Indian J. Met. Hydrol. Geophys. (1978), **29**, 1 & 2, 26-35

551.515.1 : 551.553.21 (540)

Investigation of monsoon lows by the method of spectrum analysis

MASATO MURAKAMI

Department of Meteorology, Florida State University, Tallahassee, Florida

ABSTRACT. The method of spectrum analysis is applied to the time-series data over India during the summer monsoon season 1962. The periodicity around 5 days appears as a spectral peak in the lower troposphere over the monsoon trough region, corresponding to the passage of so-called monsoon lows. It is confirmed by the horizontal cross spectrum analysis that these monsoon lows propagate westward and their longitudinal wavelength is about 30°.

The mean vertical structure of monsoon lows is investigated and compared by using the data of two stations located on the coast of the Bay of Bengal and on the inland of northern India. The results of both stations show that the cyclonic circulation of monsoon lows prevails in the lower troposphere and their axis tilts slightly westward with height. They also bear warm-cored structure in common in the upper levels.

The most remarkable contrast appears in the field of specific humidity. When monsoon lows are in the vicinity of the Bay of Bengal, moistening occurs in coincidence with southerly winds, *i.e.*, in the east of the trough. On the contrary, moist and cold anomalies appear in the west of the trough with northerly wind over the inland area. These contrasts suggest an intense geographic effect of Indian subcontinent on the life cycle of monsoon lows.

1. Introduction

The most well-known synoptic disturbances which occur during the summer monsoon season over India are monsoon depressions. They are usually formed in the north Bay of Bengal and travel westward along the so-called monsoon trough which extends over the Gangetic Plain in northern India. They bring the copious rain along the path of their propagation and have drawn various kinds of investigations up to date (*see* Rao 1976, for example). Statistics of monsoon depressions show that their formation in the Bay occurs with the frequency of about 1·8 per month.

On the other hand, another type of synoptic disturbances also exists in the monsoon trough region. These disturbances are not so intense as monsoon depressions, but more frequently pass through this region with the average life time around 5 days. They are called "monsoon lows" and are also responsible for causing substantial rainfall. Synoptic studies have been also made on these monsoon lows up to date. However, partly due to their diffusive appearance on synoptic maps, their structure and characteristic features have not been fully established yet.

After the success of the method of spectrum analysis applied to the disturbances over the tropical Pacific (Yanai *et al.* 1968, Wallace and Chang 1969 and others), some attempts have been made to apply this method to monsoon disturbances. Ananthakrishnan and Keshavamurty (1970) found some definite spectral peaks which show the periodicity longer than 10 days and around a week in the surface pressure oscillation. Krishnamurti *et al.* (1973) also found that the variation of the intensity of Tibetan high shows the periodicity around 13 to 15 days and around 3 days. Keshavamurty (1973) further tried to identify the spectral peaks appearing in the variation of meridional wind with the known disturbances like monsoon lows and depressions. In this study, it is shown that dominant spectral peaks around 15-20 days, 7-9 days and 5-6 days appear in the variation of meridional wind. He regarded these peaks as the reflection of the passage of monsoon depressions, middle tropospheric troughs and monsoon lows, respectively.

Recently, Murakami[1] (1976) made a spectral analysis of the temporal variations during summer monsoon period over India. He picked up two major periodicities commonly appearing in the variation of meteorological quantities in the monsoon trough region. One is the periodicity around 15 days and another is around 5 days. In his study, the characteristic features of these periodicities are examined and it is concluded that the periodicity around 5 days reflects the passage of so-called monsoon lows. The oscillation around 15 days seems to be related with the active/weak cycle of the monsoon. He further investigated the vertical structure of monsoon lows by the method of cross spectrum analysis. However, since the large-scale situation for these synoptic-scale disturbances change rather significantly between the oceanic and the inland area along the monsoon trough, their structure is likely to be affected when they travel through these two different regions. Therefore, we should make careful investigations when we try to draw some conclusions on the structure of these monsoon lows.

In this study, we intend to discuss the monsoon lows whose passage appears as a spectral peak around a 5-day period in the lower troposphere. Though part of the results are already shown in M, we try to investigate their nature more thoroughly in this paper by examining both the oceanic and inland area of the monsoon trough through which monsoon lows frequently travel. The data are rearranged from the *Indian Daily Weather Report* 1962 and the upper air observation stations are shown in Fig. 1. The period June through August is selected as the summer monoon season and the year 1962 is expected to be the one when the nearly normal monsoon condition occurs.

2. Mean resultant field

In this section, we examine the horizontal distribution of the mean resultant fields and discuss their difference along the monsoon trough in northern India. Though the period of analysis extends for three months, the mean resultant fields of July are shown in this section. This month is presumed to bear the most intense monsoon activity and to show the typical situation of the monsoon season as the mean field with the least distortion due to the seasonal trend.

[1]Hereafter referred to as M.

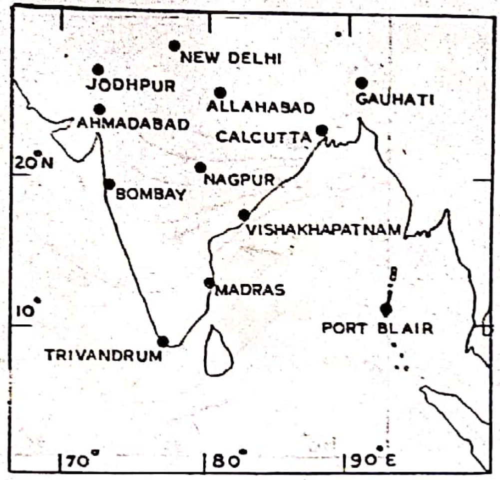
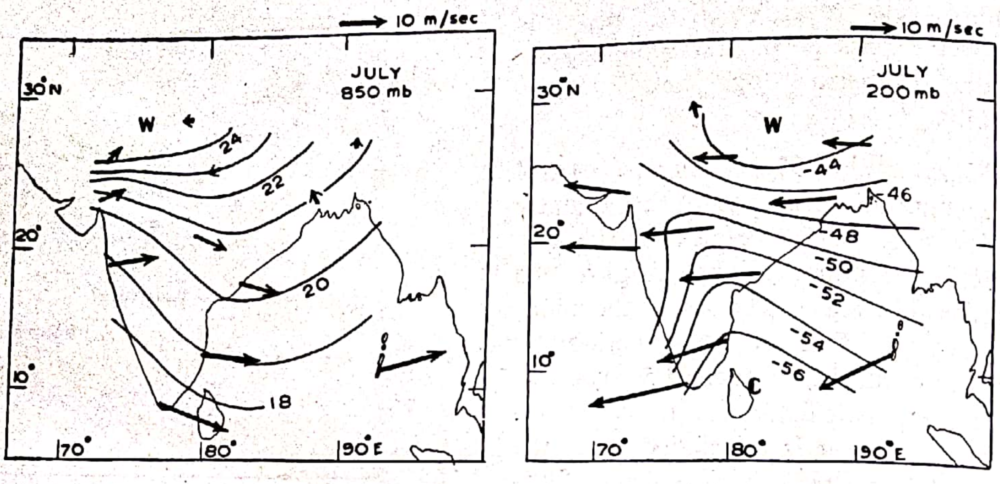


Fig. 1. Upper air observation stations over India used in this study

Figs. 2(a) and (b) show the horizontal distribution of the mean resultant wind and temperature as to the lower and upper troposphere. In the lower troposphere exhibited in Fig. 2(a), monsoon westerlies prevail over the central and southern part of India, while the easterlies appear over the northern India. The zone with cyclonic shear appears between these two wind regimes, corresponding to the monsoon trough. This zone lies roughly along 25°N and we can see that the southerly wind component is intensified near the head Bay of Bengal compared with the inland part of the monsoon trough. In the upper troposphere shown in Fig. 2(b), strong easterlies prevail over the whole Indian subcontinent, reflecting the existence of the easterly jet in the south of the Tibetan high.

Though the gradient indicating northward increase of the temperature is outstanding throughout the lower and upper troposphere, we can also see some longitudinal differences in the temperature field. In the lower troposphere in Fig. 2(a), the maximum temperature appears in the northwestern part of India, reflecting the surface heat low over the desert in this region. Between this area and the north Bay of Bengal, there exists a longitudinal temperature gradient which shows the increase towards the inland area along the axis of monsoon trough. In the upper troposphere in Fig. 2(b), maximum temperature appears in the northern part of India near the Himalayas in connection with



(a) (b)

Fig. 2. Horizontal distribution of the mean resultant wind (arrows) and the temperature (solid lines; °C), (a) at 850-mb level and (b) at 200-mb level

the warm Tibetan high in the upper levels. The distribution of this upper level looks rather zonal over the monsoon trough region, though there exists an obvious longitudinal contrast over southern India between the Bay of Bengal and the Arabian Sea.

The vertical stratification of the atmosphere also shows the difference between the coastal and the inland area. This difference is mostly due to the different vertical distribution of the atmospheric moisture. The situation is illustrated in Fig. 3 in which the vertical distribution of mean potential and equivalent potential temperatures are shown as to both Calcutta and Allahabad. As for the profile of dry potential temperatures, both stations show similar profiles apart from the difference of their absolute values. However, the moist equivalent potential temperatures show different stratifications between the two. Though both of them represent the existence of the conditionally unstable layer in the lower troposphere in common, the conditional instability at Calcutta is more intense than Allahabad and is more concentrated in the lowermost layer below the 850-mb level. The profile of equivalent potential temperature at Allahabad represents that the instability is relatively weak and the unstable layer is broadened vertically in the lower troposphere. In other words, the vertical distribution of the equivalent potential temperatures becomes more uniform at Allahabad.

However, it is not yet assured at this stage using only two stations that the above difference actually comes from the contrast between the coastal and the inland area. In order to examine this problem, we define an index *Ie* which represents the moist stability in the lowermost layer as follows,

$$I_e \equiv \frac{\overline{\theta}_{e,850} - \overline{\theta}_{es}}{\overline{P}_s - 850} \times 100$$

where $\overline{\theta}_{e,850}$ and $\overline{\theta}_{es}$ denote the mean equivalent potential temperature at the 850-mb level and the surface, respectively. $\overline{P}_s$ denotes mean surface pressure. By using the index I_e, the moist stability in the lowermost troposphere near the surface is examined over the whole Indian subcontinent. The results are exhibited in Fig. 4. This figure shows the horizontal distribution of the values of I_e for July. Negative values represent the moist instability of the atmosphere below the 850-mb level and their absolute values denote intensity. It can be seen in this figure that the values are distributed systematically and their absolute values decrease rapidly across the coast towards in the inland area. Relatively, the most stable (least unstable) area appears over the northwestern part of India near Thar Desert. It is noteworthy that the relatively stable area also extends to the southern part of India behind the Western Ghats which range along the western coast of India. This region corresponds to the leeside of the mountains during the season of the monsoon westerly and is known as the semi-arid region during this period.

The results discussed above show that there exists some remarkable contrasts between the coastal and the inland area over northern India, especially in the lower troposphere. They can be seen not only in the values of the temperature and the wind in horizontal domain, but also in the vertical stratifications of the lower atmosphere. These contrasts are

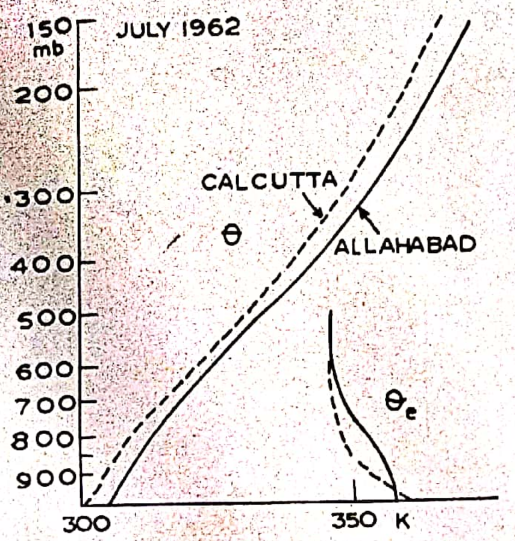


Fig. 3. Vertical distribution of the mean potential temperature (θ) and the mean equivalent potential temperature (θ_e) at Calcutta and Allahabad

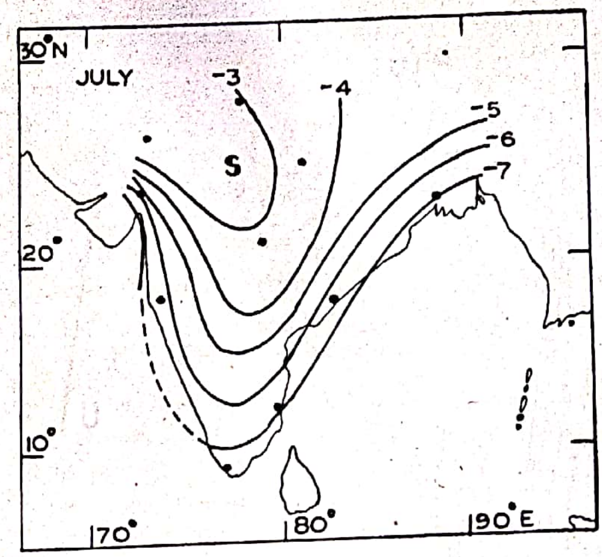


Fig. 4. Horizontal distribution of I_e over India. (S denotes relatively stable area)

likely to affect the monsoon lows propagating through this region. In the next section, we investigate their horizontal propagation and examine whether any significant change takes place in their structure during the propagation.

3. Spectrum and cross spectrum analysis

3. 1. *Horizontal extent and the propagation*

Though this part of the results has been already discussed by M, the item concerning the monsoon low is repeated here briefly for the convenience of the following discussions.

Fig. 5 shows the result of the power spectrum analysis applied to the zonal and the meridional wind at Calcutta. In this figure, it can be seen that the spectral peak around a 4 to 5-day period appears in both zonal and meridional winds consistently through the lower troposphere. The spectral peak of this periodicity also appears at other stations as well. Fig. 6 shows the horizontal distribution of the power of meridional wind oscillation contributed by this period range. The distribution in the figure indicates that the amplitude of the oscillation around 5 days is large in the range from the north Bay of Bengal through the monsoon trough region in northern India. In addition, the larger power over the monsoon trough region disappears in the upper troposphere, though the figure is not shown in this paper. It indicates that the disturbance in this period range is prominent mainly in the lower troposphere.

Above facts on periodicity and three-dimensional extent seem to suggest that the spectral peak around 5 days reflects the passage of monsoon lows through this region. In order to verify this speculation, we further examine the horizontal scale and propagation by the method of cross spectrum analysis. This method is applied to the stations located in the range of large power shown in Fig. 6. The result is exhibited in Fig. 7. It represents the relationship between the phase difference of the disturbance and the longitudinal difference of the stations. Values are obtained by using the data of meridional wind and then averaged in the lower troposphere 0·3 through 5·4 km level. The values with coherence less than 0·6 are excluded from the process of estimation. After that, the regression line is drawn subjectively in the diagram.

In this diagram, it is clearly seen that the phase difference increases systematically with increasing longitude and the values are well approximated by the line. This fact indicates that the disturbances in this period range propagate westward in the lower troposphere. We can estimate their longitudinal wavelength from the inclination of the line. It is about 30° in longitude. Furthermore, we can also estimate that the longitudinal phase speed of the disturbance is about 6°/day.

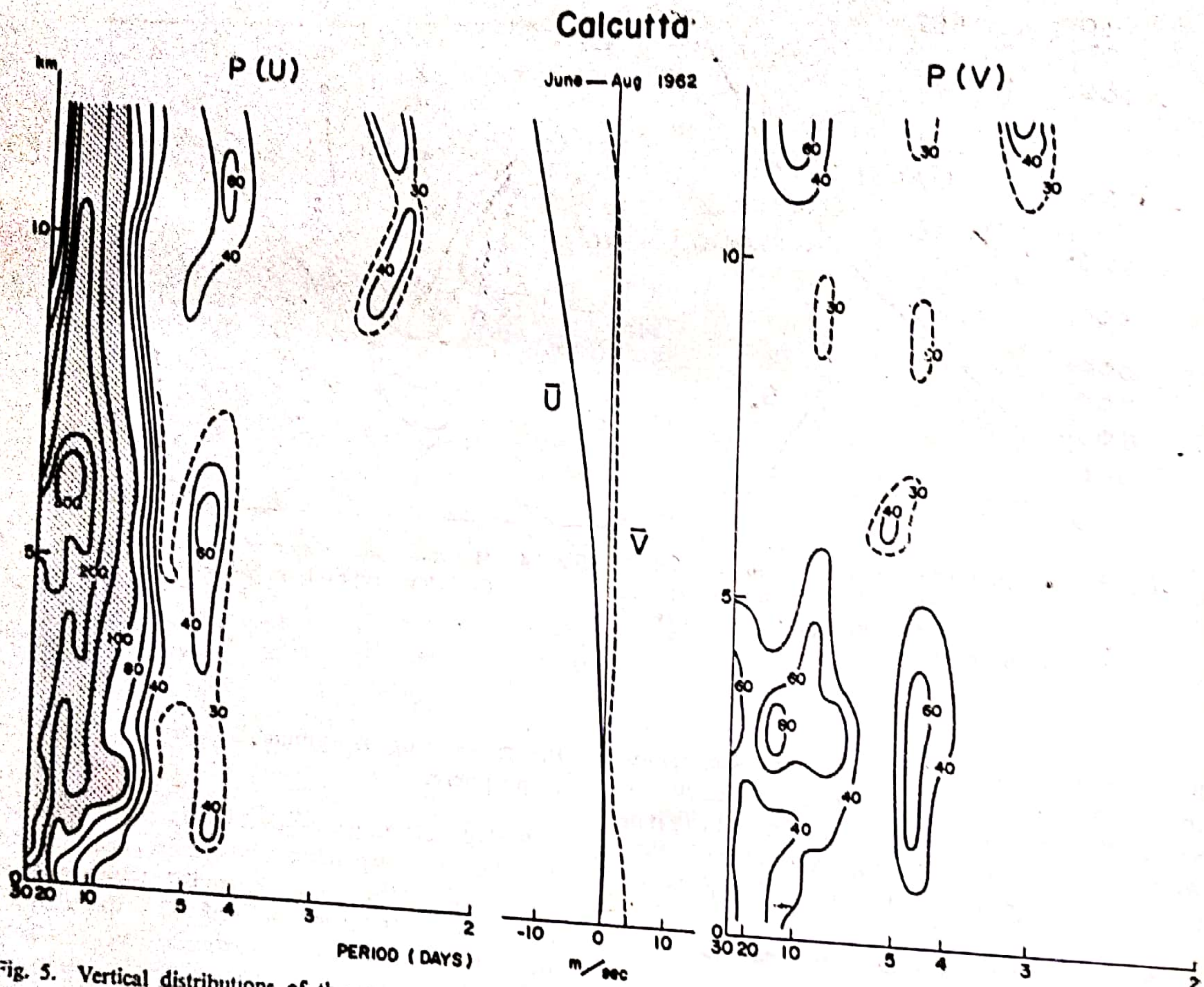


Fig. 5. Vertical distributions of the power spectral densities of the zonal (left) and the meridional (right) wind components and their mean values. (Units of the power spectral densities are (m/sec)^2 day and values more than 100 are shaded)

The results mentioned above are consistent with our knowledge that monsoon lows are the synoptic-scale disturbances travelling westward from the head of the Bay of Bengal through the monsoon trough region and they are dominant in the lower troposphere. In the next subsection, we discuss the vertical structure of these monsoon lows and see to what extent they are affected by the different situations mentioned in the previous section during their propagation.

3. 2. *Vertical structure*

In this subsection, the mean vertical structure of the monsoon low is discussed by applying the inter-level and inter-variable cross spectrum analysis to the data of Calcutta and Allahabad. As shown in Fig. 1 previously, Calcutta is located on the coast at the head of the Bay of Bengal, while Allahabad can be presumed to be the inland station. Both stations also belong to the area which shows the large amplitude of the disturbance as exhibited in Fig. 6 previously.

Fig. 8 represents the results of inter-level cross spectrum analysis at Calcutta in terms of the vertical distribution of powers, coherences and the phase differences relative to the 3-km level. In this figure, it is shown that the power of the meridional wind component decreases with height roughly above the 3-km level. The coherences relative to this level are also small in the upper levels. As for the distribution of the phase differences, it is remarkable that they show the systematic phase increase with height. Considering this with the result that the disturbance propagates westward, it can be

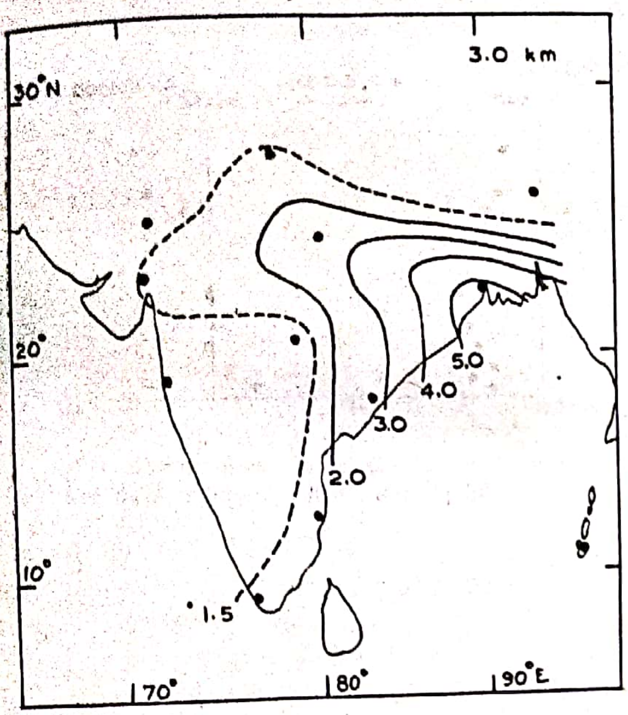


Fig. 6. Horizontal distribution of the power at 3-km level produced by the meridional wind in the period range 4·0 through 6·0 days

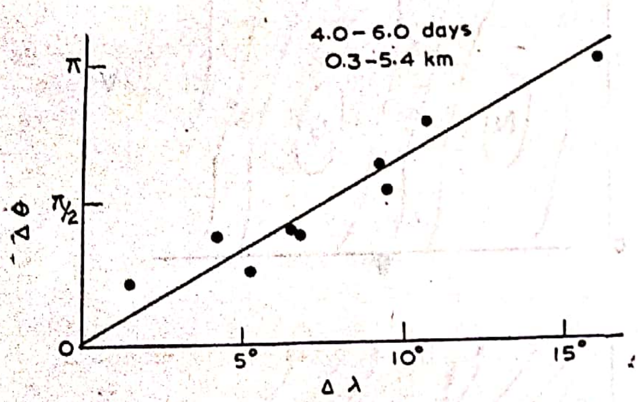


Fig. 7. Relation between the phase difference (Δθ) of the meridional wind and the longitudinal difference (Δλ) of the stations in the period range 4·0 through 6·0 days

concluded that the axis of these monsoon lows tilts slightly westward with height at Calcutta.

Fig. 9 exhibits the results of the same analysis applied to the data of Allahabad. The figure shows that the power also decreases with height above the 3-km level and the phase of meridional wind increases with height, too. This means that monsoon lows bear nearly the same structure of meridional wind both at the coastal and the inland area. At both stations, the amplitude of the meridional wind is prominent in the lower troposphere below the 5-km level and both show the westward tilt of the axis with height. This structural consistency supports *a posteriori* the method of horizontal cross spectrum analysis applied to the same meridional wind in the previous subsection in order to estimate the horizontal wavelength of monsoon lows. Unless nearly the same structure is maintained throughout the propagation, this method is likely to lead to the misunderstanding about their horizontal scale.

The inter-level cross spectrum analysis can be also applied to the data of temperature and specific humidity as well. The vertical distributions of the power and the phase differences were also examined for each variable at both stations. However, instead of repeating the detailed discussion on the individual result here, we would rather discuss the synthesized results which show the mean vertical structure of monsoon lows. This structure is obtained by estimating the amplitude from the power and reconstructing the relative phase relationship from the results of inter-level and inter-variable cross spectrum analysis.

Fig. 10 represents thus obtained mean vertical structure of monsoon lows at Calcutta. It shows the mean vertical structure of monsoon lows passing over this station for one cycle. Relative phase relationship is exhibited with respect to the centre of the surface low. Though it is originally obtained from the phase differences in time, they are transformed into the longitudinal differences by considering the facts revealed in the previous subsection that the disturbance propagates westward and its longitudinal wavelength is 30°. The vertical trough line is determined as the line where the meridional wind changes from the northerly to the southerly.

The structure of meridional wind in this figure shows that the cyclonic circulation of the monsoon low is prominent in the lower troposphere below the 500-mb level. The trough line coincides with the surface low at the lowermost layer and tilts slightly westward with height as discussed previously. The temperature anomalies associated with monsoon lows are small near the surface, while they become large in the upper levels. In these upper levels, the area of warm anomalies nearly coincides with the trough. It indicates that the monsoon low has a warm core in the upper levels. This upper warm core is consistent with the fact that the intensity of the cyclonic circulation decreases

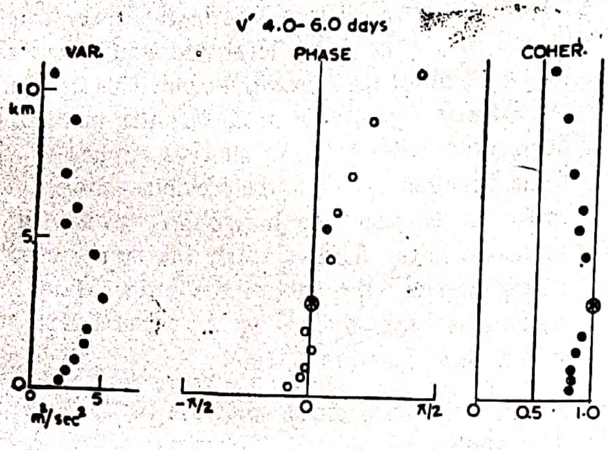


Fig. 8. Vertical distributions of powers (left), phase differences (middle) and coherences (right) of the meridional wind in the period range 4·0 through 6·0 days at Calcutta

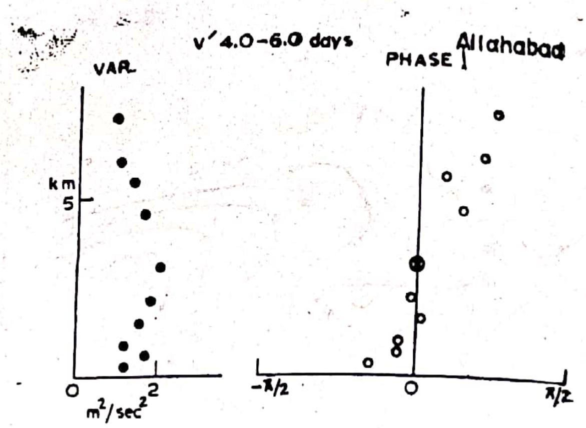


Fig. 9. Same as Fig. 8 except for powers (left) and phase differences (right) at Allahabad

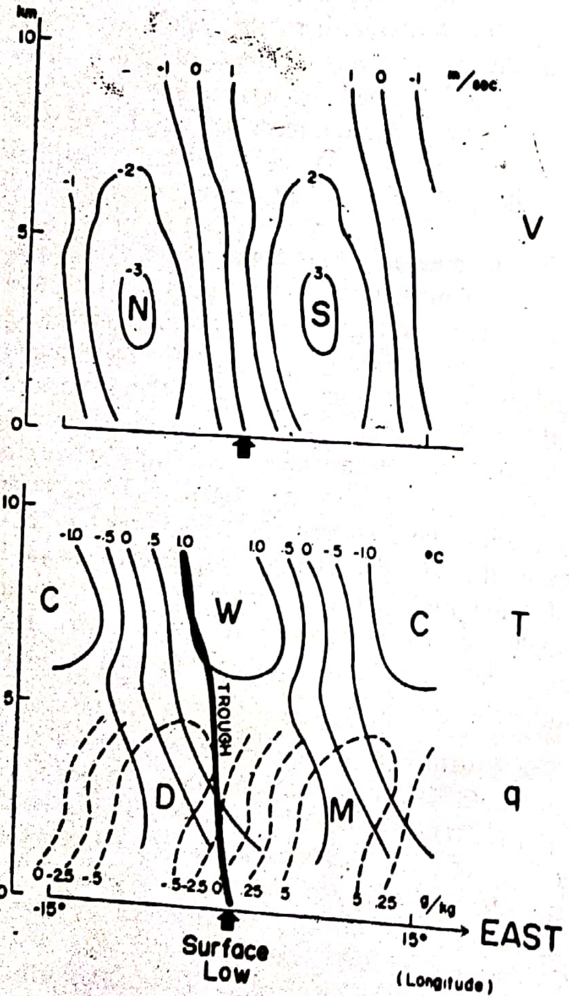


Fig. 10. Mean vertical structure of monsoon lows at Calcutta

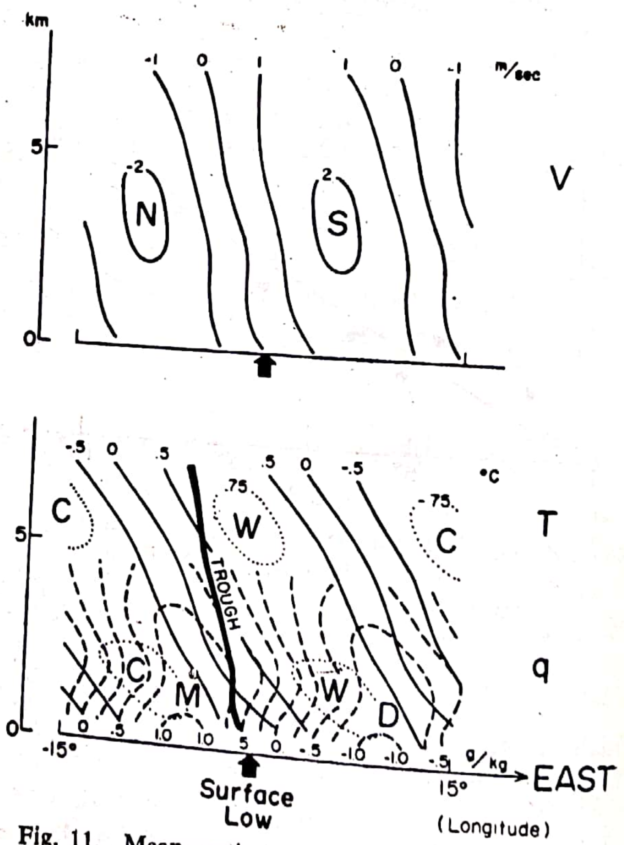


Fig. 11. Mean vertical structure of monsoon lows at Allahabad

in these upper levels. As for the variation of specific humidity, the area of moist anomalies appears in the east of the trough in the lower troposphere. This area coincides well with the southerly wind from the Bay of Bengal. Relatively dry anomalies take place with the northerly wind at this station.

Fig. 11 represents the mean vertical structure at Allahabad obtained in the same manner as Fig. 10, though the levels above 9 km are not available at this station due to the large number of missing observations. Comparing these two figures, it is obvious that the structure of meridional wind is nearly the same both at Calcutta and Allahabad. Both show that the cyclonic circulation of monsoon lows is prominent in the lower troposphere and its axis tilts slightly westward with height, while the intensity of cyclonic circulation is reduced at Allahabad reflecting the decay of lows during their propagation into the inland area.

On the other hand, temperature anomalies show more significant change between the two stations, especially in the lower levels. At Allahabad in Fig. 11, there exists two major amplitudes of temperature variation in the lower and upper levels, while only one major amplitude appears in the upper levels at Calcutta. In the lower levels at Allahabad, the warm anomaly takes place in the east of the trough and the cold anomaly occurs in the west, though the trough itself belongs to the relatively cold regime near the surface. We can seen that the phase of the temperature relative to the meridional wind advances with height so that the warm anomaly nearly coincides with the trough in the upper levels above 5 km. It means that the monsoon low at Allahabad also bears a warm-cored structure in these levels as at Calcutta.

The most outstanding contrast appears in the field of specific humidity. At Calcutta shown in Fig. 10, moist anomaly takes place in the east of the trough in coincidence with the southerly wind blowing from the Bay of Bengal. On the contrary, the moistening occurs in the west of the trough in case of Allahabad. Thus, at this inland station, the relatively moist and cold regime appears in the west of the trough in coincidence with the northerly wind and *vice versa* in the east of the trough. It should be noted that the amplitude of these thermal variables (*i.e.*, temperature and specific humidity) near the surface are even intensified in this inland area in spite of the decay of the cyclonic circulation of monsoon lows.

It also deserves interest that the mean vertical structure of monsoon lows in the inland area discussed above resemble the composited structure of monsoon depressions obtained by Godbole (1976). In his work, it is shown that the cyclonic circulation of the depression is confined in the lower troposphere below the 400-mb level and its axis slightly tilts westward in the longitude-height plane. He also showed that the very moist regime takes place ahead of the depression, *i.e.*, in the west of the trough. In addition, he obtained a very definite cold-cored structure in the lower troposphere and a warm core in the upper levels, being similar to the results obtained in the case study by Krishnamurti *et al.* (1975). These results almost agree with those on monsoon lows except for the lower cold core which is not very obvious in case of monsoon lows. This resemblance and the fact that the composited structure of depressions is based mainly on the observation over the land seem to suggest that both monsoon lows and depression over the inland area belong to the same family of disturbances. It seems that depressions are much more intensified than lows under some favourable conditions which are not revealed yet.

4. Summary and concluding remarks

In this study, we discussed the horizontal distribution of the mean basic state of the atmosphere and investigated the characteristic features of the oscillation associated with monsoon lows. As for the distribution of the mean basic state, we can see some longitudinal differences between the inland and the coastal area along the monsoon trough. These differences are remarkable especially in the lower troposphere. We can see the definite increase of the temperature toward the inland area and the intensification of the southerly wind on the coastal area around the head of the Bay of Bengal. Moreover, the vertical stratification of the lower atmosphere shows that the intensity of the conditional instability rapidly decreases across the coast towards the inland area. This situation of the monsoon trough is in contrast with those of ITCZ in the Pacific or Atlantic in which the approximation of zonal symmetry can be applied as the basic state for the synoptic-scale disturbances.

The passage of monsoon lows through the monsoon trough region appears as a spectral peak around the 5-day period in this area. By applying the method of horizontal cross spectrum analysis to this period range, it is confirmed that monsoon lows propagate westward and their wavelength is about 30° in longitude. It means that their longitudinal phase speed is about 6°/day. Their mean vertical structure is also investigated over the inland and the coastal area, based on the recognition of the regional differences mentioned above.

Some contrasts as well as similarities are revealed as results. As for the kinematic field, nearly the same structure is maintained throughout the propagation, though the amplitude of cyclonic circulation is reduced according to the decay of the monsoon lows. The comparison of temperature fields revealed that monsoon lows bear a warm-cored structure in the upper levels throughout the propagation. On the other hand, the secondary peak of the amplitude appears near the surface when monsoon lows are in the inland area. Near the surface over this region, the warm anomaly occurs in the east of the trough and the cold anomaly appears in the west.

The most remarkable contrast takes place in the field of specific humidity. When monsoon lows are located near the head of the Bay of Bengal, the moist anomaly occurs in the east of the trough with the southerly wind from the Bay. This seems plausible when we consider the existence of a very moist air mass over the Bay. On the contrary, a moist anomaly appears in the west of the trough when they proceed into the inland area. This configuration, however, is consistent with our knowledge that the rainfall associated with monsoon lows and depressions mainly occurs ahead of the trough when they travel westward through the inland area of northern India.

The above results on the monsoon lows over the inland area suggest that the enhanced convective activity associated with them is well-defined in the west of the trough when lows are located in the inland area. But, the situation seems to be different when they are in the vicinity of the Bay of Bengal. The advection of the moist air-mass from the Bay and a large amount of latent heat supply from the sea surface are expected when lows are at the head of the Bay or in its vicinity. Besides, the lows do not receive such a great deal of large-scale topographic effect in the oceanic area as they do when they travel through the inland area. All these contrasts are likely to affect the configuration of major convection activity as well as its intensity and consequently lead to the different field of thermal variables discussed so far. These differences can eventually lead to the different energy budget of the monsoon lows between the two regions.

As a subject of future observation, it seems important to say that the results of this study claim the sufficiently dense observation network over the north Bay of Bengal as well as the inland area of India in order to investigate the whole life cycle of monsoon lows and depressions. The forthcoming MONEX (Monsoon Experiment) is expected to provide a valuable opportunity to examine the above-mentioned problems.

Acknowledgements

The author wishes to express his thanks to Professor T.N. Krishnamurti and Dr. R.V. Godbole for their stimulative discussions and valuable comments. The author is also indebted to Mrs. C. Yata for drafting all the figures and to Mrs. Marge von Goeben for typing the manuscript.

REFERENCES

Ananthakrishnan, R. and Keshavamurty, R. N. 1970 On some aspects of the fluctuation in the pressure and wind fields over India during the summer and winter monsoon seasons. Proc. Symp. Tropical Met., Honolulu, Hawaii.

Godbole, R. V. 1976 The composite structure of the monsoon depression (To be published in *Tellus*).

Keshavamurty, R. N. 1973 *Indian J. Met. Geophys.*, **24**, pp. 117-124.

Krishnamurti, T. N., Daggupaty, S.M. Fein, J., Kanamitsu, M. and Lee, J. D. 1973 *Bull. Amer. met. Soc.*, **54**, pp. 1234-1249.

Krishnamurti, T. N., Kanamitsu, M., Godbole, R., Chang, C.B., Carr, F. and Chow, J. H. 1975 *J. met. Soc. Japan*, **53**, pp. 227-240.

Murakami, M. 1976 *Ibid.*, **54**, pp. 15-31.

Rao, Y. P. 1976 *Southwest Monsoon*, Met. Monogr., India met. Dep.

Wallace, J.M. and Chang, C. P. 1969 *J. atmos. Sci.*, **26**, pp. 1010-1025.

Yanai, M., Maruyama, T., Nitta, T. and Hayashi, Y. 1968 *J. met. Soc. Japan*, **46**, pp. 308-323.

DISCUSSION

U.K. BOSE : Did you examine the data of any station other than Calcutta and Allahabad; for example Gwalior ?

AUTHOR : The stations used are Calcutta, Visakhapatnam, Gauhati, Nagpur, Allahabad, Ahmedabad, Bombay, New Delhi and some others in Southern India. Formally, we can apply the same method for all these stations. But we should be aware that in order to get appropriate X-Z structure including the centre of the lows, we should choose the stations which are located in mean path of lows. In addition, the power at such stations should be sufficient to get reliable results of the cross spectrum analysis. Considering above criteria, I chose Calcutta and Allahabad as proper stations for this purpose.