Mausam, (1988), 39, 4, 375-382

551.553.6

Low frequency oscillations in summer monsoon rainfall over India

A. CHOWDHURY, R. K. MUKHOPADHYAY and K. C. SINHA RAY

Meteorological Office, Pune

(*Received 8 September 1987*)

सार — यह शोध -पत्र भारत पर दक्षिण-पश्चिम मानसून वर्षा के स्थान एवं कालिक के विभिन्न आवृत्ति बहुलक (मोड) परिवर्तन के सम्बन्ध में हैं। देश के प्रसामान्य वर्षा के दैनिक आंकड़ें (1901-1970) और 1978-1983 अवधि के अलग-अलग वर्ष के 220 अच्छे वितरित स्थानों के आंकड़ों का प्रसंवादी (हारमोनिक) विश्लेषण कर विभिन्न आवृत्ति बहुलक के योगदान का मूल्यांकन किया है।

परिणाम से यह प्रकट होता है कि, अलग-अलग वर्षों में तथा दीर्घकालीन प्रसामान्य अवधि में 30 से 60 दिनों की आवर्तता केन्द्रीय प्रायः द्वीप में प्रबल अथवा प्रभावी बहुलक उपस्थित रहती है। मध्य भारत में अच्छी मानसून के वर्षों में उपरोक्त व्याख्यित प्रसरण 30-60 दिनों की अपेक्षा 10-20 दिनों के दोलन का अधिक होता है।

अच्छे मानसून वर्षों में आधारभूत बहुलक प्रायः 25° उ० के उत्तर में प्रभावी होता है जबकि बुरे मानसून वर्षों में यह दक्षिणी अक्षांश की ओर बढ़ता है।

ABSTRACT. The paper deals with spatial and temporal variations of different frequency modes of the southwest monsoon rainfall over India. Daily normal rainfall data (1901-1970) and that of the individual years for the period 1978-1983 for 220 well distributed stations throughout the country are subjected to harmonic analysis to investigate the contributions of different frequency modes.

The results reveal the presence of 30-60 day periodicities as a predominant mode over central Peninsula in the long term normal as well as individual years. The variance explained by the 10-20 days oscillations exceed that of 30-60 days over central India during the good monsoon years.

In good monsoon years the fundamental mode is predominant north of about 25° N while during the bad monsoon years it extends to more southern latitudes.

1. Introduction

Oscillation in the northern hemispheric summer monsoon is a well established fact. These fluctuations can broadly be divided into two frequency mode (*i*) quasi-biweekly oscillations of 10-20 days time-span corresponding to active-break cycle and (*ii*) 30-60 days cycle which is recognised as a dominant component of monsoon circulation system. Most of these studies on intra-seasonal monsoon variability were investigated on wind field (Yasunari 1976, Krishnamurti and Bhalme 1976, Mehta and Ahlquist 1985 etc). Fluctuations in cloudiness have also been examined by many research workers (Yasunari 1979, 1980; Sikka and Gadgil 1980, Murakami 1984, Chowdhury *et al.* 1988 etc). A few studies (*e.g.*, Ananthakrishnan and Keshavamurty 1970, Murakami 1972, Krishnamurti and Ardanuy 1980, Ramasastry *et al.* 1986) have sought periodicities in pressure and rainfall.

The present diagnostic study examines dominant modes of fluctuations in rainfall, its time-space variation and propagation over India during the summer monsoon as rainfall field is an important indicator of the fluctuations of monsoon circulation. The study also presents observational results on the seasonal and inter-annual variability in the meridional direction of low frequency modes in rainfall. We have concentrated on oscillations of time scales longer than 10 days which cover the period of active-break on one extremity and the large scale circulation features (including planetary scale waves) on the other.

2. Data analysed

Daily normal rainfall data of about 220 well distributed stations are collected from the records of India Met. Dep., Pune. Stations in Jammu & Kashmir which receive maximum rainfall by eastward moving westerly systems during winter have not been included in the study. Similarly, northest India with least variability in monsoonal rainfall has been ignored. The normal rainfall, in general, is based on data of 50 years or more. The India Met. Dep. considers 1 June to 30 September as the monsoon season and as such, data for this period only have been used in the study. Study of normal rainfall has been taken to investigate whether any low frequency mode actually exists in any part of the country in the normal pattern itself. The structure of the monsoon surges and the characteristics of the circulation system, should as a rule, significantly differ in years of normal/above normal monsoon rainfall and the deficient or sub-normal rains. The variability and persistence of the oscillation from year to year, however, is still unknown. A pair of years, was selected to analyse the oscillations and bring out intrinsic characteristics. One pair covers the years of monsoon failures (1979 and 1982) and the other, the years of good rainfall (1978 and 1983). In addition, in two years, *i.e.*, 1980 and 1981 the rainfall could be termed as nearly normal and these have also been considered as a separate pair. The area weighted rainfall for all these years are given in Table 1 alongwith departure from normal rainfall for the country.

3. Method adopted

Numerous methods exist in scientific literature to determine periodicity in a time-series. In the present study the data have been subjected to harmonic analysis to investigate presence of pronounced frequency modes. The amplitudes of the modes have been statistically tested at 5% level of significance. To eliminate small scale fluctuations from the data of individual years as well as the normal daily rainfall data, time-smoothening (of 7 days running mean) is applied before the data are subjected to harmonic analysis.

4. Results and discussion

4.1. *Spatial correlation of rainfall*

Before describing temporal oscillations of rainfall, space correlation in normal rainfall has been discussed. For this purpose a station Banda (25.5°N, 80.4°E) which lies in the normal path of the monsoon axis was chosen as a reference point. Daily normal values of rainfall for Banda are then correlated with over 210 stations. The result is shown in Fig. 1. A band of significantly high correlation, exceeding 0.8 extends southeastwards from northwest India to Bihar. This broad zone practically lies around the mean monsoon trough axis. North of the line from Surat to Masulipatnam, the correlations are quite large, *i.e.*, greater than 0.4. In contrast, over western Peninsular India, correlations are, if positive only small but over Madhya Maharashtra, Marathwada, Karnataka and Kerala they are negative.

It is well known that monsoon rainfall increases over Gangetic plains and central India during active monsoon conditions. But during the break monsoon situations, over major parts of India, a significant decrease in rainfall activities is observed. The rainfall deficiency according to Rao (1976), over west coast, Madhya Maharashtra and coastal Karnataka, is however much less (about 15% or less). Thus, these areas continue to experience rather active monsoon conditions as compared to north or central India. These regions almost coincide with the region of negative or low values of positive correlation coefficients. As such it may not be out of context to conclude that the negative-positive correlation pattern can be attributed to the "active-break" conditions in the Indian summer monsoon.

A part of this wide negative correlation zone also contains a small area (over Madhya Maharashtra, Marathwada and adjoining area) where, as we shall observe later, the seasonal scale cycle is not very conspicuous but where the significant contribution happens to be related to 30-60 day mode.

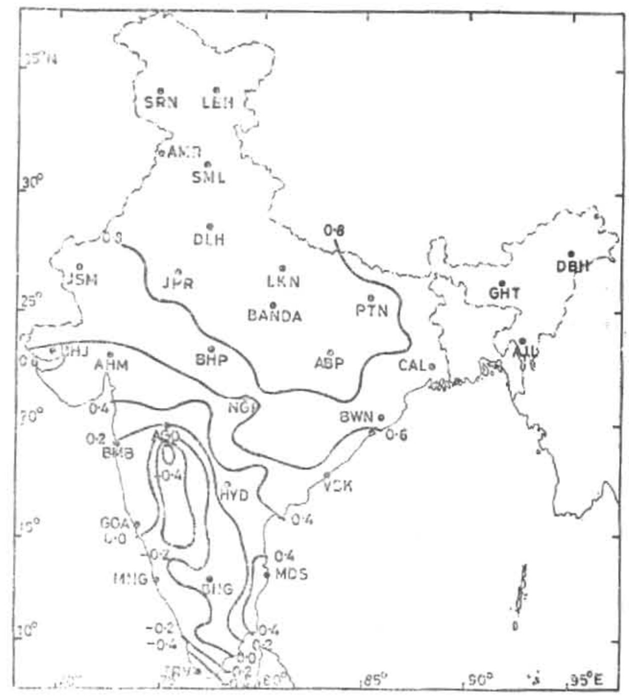

Fig. 1. Correlation field of daily normal rainfall with respect to Banda

TABLE 1

Area weighted mean monsoon rainfall over India

Year	Mean rainfall (mm)	Departure from normal (%)
1978	908	6.4
1979	746	—12.5
1980	881	3.3
1981	842	—1.3
1982	757	—14.6
1983	1004	—13.1

4.2 *Quasi-periodic fluctuations*

4.2.1. *Normal rainfall field*

(a) *Predominant periodicities* — In the normal rainfall pattern, the seasonal cycle (of 120 days) appear to be the most pronounced mode over India. This seasonal mode by no means is monotonous and is often interrupted by higher frequency modulations. Thus, over interior Peninsula, 30-60 day mode is seen to be predominant. Small patches over SW Rajasthan and Andhra coast also exhibit significant modes in 30-60 day time-scale (Fig. 2a).

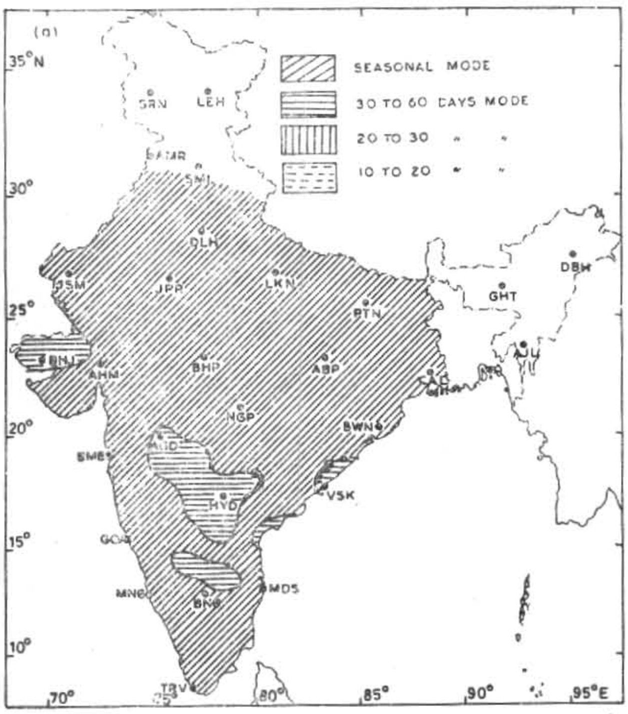

Fig. 2(a). Predominant modes in normal rainfall

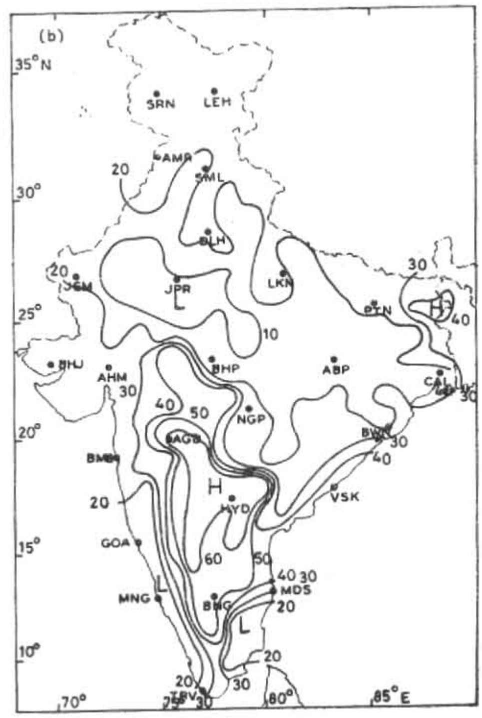

Fig. 2(b). Variance explained by 30-60 day modes for normal rainfall

Analysis of the variance explained by most prominent mode revealed that areas where the first harmonic predominates, the variance explained exceed 60%, except extreme northwest India, where it is less than 60%. The total variance explained by 30-60 day mode is shown in Fig. 2 (b). In Marathwada, Telangana and north interior Karnataka 30, 40 or 60-day is the most prominent mode. In these areas total variance explained by 30-60 day oscillations is as large as 60-80%, suggesting that monsoon rainfall in these areas is controlled mostly by planetary scale, Hadley and Walker circulations. The quasi-biweekly cycle (of 10-20 days) is in the normal rainfall analysis, not found to be an important mode over any part of the country and is, as such, not expected to contribute much to the variance. However, over very large parts in central India, extreme south, northwestern fringe and parts of Bihar and Bengal, the variance contributed by modes within this time frame remains substaintially large (*i.e.*, greater than 10%). The fairly large variance of the 10-20 days period may perhaps be attributed to the small scale disturbances associated with "active-break" monsoon conditions. Krishnamurti and Bhalme (1976) also observed 10-15 day periodicity in monsoon rainfall, which they attributed to fluctuations in clouds.

(b) *Latitudinal area weighted rainfall* — The discussion in the foregoing sections was based on the rainfall data of individual station. It was thought worthwhile to find out, if any, changes in the pattern of modes when the rainfall is averaged for latitudinal strips and weighted according to the area of the strip. For this purpose, only normal daily rainfall was considered and India was divided into 6 latitudinal zones, *viz.*, 8°-12°N, 12°-16°N, ..., 28°-32° N. The variance explained by different harmonics is shown in Table 2. It may be seen that along all latitudinal belt the seasonal component (120-day period) remains predominant. This is more so in latitudes north of 20°N where nearly four-fifth to nine-tenth of total variance is explained by the 120-day mode. However, in the lower latitudes significant contribution also comes from modes of higher frequencies. This suggests that synoptic and physical processes which govern rainfall over India north of 20°N are different from those in south India. It may be worth mentioning that in the region between 16° & 20°N nearly 40% of the variance is accounted for by lower period oscillations. This region corresponds to the cyclogenesis area of monsoon lows and depressions over Bay of Bengal and adjoining land mass.

4.2.2. *Fluctuations during drought year*

Examinatin of normal characteristics in the context of oscillations in monsoon rainfall may not be very useful, since hardly any year can be strictly termed to follow normal pattern. Moreover, the nature of the predomnant modes are expected to vary in a wide spectrum in years of sustained or suppressed monsoon activities.

In recent years, 1979 and 1982 are well known years of monsoon failure over India. It was, therefore, thought worthwhile to examine the rainfall oscillations in different period ranges with particular reference to the normal. When the monsoon rains fail in India, the seasonal cycle is mostly observed as the prominent mode in north India, north of about 22°N as well as Karnataka-Kerala coast and parts of Tamilnadu. The longer periodicity may, perhaps, be attributed to long-lasting

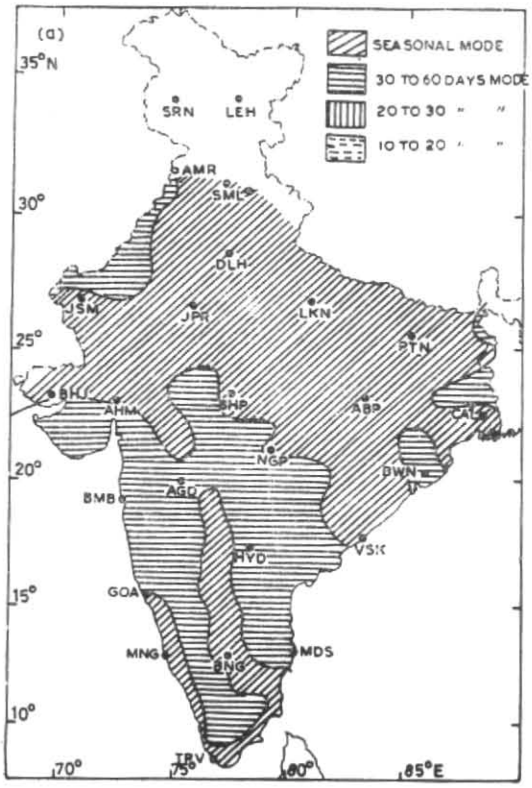

Fig. 3(a). Predominant modes during 1979 monsoon

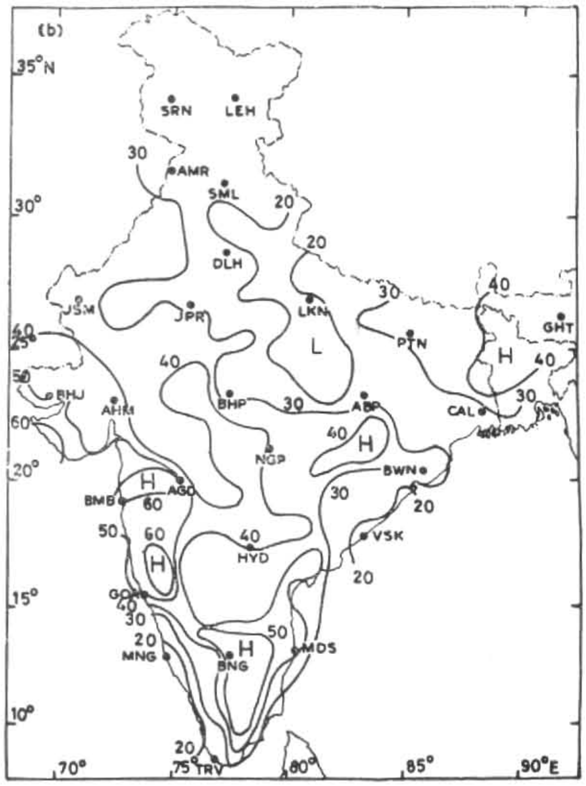

Fig. 3(b). Variance explained by 30-60 day modes during 1979 monsoon

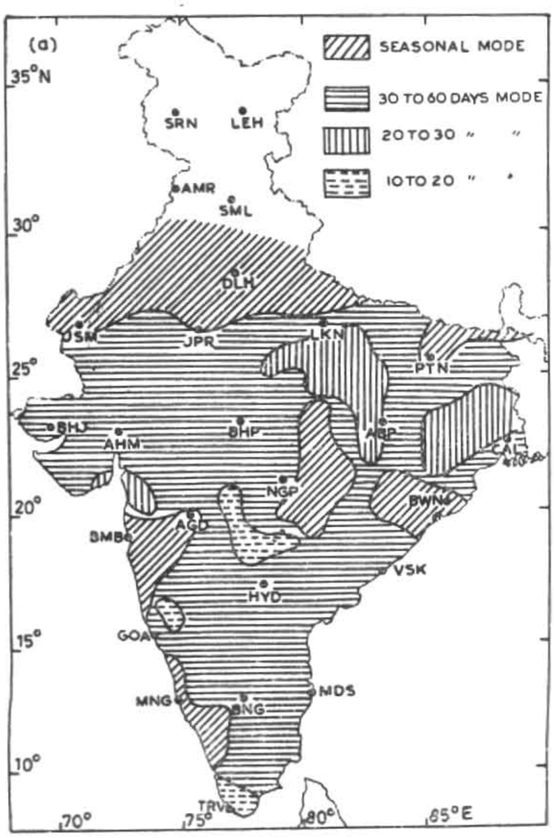

Fig. 4(a). Predominant modes during 1978 monsoon

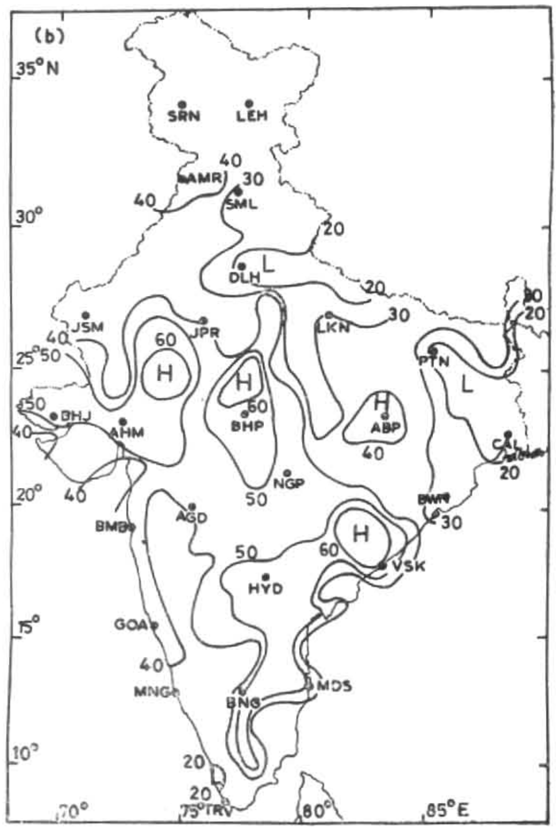

Fig. 4(b). Variance explained by 30-60 day modes during 1978 monsoon

TABLE 2

Variance explained by various harmonics (latitudinalwise) for normal rainfall

Lat. belt (°N)	Variance explained by harmonics period (day)					
	1st (120)	2nd (60)	3rd (40)	4th (30)	5th (24)	6th (20)
8°-12° (14 stns)	53	0	23	1	4	6
12°-16° (19 stns)	69	10	3	7	2	3
16°-20° (33 stns)	54	17	9	11	0	2
20°-24° (60 stns)	79	13	4	1	0	1
24°-28° (59 stns)	86	10	1	1	0	0
28°-32° (25 stns)	91	6	1	0	0	0

breaks so common in drought years. On the contrary in the Peninsular India, and northwestern fringe, it is the 30-60 day cycle which is conspicuous (Fig. 3a). It is, however, surprising that the prominent mode whether seasonal or sub-seasonal, individually hardly explain more than 40% of the variance. The seasonal mode itself explains 30-40% variance, though in some parts, *e.g.*, central Madhya Pradesh it is between 50 & 60%. But in contrast the total variance explained by 30-60 day cycle is, in general, greater than 30% and in some smaller cells it contributes to over 60% variance (Fig. 3 b). In drought years the contribution of 10-20 day mode also is found significant (between 20 & 30%) though over northwest and parts of Peninsular India, it exceeds even 30%.

The above characteristics in the predominant modes and the variance have been observed, by and large, during both the drought years with very slight alterations.

Synoptically, drought situation over India is due to frequent and/or prolonged 'break' conditions during the monsoon. Yasunari (1981) postulated that low frequency cycles are mainly associated with fluctuations of the Hadley cell. According to him, during the active-monsoon condition the ascending limb of the Hadley cell is around 10°-20° N while the descent occurs over the sub-tropical high region. During the break-monsoon conditions, the upward motion takes place at more southern latitude and the subsidence occurs over the central and north India. Thus, it is evident that during the drought year, in the Peninsular Indian region, the Hadley cell is more localised, which in turn gives rise to the confinement of 30-60 day oscillation in the Peninsular India.

Similarly the southward extension of the seasonal mode, as compared to normal in the drought years, may beviewed as follows :

Break periods are generally characterised by equatorward extension of large amplitude troughs from higher latitudes which sometimes are due to enlargement of circumpolar vortex as has been shown by Ramaswamy (1971), Rao (1976) etc. The trough/expanded vortex, displaces the subtropical anticyclone southwards (Chowdhury and Ganesan 1981), suppressing the monsoon activity over central and north India. The prevalence of seasonal mode over these areas in drought years can thus be associated with the planetary scale movements of westerly waves.

4.2.3. *Years of good monsoon*

Analysis of the data shows that distinct, systematic and significant changes occur in the oscillations during years of good monsoon. In such years the seasonal mode is mostly confined to northern latitudes and the meridional Hadley circulation becomes more enhanced. For example in 1978, the 120-day cycle is seen north of 27°N, over the west coast and some areas of Orissa and adjoining Madhya Pradesh as the major mode. Over the rest of the country, modes of higher frequencies are the prominent modes. In fact, it is mostly 30-40 day oscillations that prevail over the country (Fig. 4 a). From an analysis of satellite cloudiness over India and neighbourhood, Yasunari (1980), observed that except in drought year, periodicities of 30 or 40 days exist as a predominant mode. It is also clear that strength of the convection and the physical process which induces rainfall may be different over north India and the Peninsula. Webster (1985) postulated that convective outflow drives this oscillation leading to strengthening of subtropical jet. Yasunari (1981) concludes that cumulus convection is gradually enhanced from the south to north with the northward shift of maximum cloudiness.

Variance explained by the seasonal cycle too remains insignificant. The modes in the time-span of 30-60 days, explain 60-70% over some areas (Fig. 4 b). But contribution of quasi-biweekly oscillation (*i.e.*, 10-20 days) is quite large and except certain areas like northwest Madhya Pradesh, Konkan-Karnataka coast etc, it even overshadows that of 30-60 days' cycles.

In recent years, 1983 was one of the best years of monsoon activity. Analysis of the rainfall data of this year reveals that the shorter time interval cycle than 120-day cycle extends right up to 30°N over most parts (Fig. 5a). The west coast also have lower period cycle. The changes observed in the variance pattern and the prevalence of 30-60 day mode over the seasonal cycle, perhaps, results from the poleward transport of angular momentum whose production in tropics vary considerably. The seasonal mode is observed over northwest India and Gujarat. However, over a small area in central India seasonal cycle persists as in case of 1978.

Contribution of the seasonal mode is between 20% & 30%. Relatively large variance of lower period oscillations over the seasonal component occurs over wide areas. The total contribution by 30 to 60-day oscillations exceed 40% and in Madhya Maharashtra and adjoining Marathwada, it accounts for more than 50% of the variance (Fig. 5b). As in 1978, the 10-20 days cycles also contribute substantially, *i.e.*, 20% to 30%. In fact the contribution of these cycles over northwest India far exceeds that of the seasonal mode.

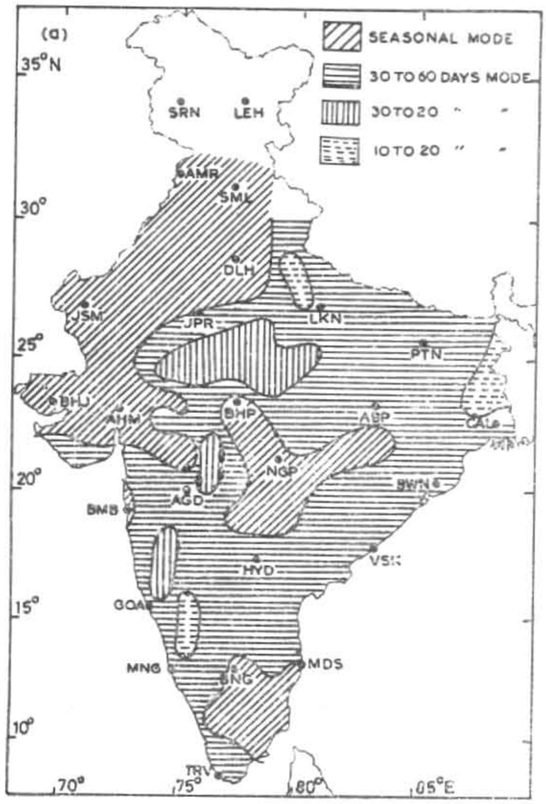

Fig. 5(a). Predominant modes during 1983 monsoon

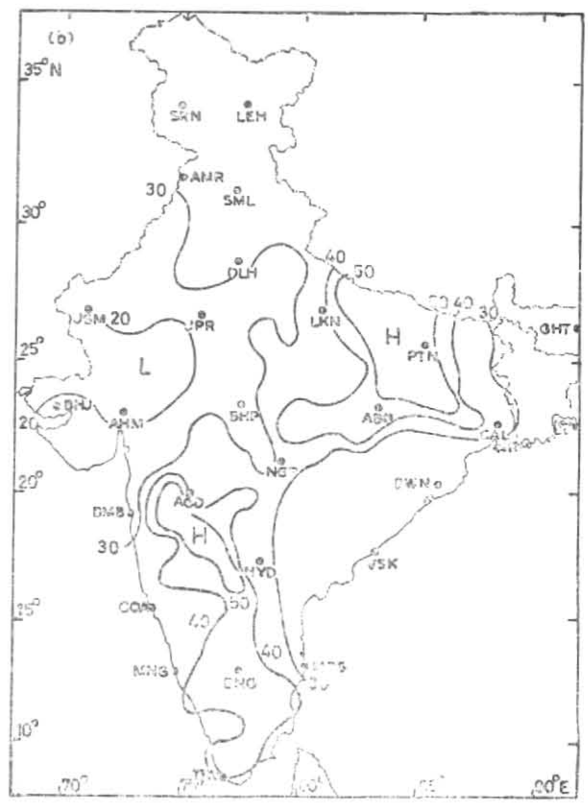

Fig. 5(b). Variance explained by 30-60 day modes during 1983 monsoon

4.2.4. *Year of nearly normal rainfall*

Rainfall over India during 1980 and 1981 may be termed as nearly normal. Equatorward extension, though small, of areas with fundamental mode of 120-day compared to the years of good monsoon is unmistakable in both the years. This mode also appears over some interior parts of the Peninsula. But as in years of good monsoon over the rest of the country, modes mostly of time scale 30-60 days remain the predominant mode.

The 120-day mode is prominent over NW India and the Kerala coast. Over the rest of the country, modes of higher frequencies predominate. Over many areas, in fact cycles of 40-day or less are prominent, variance explained by seasonal mode is about 30-40%. Contribution of 30-60 day mode, however, is very large (except in areas where 120-day is fundamental mode and over central India).

Mostly these cycles explain greater than 30% variance. Over west coast, north Maharashtra and interior Karnataka-Tamilnadu area it even exceeds 50%. The 10-20 day oscillations also explain fairly large variance, particularly over Peninsula. The 10-20 day modes, in northwest India explain variance more than that explained by 120-day cycle. In remaining parts, its contribution is slightly less than that of 30-60 day oscillations. But over eastern India, variance explained by the 10-20 day mode exceeds that by 30-60 day cycles.

4.2.5. *Quasi-biweekly fluctuations in the rainfall field*

In previous sections, characteristics of temporal fluctuations of rainfall were discussed and the dominant periodicities in daily monsoon rainfall estimated. Because the 10-20 day cycle is found to be rather intense, relatively regular, and occurs over large areas, particularly during the good monsoon years, a separate section is devoted to discussion on this quasi-biweekly oscillations.

According to Yasunari (1981), quasi-biweekly modes are relatively large and are related to the frequency of some weather phenomenon over and around the monsoon trough zone, like monsoon depressions. From the phase-lag relationship at 850 mb wind, he concluded that the horizontal scale of these modes ($\simeq$ 10,000 km) is far larger than that of monsoon depression. Other studies (Krishnamurti *et al.* 1977 ; Krishnamurti and Ardanuy 1980) presented evidence that this mode is attributed to the westward propagating waves with scale of 8$\sim$10,000 km.

Though this mode is observed in the analysis of normal rainfall as well as in years of sub-normal rainfall, periodicities of $\simeq$2 weeks dominantly appear over larger areas in years of normal or above normal monsoon rainfall. Taking variance explained as an indicator, the difference in total variance explained by 10-20 day and 30-60 day

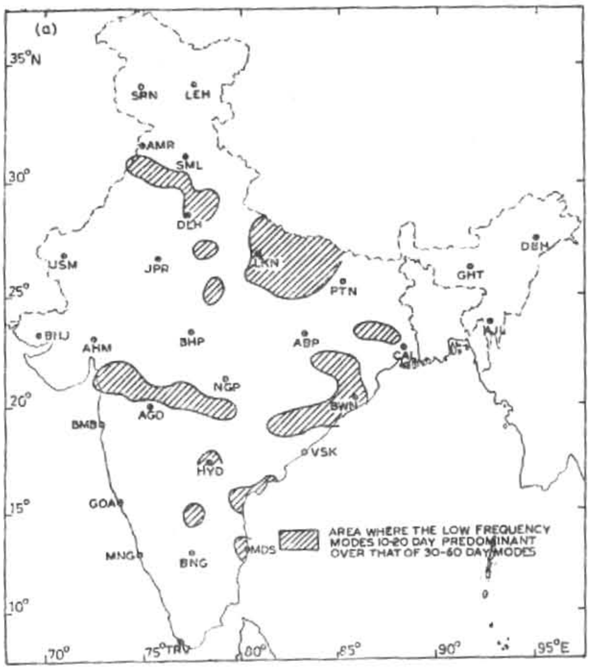

Fig. 6(a). Predominance of 10-20 day modes over 30-60 day modes in 1982

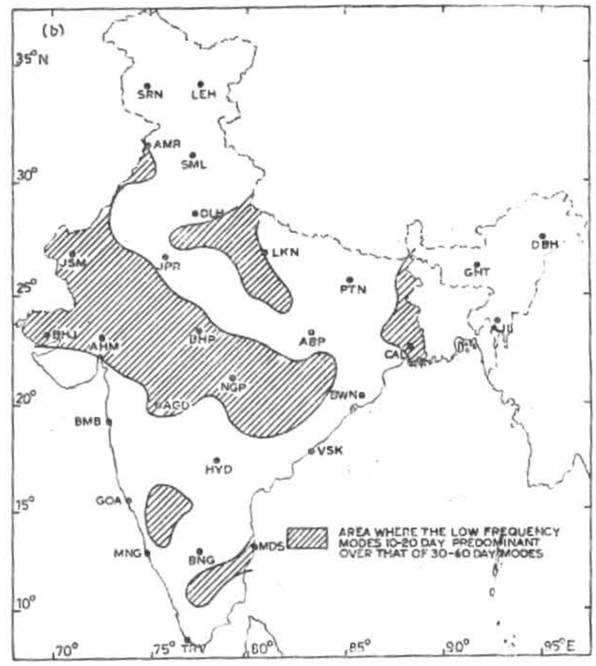

Fig. 6(b). Predominance of 10-20 day modes over 30-60 day modes in 1983

mode for 1982 and 1983 is depicted in Figs. 6 (a) and 6 (b). It is seen that north of 20° N, quasi-biweekly mode dominates over the 30-60 day mode in years of good monsoon, whereas in a drought year this dominance is suppressed and can be observed at only isolated cells in north India. In south India, however, in both categories of rainfall, 30-60 day cycle generally is stronger than the quasi-biweekly cycle.

The 10-20 day cycle can, perhaps, be related to variation in relation between sub-synoptic scale circulation and large scale or synoptic scale system. Presence of quasi-biweekly oscillation in drought years over coastal Tamilnadu suggests that pulses of these time-scale do not occur with sufficient frequency over large parts or are located over the southern latitudes only (Koteswaram 1950). Though Murakami (1976) thought that this mode is of very large scale, covering Bay of Bengal, Indian sub-continent, Indo-China and Tibetan Plateau, the present analysis reveals that except in good monsoon years the oscillations in 10-20 day period cover fairly large areas over India while in other years, the area covered is rather limited and it is so even in normal rainfall. Thus, the quasi-biweekly component is not a distinctly dominant or significant cycle.

The mechanism of 10-20 day oscillations, according to Webster (1983) is the location of convectively unstable region associated with changes in the ground moisture due to precipitation.

4.2.6. *Propogation of modes*

Analysis of phase angle enables to find rate of propagation of different modes. Concentrating again on good and bad monsoon years and the 30-40 day oscillations phase angles are calculated for 1982 and 1983. The phase angles are converted into time period (days) through standard method. In a drought year high values are seen in Peninsula approximately over the areas where in the normal rainfall analysis 30-60 day mode prevails. Over the rest of the country dates are 20 June or earlier. More or less, a similar pattern persists in a good monsoon year, *i.e.*, 1983 except that the phases are earlier in most parts of India.

From a composite analysis of pressure data of 40 years Krishnamurti and Ardanuy (1980) found a dominant westward propagating mode in the 10 to 20-day time period during 'breaks'. Weickmann *et al.* (1985) found that the 30-60 day life cycle includes an eastward propagating equatorial convection anomaly between 60°E and 160°E. Choosing about 22°N latitude the movement of 10 and 20-day oscillations are separately determined for a good monsoon year, *i.e.*, 1978 and a drought year, *i.e.*, 1982. The data are duly smoothened by forming overlapping means of 2 successive values, and then overlapping means of 2 of these modified values. This method is suitable for smoothing the noise in the cyclic series, which are generally present in a short period of observations (Brooks and Carruthers 1953). The results are shown in Figs. 7 (a) & (b). In a year of deficient summer rainfall over India, nearly steady east to west propagation of phase by 10 and 20-day mode appears to exist, though some retrogation is seen towards extreme west. In a good monsoon year in the 20-day time-frame, some indication, though weak, is seen of the eastward propagation, but is not very prominent in the 10-day wave.

5. Conclusion

Analysis of daily rainfall fluctuations over India during the northern hemispheric summer reveals that :

(*i*) Rainfall, in general, consists of many simultaneously pulsating cells of different periods instead of one main cell. These periods can be divided

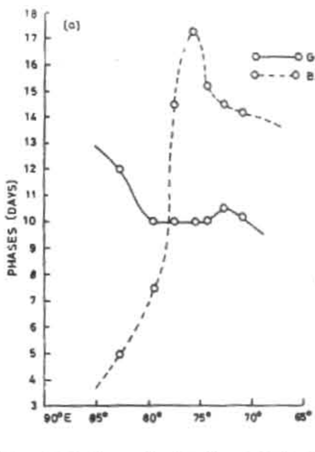

Fig. 7(a). Longitudinal analysis of phase, 20-day mode

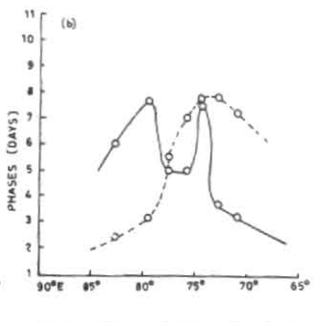

Fig. 7(b). Longitudinal analysis of phase, 10-day mode

into 3 broad modes, *viz.*, seasonal 30-60 days and 10-20 days.

(*ii*) A quasi-stationary periodicity of 120 days exists as a dominant mode over northern Indian latitudes and some pockets in central India irrespective of the rainfall activity over the country.

(*iii*) In drough tyears the seasonal mode extends to even lower latitudes and is caused by periodic outbreak of upper tropospheric westerly systems.

(*iv*) The influence of low frequency oscillation on summer monsoon rainfall over India, whether suppressed or enhanced, is undoubtedly, unmistakable and cannot be ignored. The 30-60 day cycles can be linked to the fluctuation in the location of Hadley circulation and its persistence over central Peninsula in all years.

(*v*) 30-60 day oscillations penetrate to north India during active monsoon.

(*vi*) Perturbations of quasi-biweekly period have distinct role in contributing to summer monsoon rainfall over India.

(*vii*) On the basis of the predominant modes, India can be divided broadly into two zones, *viz.*, northern India, north of about 20°N and the Peninsula, each having different mechanism for rainfall occurrences.

Acknowledgements

The authors wish to express grateful thanks to Dr. R.P. Sarker for suggesting the problem, constant encouragement and useful advice throughout the work. Thanks are due to Mrs. M. M. Dandekar and Shri P. S. Urankar for help rendered in the study and to Mrs. M. S. Chandrachood for typing the manuscript.

References

Ananthakrishnan, R. and Keshavamurty, R.N., 1970, 'On some aspects of the fluctuations in the pressure and wind fields over India during the summer and winter monsoon seasons', Proc. Symp. Tropical Meteorology, Honolulu, Hawaii, L III, 1-5.

Brooks, C.E.P. and Carruthers, N., 1953, *Handbook of statistical methods in meteorology*, Air Ministry M. O. 538, Her Majesty's Stationery Office, London, 260 pp.

Chowdhury, A. and Ganesan, H.R., 1981, 'Man and Climatic variability', *Vayu Mandal*, **11,** 1 & 2, pp. 9-13.

Chowdhury, A., Sinha Ray, K.C. and Mukhopadhyay, R.K., 1988, 'Intra-seasonal cloud variations over India during northern hemispheric summer, *Mausam*, **39** 4, pp. 359-366.

Koteswaram, P., 1950, 'Upper level 'lows' in low latitudes in the Indian area during southwest monssoon seasons and 'breaks' in the monsoon", *Indian J. Met. Geophys.*, **1,** pp. 162-164.

Krishnamurti, T.N. and Bhalme, H.N., 1976, 'Oscillations of monsoon system, Part I : Observational aspects', *J. atmos. Sci.*, **33,** 1937-1954.

Krishnamurti, T.N., Molinari, J., Hau-lu, Pau and Wong, V., 1977, 'Down stream amplification and formation of monsoon disturbances', *Mon. Weath. Rev.*, **105,** 1281-1297.

Krishnamurti, T.N. and Ardanuy, P., 1980, 'The 10 to 20-day westward propagating mode and "Breaks in the Monsoons", *Tellus*, **32,** 15-26.

Mehta, V.M. and Ahlquist, J.E., 1986, 'Interannual variability of the 30-50 day activity in the Indian summer monsoon', *Met. Atmos. Phys.*, **35,** 166-176.

Murakami, M., 1976, "Analysis of summer monsoon fluctuations over India", *J. met. Soc. Japan*, **54,** 15-31.

Murakami, M., 1984, "Analysis of the deep convective activity over the western Pacific and southeast Asia, Part II : Seasonal and intraseasonal variations during northern summer", *J. met. Soc. Japan*, **62,** 88-108.

Murakami, T., 1972, "Equatorial stratospheric waves induced by diabatic heat sources', *J. atmos. Sci.*, **29,** 1129-1137.

Ramasastry, A.A., De, U.S., Vaidya, D.V. and Sundary, G., 1986, "Forty-day mode and medium range forecasting", *Mausam*, **37,** pp. 305-312.

Ramaswamy, C., 1971, "Satellite determined cloudiness in tropics in relation to large scale flow pattern : Part I—Studies of different phases of the Indian southwest monsoon", *Indian J. Met. Geophys.*, **22,** pp. 289-294.

Rao, Y.P., 1976, "Southwest monsoon", Met. Monogr. Synop. Met. No. 1/1976, India Met. Dep., pp. 186-200.

Sikka, D.R. and Gadgil, S., 1980, "On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon", *Mon. Weath. Rev.*, **108,** 1840-1853.

Webster, P.J., 1983, "Mechanisms of monsoon low-frequency variability : Surface hydrological effects", *J. atmos. Sci.*, **40,** 2110-2124.

Webster, P.J., 1985, "Theory of low frequency motions", GARP special report 44, II, 1-2.

Weickmann, K.N., Lussky, G.R. and Kutzbach, J.E., 1985, "Intraseasonal (30-60) days fluctuation of outgoing long wave radiation and 250 mb stream function during northern winter", *Mon. Weath. Rev.*, **113,** 941 961.

Yasunari, T., 1976, 'Spectral analysis of monsoonal precipitation in the Nepal, Himalaya', *Seppya*, 38, Special issue, 59-65.

Yasunari, T., 1979, 'Cloudiness fluctuations associated with the northern hemisphere summer monsoon', *J. met. Soc. Japan*, **57,** 227-242.

Yasunari, T., 1980, 'A quasi-stationary apprearance of 30 to 40-day period of the cloudiness fluctuation during the summer monsoon over India', *J. met. Soc. Japan*, **58,** 225-229.

Yasunari, T., 1981, 'Structure of an Indian summer monsoon system with around 40- day period', *J. met. Soc. Japan*, **59,** 336-354.