	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.1	0.1	0.0	0.0	0.0	0.0
0.1	0.0	0.1	0.0	0.0	0.1
0.1	0.1	0.0	0.0	0.0	0.0
0.1	0.1	0.0	0.1	0.0	0.0
0.0	0.2	0.1	0.0	0.0	0.1
1.0	0.1	0.0	0.1	0.1	0.2
0.1	1.0	0.1	0.1	0.0	0.0
0.0	0.1	1.0	0.4	0.3	0.0
0.1	0.1	0.4	1.0	0.3	0.0
0.0	0.1	0.1	0.4	1.0	0.1
0.2	0.0	0.0	0.0	0.1	1.0

oscillation increases with height at least in the lower two-thirds of the atmosphere. In this regard, the 5-day oscillation is akin to the diurnal pressure wave (Godske, 1957). The phase-lines of the 5-day fluctuations are vertical and significant coherence attains up to 300 mb. This points to the strong barotropy of these oscillations and suggests that they belong to the category of free modes in the atmosphere.

6.2. At this stage, a remark is necessary as regards the manifestation of these oscillations in the higher levels of the atmosphere. As we have seen in Section 5, many of the stations fail to obtain the signal as they do for the lower levels. At the lower strata of the atmosphere, the 5-day fluctuations appear to be the most dominant. However, the result cannot be accepted fully before one has examined more recent upper tropospheric data for these stations. The case for the phase propagation is somewhat different. The tropical upper troposphere, at least the area in which the station data have been used in this study shows a dominant 5-day oscillation with the wavenumber 4 or 5. Even though this gets manifest in the summer season only, it must be contributing in the variance decomposition. In order to investigate the phase propagation in the upper troposphere, the wavenumber one fluctuation need be isolated from the total variance. This has not been done in this study.

6.3. Apart from the upper tropospheric waves identified by Yanai and co-workers, another

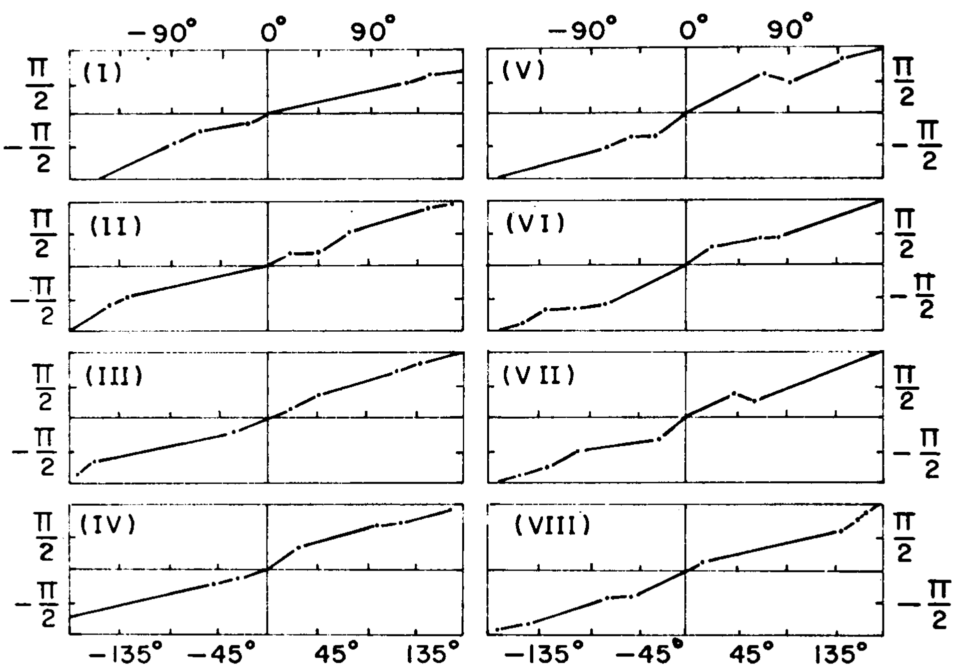


Fig. 9. Phase difference against longitude difference plot for the 700 mb height data for the 4.6-day periodicity.

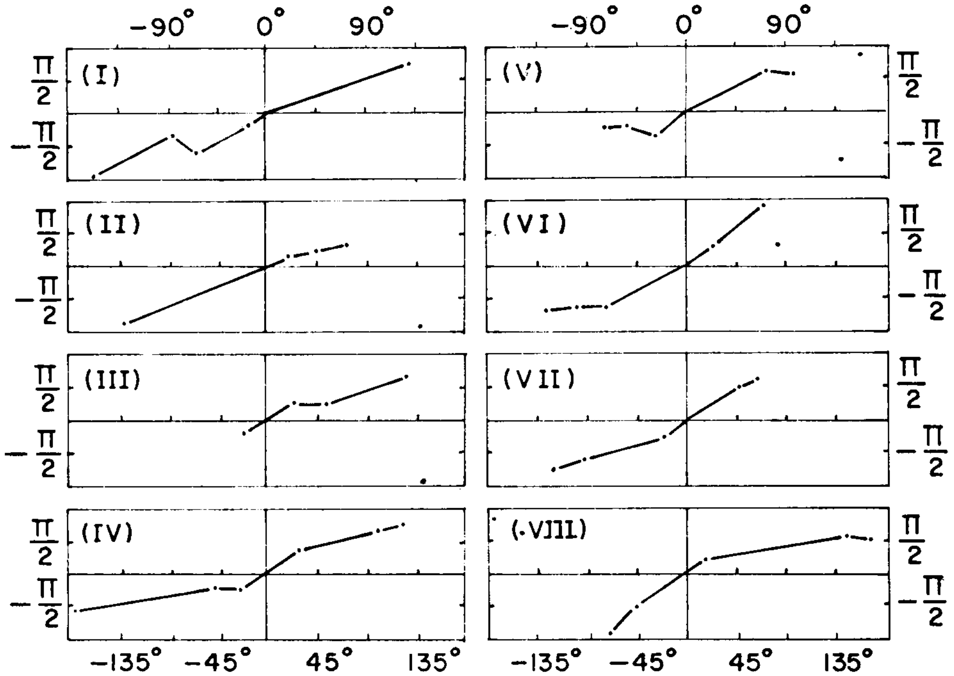


Fig. 10. Phase difference against longitude difference plot for the 500 mb height field for the 4.6-day periodicity.

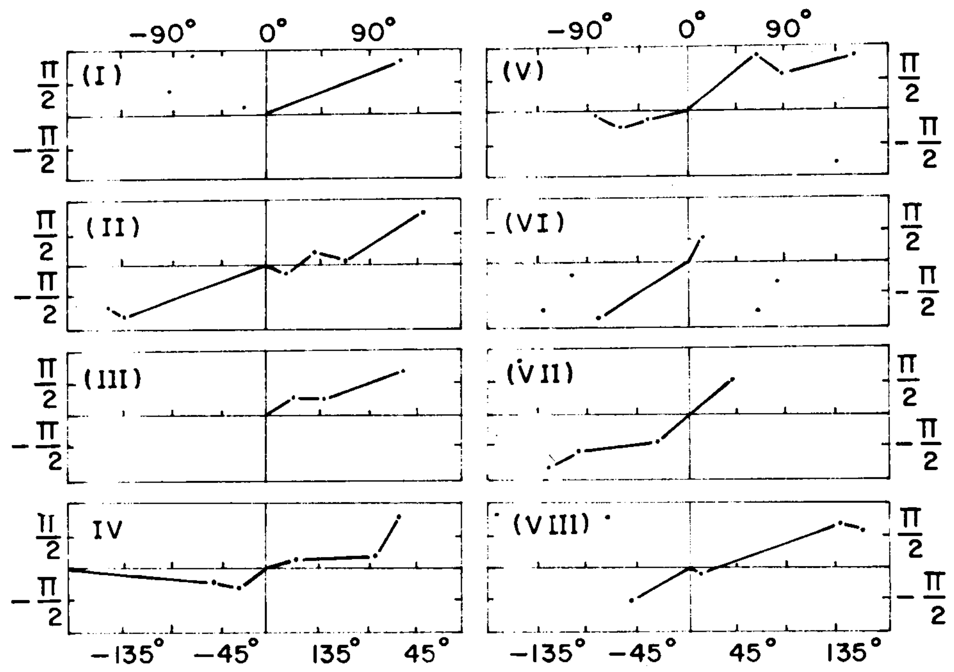
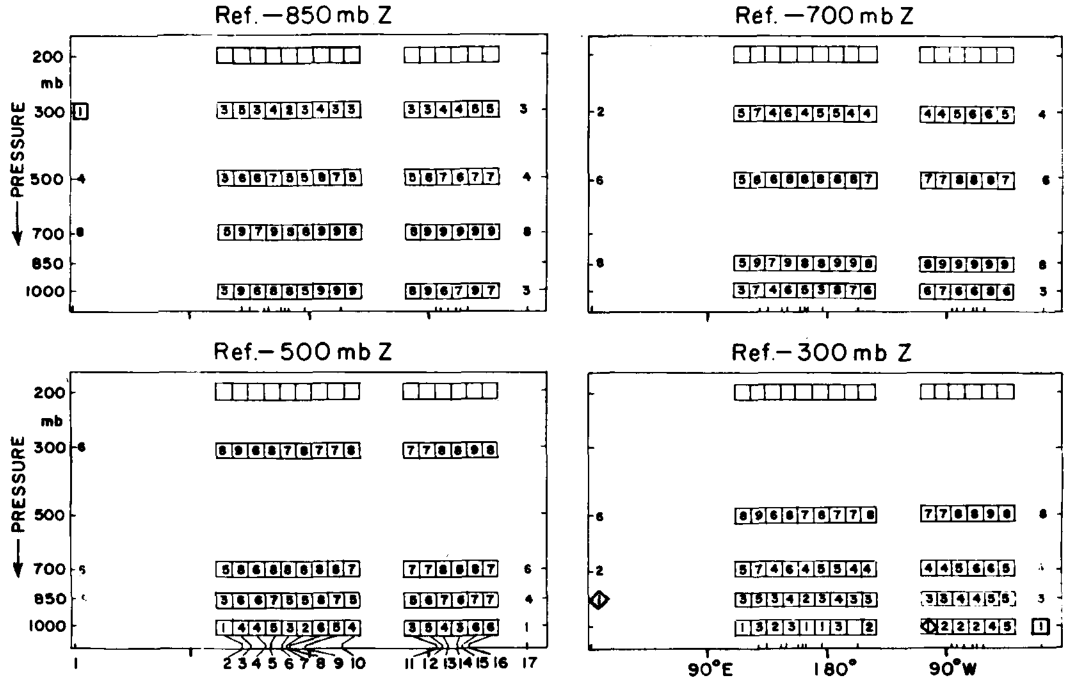


Fig. 11. Phase difference against longitude difference plot for the 300 mb height field for the 4.6-day periodicity.



INTER-LEVEL COHERENCE (X 10) FOR GEOPOTENTIAL HEIGHT FLUCTUATIONS IN 4·6 DAYS PERIOD. □ DENOTES PHASE LEAD OF ~30° AND ◇ DENOTES PHASE LAG OF ~30°. OTHER PHASES ARE NEGLIGIBLE. STATION LOCATIONS ARE MARKED BELOW THE DIAGRAMS

Fig. 12. Inter-level coherence (× 10) and phase for geopotential height fluctuations in a 4.6-day period.

important observation has been made recently, this is the stationary oscillation of 5 days' time observed in the cloud brightness spectra in the Pacific area (Wallace, 1971). In a recent diagnostic study, Holton (1972) has shown that a stationary oscillatory heating function can give rise to the travelling westward modes in the upper troposphere because of beta-effect and vertical propagation. Now, if the cloud oscillations are responsible for the excitation of the upper tropospheric systems, one has to search for the cause of the stationary cloud oscillations. A possible conjecture is whether the free oscillations as evidenced here and elsewhere can give rise to resonance pumping of moisture in 5 days' time. Some discussions were held on this topic during the colloquium on the Dynamics of the tropical atmosphere held at Boulder in 1972.[1] However it remains to be seen how the two events are coupled and also whether the cloud oscillations have any feed back on the pressure oscillations.

Table 3

Isobaric levels (mb)	Δz (m)	T (°K)	1 (gm/cc)	$\Delta p = \lg \Delta z$ (mb)
850	16	291	1.03×10^{-3}	1.6
700	17	282	0.86×10^{-3}	1.5
500	22	267	0.65×10^{-3}	1.4
300	32	241	0.44×10^{-3}	1.4
200	37	220	0.32×10^{-3}	1.2

6.4. In a few recent papers, Fritz & Soules (1970, 1972) have shown evidence of planetary variation of stratospheric temperatures. From the 15 μ CO_2 band radiance data measured by the satellite infrared spectrometer on *Nimbus III*, they show that the stratospheric warmings in the winter hemisphere are accompanied by

[1] Colloquium Notes, Dynamics of Tropical Atmosphere, Advanced Study Program, National Center for Atmospheric Research, Lindzen's lecture on Tropical Boundary Layers, p. 179.

simultaneous coolings in the stratosphere of the tropics and the summer hemisphere. In the discussion of their results they refer to the observations of Frolow (1942) and Brier & Simpson (1969) regarding the simultaneous widespread pressure changes in the tropical areas. The simultaneous pressure changes observed by these authors as well as many others in the tropical areas are obviously due to the phase movement of the wavenumber one progression in 5 days' time. As is elegantly shown by Madden & Julian (1972), about half the globe shows similar tendency of pressure rise or fall under the spell of this wave. The amplitude of this wave has a latitude variation but no longitude or seasonal variation; hence the wave appears on any meridian belt completely in phase. From this angle, the author feels that the meridional cell proposed by Fritz & Soules (1970) may not be connected with the movement of this wave.

6.5. More recently, Deland (1973*b*) has raised some points regarding the inter-hemispheric connection of the 5-day pressure waves. From a study of the available SIRS radiance data, he finds that the amplitudes of the westward travelling modes are greatest in the equinoctical months in the middle latitudes and from the average eastward phase-shift with latitude, he concludes that the travelling waves in the tropical stratosphere as evidenced by Fritz (1970) are forced by middle latitude planetary scale waves. However, to extend the idea to the 5-day pressure waves and to say that the wave in the tropics is an extension of waves in the respective hemisphere of similar speed but independent phases is incorrect. Inter-hemispheric connection in tropical areas is easy to find and is shown in an earlier paper (Misra, 1972). The direct comparison of the middle latitudes in the two hemispheres is difficult because of poor signal to noise ratio. But the coherence increases if an averaging is done over broad latitude belts. This has been shown by Madden & Julian (1973) in their reply to Deland's argument. A significant point to note is that the 4–5 days happens to be the only band in which there is any appreciable coherence between the pairs of stations in the middle latitudes of the two hemispheres and further that the coherence increases if the stations are over the oceans (Misra, 1973).

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ДАННЫЕ О КОЛЕБАНИЯХ С ПЕРИОДОМ 5 СУТОК В ПОЛЕ ГЕОПОТЕНЦИАЛА

С целью выявления распространяющихся волн давления планетарного масштаба анализируются кросс-спектры данных семнадцати станций по высотам геопотенциала для стандартных изобарических уровней. На большинстве станций на уровнях 850 и 700 миллибар присутствует пик на периоде 4,6 суток, а связанные с ним фазы соответствуют распространению волны с волновым числом, равным единице. На более высоких уровнях этот спектральный пик выражен не очень четко — наиболее вероятно благодаря плохому отношению сигнал — шум, фаза распространения также видна нечетко. Междууровенные кросс-спектры указывают на сильную баротропность флуктуаций высот геопотенциала, амплитуды которых в терминах давления почти постоянны до высоты 300 *мб* и оказываются порядка 1,5 *мб*.