Power spectra of large-scale disturbances of the Indian southwest monsoon

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ABSTRACT. The period, wavelength and vertical structure of the different types of monsoon disturbances have been studied by applying the technique of power and cross spectrum analysis to wind data over the Indian region.

The spectra of the meridional component of wind show dominant peaks around 15-20 days and 5-6 days in the lower troposphere and 7-9 days in the middle and upper tropospheres. These are shown to correspond to known monsoon disturbances.

1. Introduction

The disturbances of the monsoon like monsoon lows and depressions have been studied extensively by synoptic methods. The structure of monsoon depressions was studied by Desai (1948), and Koteswaram and George (1960). A statistical study of the frequency of depressions in the Bay of Bengal was made by Rao and Jayaraman (1958). The frequency of occurrence and tracks of these depressions were studied by Ananthakrishnan (1964).

More recently the technique of power and cross-spectrum analysis is being applied increasingly to study the structure of tropical disturbances. A preliminary study of the periodicities of the v and u components of the wind at some Pacific stations was made by Rosenthal (1960). Yanai *et al.* (1968) made an extensive study of the power and cross-spectra of the v component of wind at Pacific stations. They found a peak around 4 days in the lower troposphere corresponding to easterly waves whose scale was found to be about 6000 km. They also found large spectral density around 4-5 days in the upper troposphere and lower stratosphere corresponding to westward moving waves of scale 10,000 km. Wallace and Chang (1969) studied the spectra of v and u components, surface pressure, temperature and relative humidity of tropical stations in the lower troposphere. They found easterly waves with periods of 4-5 days and horizontal wavelength of 3000 km, planetary scale pressure fluctuations with period around 4 days and low frequency oscillations with periods greater than 10 days in the u component with wavelength of the order of 10,000 km. Ananthakrishnan and Keshavamurty (1970) found large spectral density in periods longer than 10 days in the u component and surface pressure departure (from normal) and

one week period in v, u and suface pressure at Indian stations during the southwest monsoon period.

In this paper we study the periods and horizontal and vertical structure of monsoon perturbations by applying power and cross spectrum analysis techniques to wind data of Indian stations during the southwest monsoon season.

2. Data and computations

The time series of the v component of wind of the seven stations shown in Table 1 have been analysed for the southwest monsoon season of 1967. This was a normal monsoon season. The data have been analysed at standard levels, *i.e.*, 0·9, 1·5, 3·0, 6·0, 9·0 and 12 km. At Calcutta a greater vertical resolution has been used as indicated in Table 1.

The method of power spectrum analysis has been dealt with extensively by Blackmann and Tuckey (1958). The method followed here is mainly based on the formulation in *WMO Technical Note* No. 79 (1966). For cross spectrum analysis we have essentially followed the method of Munk *et al.* (1959) and Maruyama (1968).

The length of the record in our case is 120 observations (one observation daily). The maximum lag used generally is 30 so that the frequency (k) refers to cycles in 60 days and the period $P = 60/k$ days.

No attempt, has been made to remove the longer cycles by weighted averaging, as the length of the record would be considerably reduced; and there is no point in taking a longer period as the character of the disturbances would be different if we extended the period beyond the monsoon season.

Missing data have been filled by linear interpolation. Where the number of missing data was large,
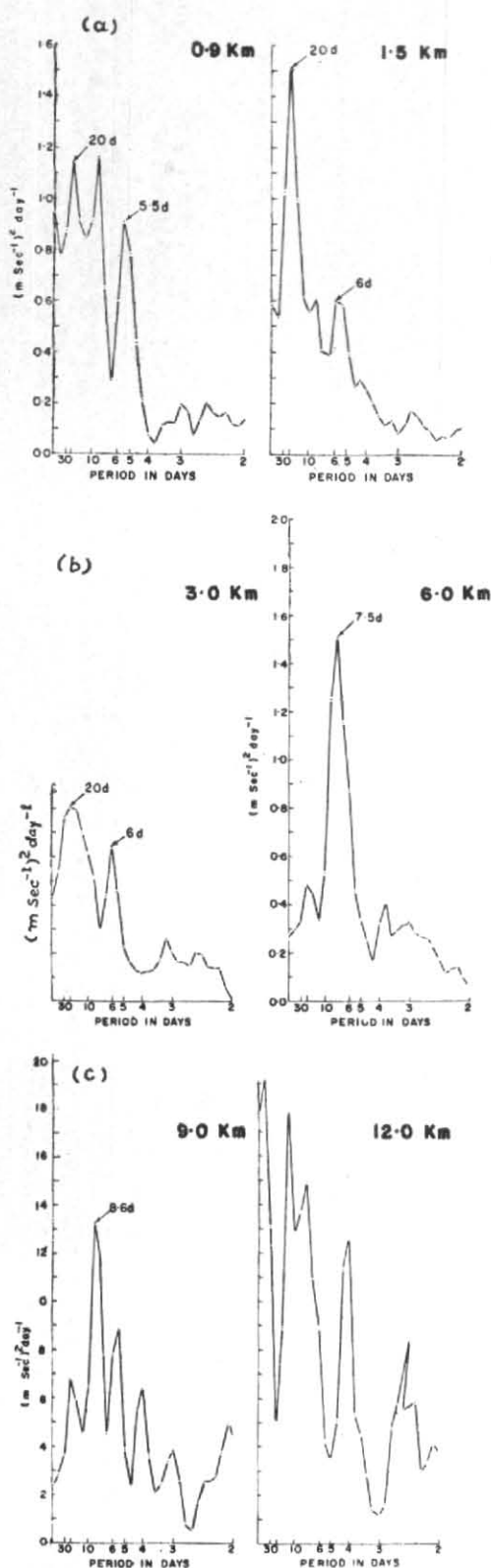
Fig. 1

Nagpur v-component, Jun-Sep 1967

TABLE 1

Station	Latitude (N)	Longitude (E)	Period	Levels (km)
Calcutta	22° 39'	88° 27'	Jun to Sep 1967	0·3, 0·6, 0·9, 1·5, 2•1, 3·0, 3·6, 4·5, 5·4, 6·0, 7·2, 9·0, 10•5 and 12·0
Nagpur	21° 06'	79° 03'	Do.	0·9, 1·5, 3·0, 6·0, 9·0 and 12·0
New Delhi	28° 35'	77° 12'	Do.	Do.
Lucknow	26° 45'	80° 53'	Do.	Do.
Visakha-patnam	17° 43'	83° 14'	Do.	Do.
Port Blair	11° 40'	92° 43'	Do.	Do.
Trivandrum	08° 29'	76° 57'	Do.	Do.

TABLE 2

Station	Period of most prominent peak (days)	Levels at height km a.s.l. (km)
Nagpur	20	0•9, 1·5, 3·0
	5·5 or 6	0·9, 1·5, 3·0
	7·5 or 8·6	6·0, 9·0
Calcutta	15	0·3, 0•6, 0·9 and 1·5
	4 6	0·9, 1·5, 2·1
	7·5 or 8·6	6·0, 7·2, 9·0, 10·5 and 12
Lucknow	5 to 6	0·3, 0·6, 0·9 and 1·5
	8·6	3·0, 6·0

(*e.g.* at 200-mb level of Visakhapatnam, Port Blair and Lucknow) no analysis has been carried out.

The results are discussed in the following sections.

3. Power spectra of v-component

Let us first consider the power spectra of the *r*-component of the wind at Nagpur Fig. 1, Calcutta Fig. 2, and Lucknow Fig. 3. The most prominent peaks are indicated in Table 2.

In the lower troposphere the dominant peaks are: (*i*) 20 days at Nagpur and 15 days at Calcutta, (*ii*) 5 to 6 days at Nagpur and 4·6 days at Calcutta and (*iii*) In the middle and upper tropospheres the dominant period is 7-9 days both at Calcutta and Nagpur.
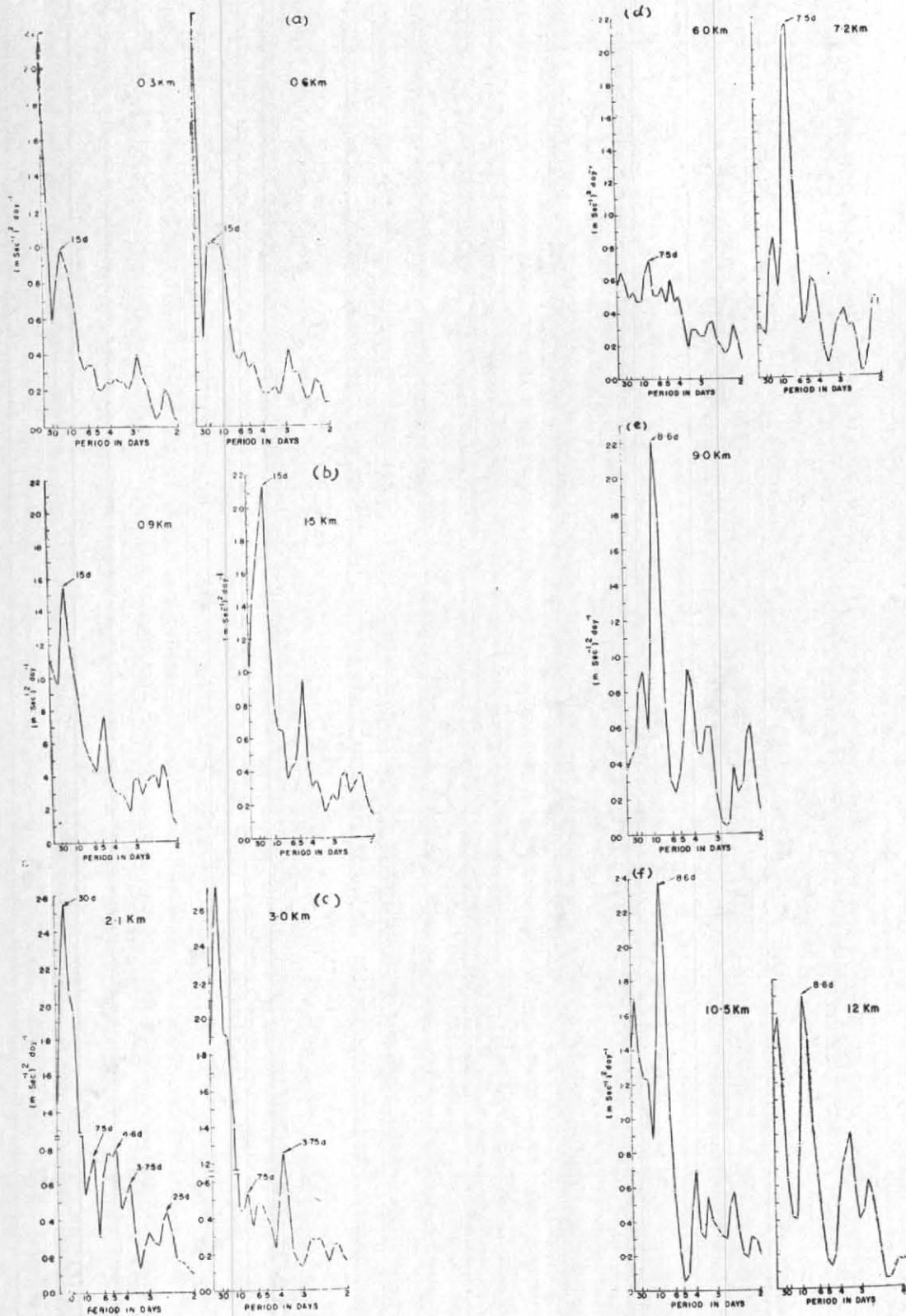
Fig. 2

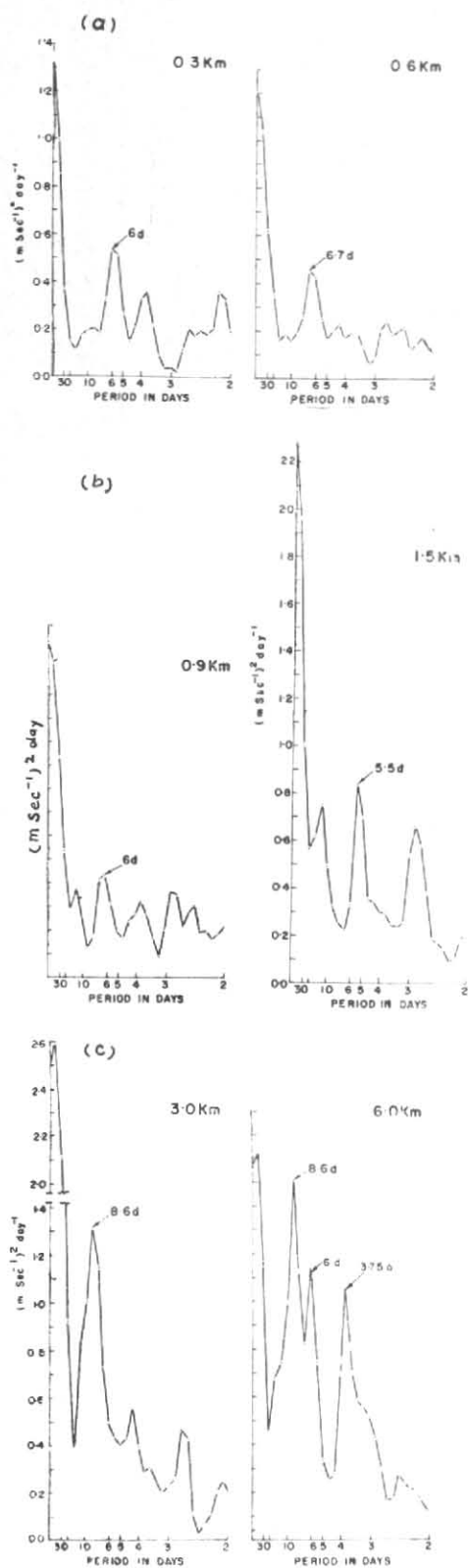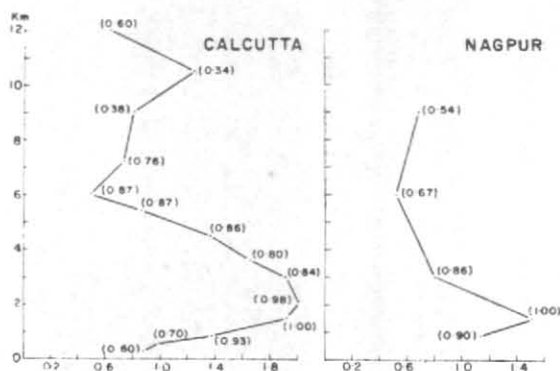Calcutta *v*-component, Jun–Sep 1967

Fig. 3

Lucknow *v*-component, Jun–Sep 1967

Fig. 4

Power spectral density *v*-component (m/sec) ^{2}/day
($P=20$) days

The frequency of lower tropospheric monsoon disturbances progressively decreases from their place of origin close to Calcutta towards their region of dissipation over northwest India. Thus it is seen that the periods obtained in the lower troposphere at Nagpur are longer than those at Calcutta. The frequency at Nagpur is roughly representative for the central parts of the country. Hence it is considered to be of interest to concentrate on the dominant peaks at Nagpur, *i.e.*, 20 days, 5-6 days and 7·5 days.

Figs. 4, 5, 6 show the vertical profile of power spectral density in these periods. Corresponding to the period of 20 days (Fig. 4) we see that both Nagpur and Calcutta show maximum power in the lower troposphere, *i.e.*, around 1·5 to 2·0 km. The power falls off with height, *i.e.*, these disturbances are most marked in the lower troposphere. The coherence of the disturbance at different levels compared with that at 1·5 km is calculated and shown in the brackets. The coherence values decrease to 0·5 only above 7·2 km at Calcutta and above 9·0 km at Nagpur showing that these disturbances extend from the surface to 7-9 km.

The vertical profiles of power spectral density in the period of 5 days show similar features, *i.e.*, maximum power in the lower levels which falls off with height (Fig 5). These were calculated with the maximum lag 15. The coherence values with 6 km as reference level show that the depth of the disturbance at Calcutta is from surface to above 9 km, at Nagpur from surface to just below 9 km. At Lucknow the coherence values have been calculated with 1·5 km as the base. The disturbance extends from surface to above 6 km. It is seen that in this period also the disturbances extend from the surface to about 7-9 km.

Let us now see the vertical structure of the disturbance in the period $P=7·5$ days (Fig. 6)
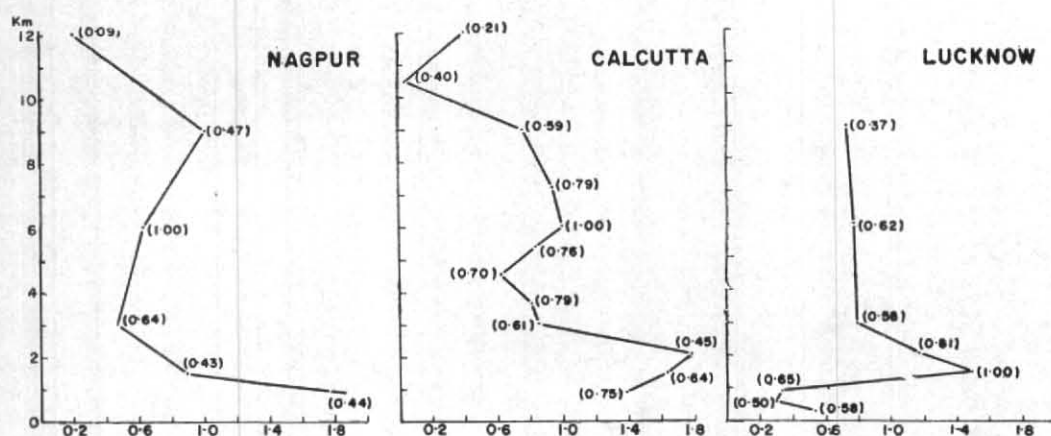
Fig. 5

Power spectral density v-component (m/sec)^2/day ($P=5$ days)

A marked contrast is seen. At Nagpur the maximum power in this period is found at 6 km and above and very small power in the lower levels. Similarly at Calcutta the maximum power is found in the upper troposphere (at 7·2 km) and very small power in the lower levels. At Lucknow the maximum power is seen at 3 km and above. The coherence values at Calcutta and Nagpur show that these disturbances extend from about 2-3 km to just around 12 km though they have maximum power in the middle and upper tropospheres.

Thus we have two types of disturbances: (i) corresponding to the period of 20 days and 5 to 6 days. These disturbances extend from the surface to 7-9 km. These have maximum power around 1·5 km which falls off with height. (ii) disturbances corresponding to period of 7 to 8 days. These have maximum power around 6-7 km but extend from 2-3 km to nearly 12 km.

4. Vertical coupling in the monsoon atmosphere

Charney (1969) has shown from considerations of scale analysis that synoptic scale motions in the tropics have no coupling between the upper and lower troposphere except in regions of deep cumulus convection. He surmises that upper tropospheric systems are coupled laterally to extra-tropics and the lower tropospheric systems develop in the ITCZ. The observational evidence of Yanai *et al.* (1968) lends support to this view. The fact that baroclinic instability theories do not explain the growth of tropical disturbances lend indirect support to this and that is how the cooperation of the cumulus scale is invoked and the theory of conditional instability of the second kind has been formulated. Yanai *et al.* (1968) found two types of disturbances, one corresponding to

easterly waves in the lower troposphere which had large coherence in the vertical from 1000-500 mb and the other—waves of horizontal extent 10,000 km with maximum intensity around 17 km which have large coherence between 200 and 50 mb.

Let us now examine the state of affairs in the monsoon atmosphere. It is seen that disturbances in the periods 20 days and 5·5 days extend from the surface upto 7-9 km with their maximum intensity around 1·5 km. The other type of disturbance corresponds to period 7 to 8 days and is most marked in the middle and upper tropospheres but extends from 2-3 km to nearly 12 km. Thus, though we have two types of disturbances one most marked in the lower troposphere and the other most marked in middle and upper troposphere, both have large vertical extents. The coherence values and the large spectral density at 500 mb in the period 7·5 days show that there is coupling across the middle troposphere. Therefore it appears that there is more vertical coupling in the monsoon atmosphere than in the rest of the tropics. The vertical coupling thus deduced from observations can be due to large-scale vertical motion or due to the persistent deep cumulus convection near the monsoon trough. Of the stations we have studied, Calcutta lies on the monsoon trough and Nagpur is not too far from it.

It is tempting to postulate that the disturbances of period 20 days result from the superposition of the lower tropospheric disturbances of period 5·5 days by the upper and middle tropospheric disturbances of period 7·5 days. Charney (1969) has postulated that nonlinear coupling of the disturbances in the lower and upper troposphere produces a beat period of 12 days which is actually observed by Wallace and Chang (1969). Following
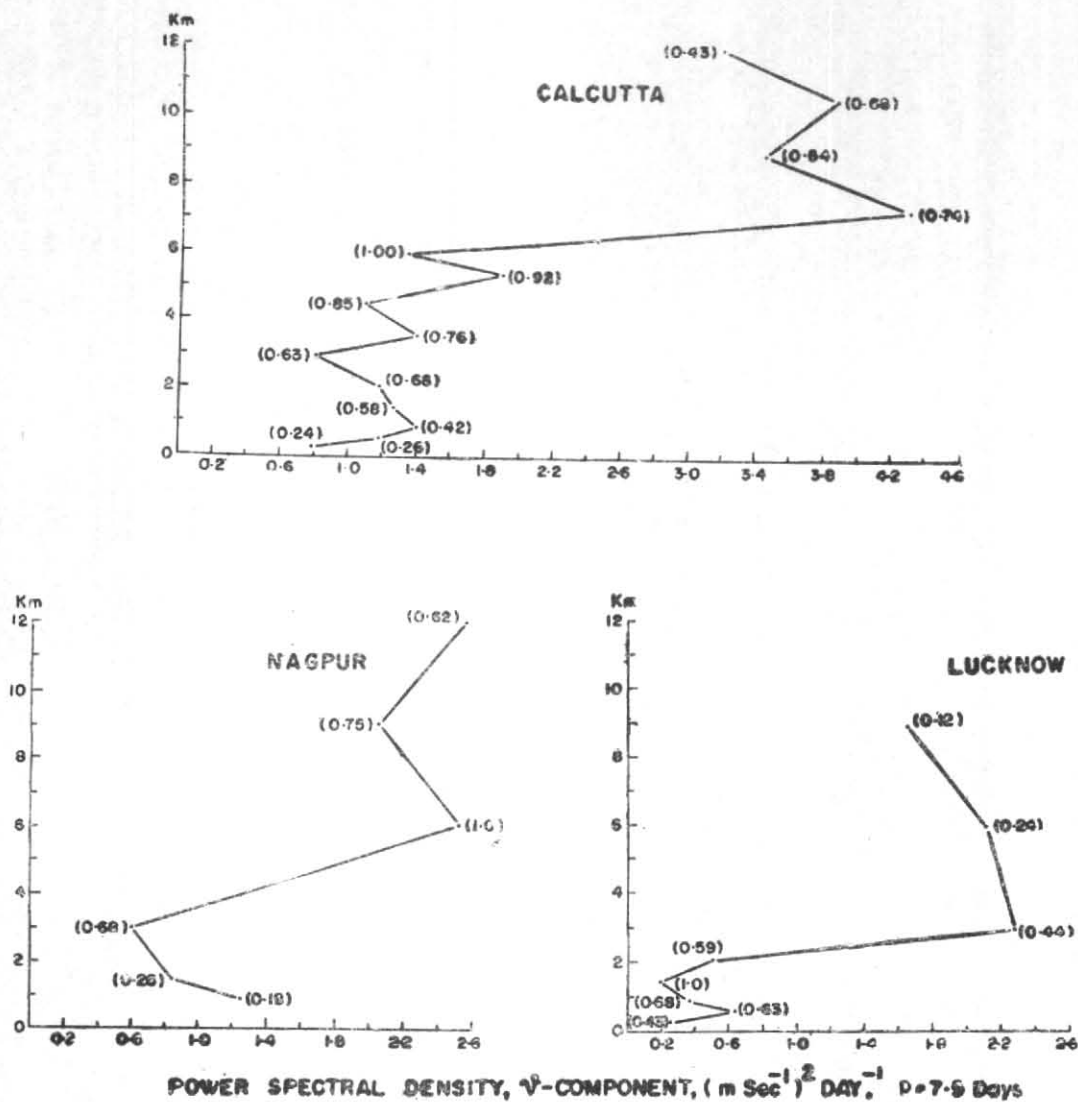
POWER SPECTRAL DENSITY, V-COMPONENT, (m Sec^{-1})^2 DAY^{-1}, D = 7.5 Days

Fig. 6

the same logic the superposition of the lower tropospheric disturbances of period 5·5 days by the upper tropospheric disturbance of period 7·5 days should lead to a beat period of $(5.5^{-1} - 7.5^{-1})^{-1}$ ≈ 20 days. This fits in exactly with the longer period found.

Synoptically speaking the lower tropospheric disturbances of period 5·5 days correspond to (weak) monsoon lows which are quite frequent. The upper and middle tropospheric disturbances of period 7·5 days correspond to the waves and lows at these levels. The superposition of every 4th lower tropospheric disturbance by every 3rd upper tropospheric disturbance (on an average) leads to intensification and results in the monsoon depression of period 20 days. These are

most marked in the lower levels and extend to 400-300 mb. This lends support to the observations of Koteswaram and George (1958) who produced synoptic evidence to show that superposition of upper tropospheric waves on low level disturbances leads to intensification. The dominant peak seen at Calcutta in the lower troposphere is of period 15 days, and that at Nagpur is of period 20 days. These correspond to monsoon depressions. It is known that their frequency is more near Calcutta and falls off to the west, as some of them dissipate.

5. Horizontal scale and phase velocities of disturbances in v-component

The horizontal structure of these disturbances is studied by computing the cross spectra between

TABLE 3

Wavelengths and phase velocities of disturbances

Level (mb)	Period (day)	Wavelength (deg. Long.)	Phase velocity (E to W)
850	20	34	1·7
850	5·5	20	3·6
500	7·5	35	4·7

v-components of different stations. The phase differences between the spectra of station pairs: Nagpur-Calcutta, Nagpur-Visakhapatnam, Nagpur-Port Blair, Lucknow-Calcutta, Visakhapatnam-Port Blair have been computed at different levels. Following Yanai *et al.* the phase difference ($\triangle\theta$) between the station pairs is plotted against their longitudinal separation ($\triangle\lambda$) (in degrees). Then a straight line is drawn and the wavelength is calculated. Of course, the stations have latitudinal separation also; but, if we reject the station pairs on this account very few will be left. While drawing the straight line, less weight is given to station pairs having large latitudinal separation. The coherence values are shown in bracket. Figs. 7 & 8 show the $\triangle\theta$– $\triangle\lambda$ diagrams at 850 mb corresponding to the periods $P=20$ days and $P=5\cdot5$ days. Disturbances in this period are most marked at this level. The straight line fit for $P=20$ days is excellent; but the coherence values are rather poor. In this case we get the wavelength of 34 degrees longitude. The movement is from east to west as stations to the east always lead. The speed of movement is $C = 34°/20$ day $= 1\cdot7°$/day. For disturbances in the period range of $5\cdot5$ days the straight line fit is not bad; the coherence values are somewhat larger than for $P = 20$ days. The wavelength is obtained as $20°$ longitude. The direction of movement is from east to west and speed of movement is $C = 20°/5\cdot5$ day $= 3\cdot6°$/day.

The disturbances in the period range around $7\cdot5$ days are most marked around 500 mb. Therefore the $\triangle\theta - \triangle\lambda$ diagram has been drawn at this level (Fig. 9). Here we find that the scatter of points is much more ; but coherence values are larger. Neglecting the farthest point which corresponds to Nagpur-Port Blair (coherence $0\cdot64$) which has very large latitudinal separation and drawing a straight line, we get the wavelength of $35°$. The movement is from east to west and the speed of movement $C = 35°/7\cdot5$ day $= 4\cdot7°$/day (Table 3).
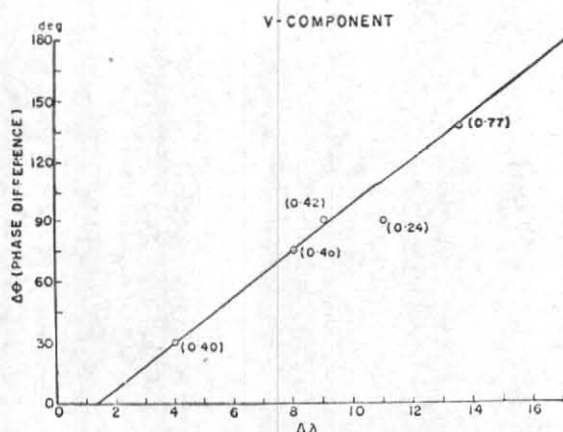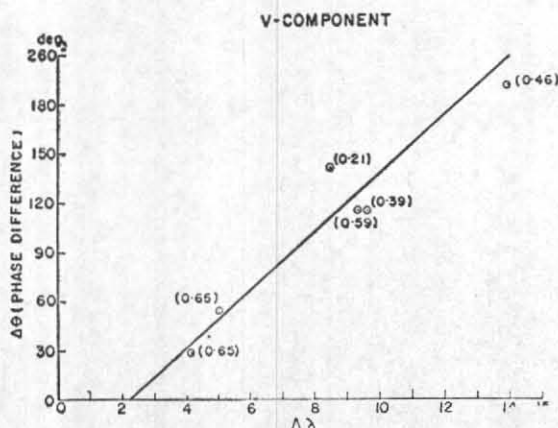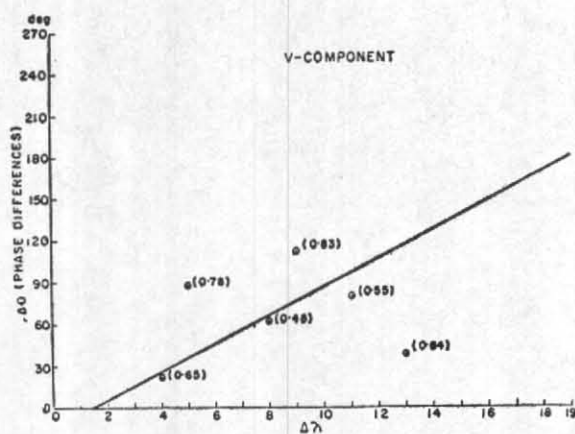

Fig. 7

$P=20$ days

Fig. 8

$P=5\cdot5$ days

Fig. 9

$P=7\cdot5$ days

So there are three types of disturbances. The one corresponding to a period of 20 days and having a scale of 34° longitude corresponds to monsoon depressions. These move slowly westwards with a speed of 1·7 deg. Long./day. These disturbances, as we have seen earlier, are most marked in the lower levels around 850 mb. The other lower tropospheric disturbance of period 5·5 days is of smaller scale, i.e., around 20 degrees longitude. These correspond to the weaker monsoon lows. These move (westwards) a little faster with a speed of 3·6 deg. Long./day.

The disturbances with a period 7·5 days which are most marked in the middle and upper troposphere have a scale of 35°. These correspond to the middle and upper tropospheric lows and or troughs. These move faster than the lower tropospheric disturbances. Because of the slightly different speeds of the disturbances of the lower and upper tropospheres, superposition and favourable location with respect to each other is possible.

The scales of the disturbances, estimated by the above method, correspond to complete wavelengths. On synoptic charts we generally concentrate on cyclonic circulations only, which would correspond more to half-wavelength. Therefore considering only the cyclonic portions the scale of the monsoon depressions and middle and upper tropospheric lows and waves would be about 17 degrees of longitude and that of the monsoon lows would be about 10 degrees. Also, the present analysis takes

the distance between the maximum southerly and maximum northerly component of wind as half a wavelength. This can be checked from charts to be around 15-degree longitude. The maximum cyclonic vorticity is, however, concentrated over a much smaller longitude belt. The present analysis cannot distinguish this fine point.

6. Conclusion

1. Three types of disturbances in the v-component of the wind have been found.

(i) Disturbances of period 15-20 days, horizontal scale 35 deg. Long. and extending from the surface to 400-300 mb. They are most marked around 850 mb. These probably correspond to monsoon depressions.

(ii) Disturbances of period 5·5 days, horizontal scale 20 deg. Long. being most marked in the lower levels. These presumably correspond to the weaker, but more frequent, monsoon lows.

(iii) Middle and upper tropospheric lows and waves of scale 35 deg. Long. All these disturbances move westward.

2. There is evidence of significant vertical coupling over the Indian region during summer monsoon.

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