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Intra-seasonal cloud variations over India during summer monsoon season

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सार — शोध-पत्र में भारत और उसके आस-पास के क्षेत्र के ऊपर दक्षिण-पश्चिम मानसून के दौरान बड़े पैमाने पर मेघाच्छन्नता के परिवर्तनों का उल्लेख किया गया है। वर्ष 1982 से 1986 की अवधि के लिए, 1 जून से 30 सितम्बर के दैनिक उपग्रह मेघाच्छन्नता आंकड़ों का हारमोनिक (प्रसंवादी) विश्लेषण मानसून मेघाच्छन्नता की आवर्तता का पता लगाने के लिए किया गया है।

अध्ययन के परिणामों से मानसून के उतार-चढ़ाव में 30 से 60 दिन की आवर्तताओं के मुख्य बहुलकों (मोड) के रूप में पुष्टि की गई है। मानसून ऋतु के प्रत्येक महीने में इन आवर्तताओं से सम्बन्धित मेघाच्छन्नता के ध्रुवों की ओर प्रसार देखा गया है। अत्यन्त कम वर्षा वाले वर्षों में 120 दिनों की आवर्तता 10° अक्षांश (उ०) के उत्तर में दिखाई पड़ती है जबकि विषुवत्तीय क्षेत्र में, भारत में मानसून वर्षा के निरपेक्ष, सामान्यत: कम आवृत्ति का बहुलक विद्यमान रहता है।

ABSTRACT. The paper deals with large scale variations of cloudiness over India and neighbourhood during the southwest monsoon. Daily satellite cloudiness values from 1 June to 30 September for the period 1982-1986 were subjected to harmonic analysis to investigate the presence of periodicities of the monsoon cloudiness.

The results confirmed presence of 30-60 day periodicities in the monsoon fluctuation as the dominant modes. Associated with these periodicities poleward propagation of cloudiness is observed in each month of the monsoon season. Periodicity of 120 days appears north of 10°N in years of deficient rainfall while in the equatorial region the low frequency mode generally prevails irrespective of the seasonal monsoon rainfall over India.

1. Introduction

Quasi-periodicities in the northern hemispheric summer monsoon have been well known for several decades. From the spectral analysis, Ananthakrishnan and Keshavamurty (1970) detected a five-day period in wind and pressure fields. Periodicities of nearly a fortnight were observed in summer monsoon rainfall over India by Murakami (1972), and Yasunari (1976) and in upper winds by Krishnamurti and Bhalme (1976). However, ever since Madden and Julian (1972) observed eastward propagating low frequency oscillations on a time scale of about 40-50 days in the equatorial Indian and the Pacific Oceans, the study of intra-seasonal fluctuations has attracted much attention. Murakami (1976) studied statistically satellite cloudiness in the northern summer by computing lag correlation and he found a northward propagation of positive (negative) correlation from Indian Ocean to Indian sub-continent at an average speed of 1° latitude per day. Yasunari (1979) investigated broad scale cloud fluctuations using satellite mosaic pictures and found a marked northward movement of cloudiness over Asian monsoon with a 40-day period. Using extensive cloud data in 1980, he confirmed presence of quasi-stationary appearance of 30 to 40 days period and its poleward movement from equatorial Indian Ocean. Sikka and Gadgil (1980) also reported fluctuation in the monsoon cloudiness on this time scale.

Frequency mode with the time scale of 30-50 days in meridionally propagating lower tropospheric troughs and ridges were found by Krishnamurti and Subrahmanyam (1982). They observed that the troughs at 850 mb form near the equator and disappear over the Himalayas. Webster (1983) proposed a model for the maintenance and meridional transport of 12-15 day oscillations and its interaction with Indian monsoon flow to give alternating active and break phases.

Murakami (1984) confirmed the existence of a relationship between active-break monsoon cycle and the meridional propagation of 30-40 days oscillations in wind field. He also showed that 30-40 day intra-seasonal variation of convective activity over West Pacific was associated with monsoon. Ramasastry *et al.* (1986) examined the presence of 40-day mode in weekly zonal wind-shear anomaly at 850 mb in relation to rainfall for 1979-83. They found that the near 40-day mode has large year to year variations and is not the dominant mode in every region/year over the Indian sub-continent.

Recently 30-60 day oscillations have been reported in global circulation models with realistic surface boundary conditions (Hayashi and Golder 1986). The predominant periods simulated in these models differ from one model to anothter though they generally lie within the range of 30 to 60 days. Hayashi and Sumi (1986) studied and

TABLE 1

Variance (%) explained by the most prominant mode and 30-60 days mode

Year		Latitude belts (in °N)												
		0 to 2.5	2.5 to 5.0	5.0 to 7.5	7.5 to 10.0	10.0 to 12.5	12.5 to 15.0	15.0 to 17.5	17.5 to 20.0	20.0 to 22.5	22.5 to 25.0	25.0 to 27.5	27.5 to 30.0	30.0 to 32.5
1982	A	13	40,30	15	30	30	30	30	120	120	120	120	120	60
	B	16	13,13	17	20	33	31	26	30	48	36	28	24	22
	C	27	26	27	39	51	48	40	32	22	32	22	27	23
	D	42	21	28	19	20	15	22	18	15	17	23	28	21
1983	A	120	17	17	30	60	20	40	40	40	40	24	60	60
	B	18	25	20	13	13	13	15	23	35	41	15	20	23
	C	9	14	24	26	26	11	16	28	48	53	28	38	33
	D	28	56	43	37	30	39	47	32	26	17	32	28	22
1984	A	40	40	40	40	30	15	15	120	60	120	120	120	120
	B	37	28	37	34	19	17	16	24	30	27	27	30	34
	C	49	46	48	42	43	22	14	25	40	36	32	35	22
	D	14	21	18	19	23	42	46	25	13	14	16	9	15
1985	A	120	30	60	30	40	40	120	120	120	120	120	120	120
	B	27	19	27	20	22	19	16	37	64	70	68	71	55
	C	32	42	44	42	30	27	25	12	12	8	9	7	13
	D	16	23	20	19	26	35	30	17	10	10	14	13	13
1986	A	30	30	30	120, 30	120	120	120	120	120	120	120	120	120
	B	26	41	28	22, 22	24	29	27	36	40	50	47	38	28
	C	33	43	45	38	46	28	22	27	29	18	17	24	30
	D	23	14	17	17	17	13	17	16	19	21	18	20	20

NOTE : A—Dominant mode (days) B—Variance explained (%) by dominant mode
C—Total variance explained by 30-60 day modes D—Total variance explained by 10-20 day modes

TABLE 2

Periods (in days) of first two significant amplitudes

Latitudes (°N)	1982		1983		1984		1985		1986	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
0-2.5	13	40	120	24	40	30	120	30	30	15
2.5-5.0	40	30	17.1	20	40	30	30	60	30	*
5.0-7.5	15	30	17.1	30	40	30	60	17.1	30	60
7.5-10.0	30	60	30	60	40	*	30	60	30	120
10.0-12.5	30	60	60	30	30	40	40	24	120	60
12.5-15.0	30	40	20	17.1	15	13.3	40	120	120	24
15.0-17.5	30	120	40	10.9	15	15	120	40	120	24
17.5-20.0	120	30	40	24	120	60	120	*	120	30
20.0-22.5	120	60	40	30	60	120	120	*	120	30
22.5-25.0	120	40	40	30	120	60	120	*	120	30
25.0-27.5	120	40	24	40	120	60	120	*	120	30
27.5-30.0	120	60	60	17.1	120	60	120	*	120	30
30.0-32.5	60	120	60	24	120	60	120	60	120	40

*None of the peaks significant

30-40 day oscillations simulated in an "aqua planet" model. Their study indicated that strong mode coupling between equatorial free waves is required in order to maintain the 30-day oscillation.

These studies confirmed that the 30-60 day mode is one of the predominant sub-seasonal modes of atmospheric general circulation originating in tropical monsoon. The temporal and spatial variations of this mode are still unexplained. This is because the amplitude and persistence attained by an element during 30-60 day cycle is determined by complicated and poorly understood dynamic and thermodynamic processes. This relatively low frequency cycle is, perhaps, influenced by other time scales and physical processes hitherto unknown. A potential useful aspect of these modes is that it allows predictability once the most likely time of onset of monsoon is known. The usefulness of this predictability is, however, limited because of interannual variation within 30-60 day periods as well as interactions of synoptic and sub-synoptic scale periodicities.

In this paper variations in daily cloudiness over India and neighbourhood have been examined for the summer monsoon months to find out dominant modes of oscillation and year to year variations in the periodicity of more than 10 days. It may, however, be mentioned that in the actual atmospheric processes, the contributions of synoptic and sub-synoptic scale periodicities and their stagnation cannot be ignored.

2. Data used

The study utilises daily satellite cloud imageries (visible) of NOAA and INSAT-1B received at APT unit, Pune. The data from 1 June to 30 September for the period 1982 to 1986 are considered. The area of investigation extends from 0° to 32.5° N and between 70° and 92.5° E.

The areas was first divided into 13 latitudinal strips of 2.5° latitude width. Each strip was further sub-divided into 9 square grids of 2.5° Lat./Long. Cloudiness in each square grid was determined in terms of the fraction of the total areas covered in each grid subjectively and expressed in octas. From five years data set the daily average cloudiness for each square grid was computed. The few data gaps were replaced by these average values. The main emphasis being on the study of northward propagation of cloudiness, the mean cloudiness for each of the 13 strips were obtained for each day of the period under study. Besides, the cloudiness in 13×9 grids were also analysed.

3. Method of analysis

To examine predominant periodicities and its amplitudes harmonic analysis was performed for data of each year from 1 June to 30 September (*i.e.,* 122 days). The mean cloudiness for each of the 13 latitudinal belts were analysed. The main advantage of this method is its simplicity in calculation. Conventional spectrum analysis such as lag correlations, no doubt, also furnishes information on cycles in a data series. However, a great disadvantage with this method is that it cannot be effectively applied to the monsoon period of duration $\sim$120 days, in case oscillations of period less than 40 days is to be obtained (Yasunari 1979). On the other hand, the classical harmonic analysis can take into account periods as small as 2 days. Thus, the harmonic analysis has the additional advantage of giving good resolution for records of shorter periods. In order to remove short term fluctuations of 2 to 3 days, the data for each grid was subjected to 3 days running mean.

4. Results and discussion

4.1. *Seasonal cloud features* — Characteristic features of the zonally average clouds are discussed below :

The dominant mode and the variance explained by cloudiness in each strip are shown in Table 1. Since the aim of the study is to examine characteristic features of the low frequency modes in relation to the Indian rainfall (as given in Table 3) total variance explained by 2nd to 4th harmonics which correspond 60 to 30-day mode respectively has also been given in the table. It can be seen that in the lower latitudes (south of $\approx10°$ N), in general, the periodicity of 30-40 days is predominant. However, in good monsoon years lower periodicity of 10-20 days is also dominant. This suggests that oscillations of these periods are of fundamental mode in the near equatorial region. Fluctuations of 60-day period, though not always predominant also occurred with relatively higher frequency.

Weak disturbances of shorter periodicity (10-20 days) also appear in cloudiness fluctuations over India in summer monsoon. These can also be associated with active-break cylcle of monsoon fluctuations. The amplitudes of these short period oscillations are statistically tested and discussed later. It was found that the 10-20 day cycles are present in all years. In years of poor monsoon they are confined to lower latitudes south of 17.5° N. However, when the seasonal rainfall is normal or above normal, the 10-20 day cycle prevailed up to 32.5° N. Since the broad scale monsoon circulation is recognised as a local meridional circulation, it follows that the short term fluctuations should also appear in the meridional plane. Webster (1985) from modelling experiments also found 10-20 day oscillations in vertical velocity field over land areas. He suggested that changes in ground moisture and fluxes of sensible heat due to copious rainfall drive these oscillations.

A remarkable feature that could be also seen from Table 2, is that when the monsoon over the country is sub-normal the seasonal mode (120-day) is predominant (In this study a year has been defined as above normal when the positive departure of the summer monsoon rainfall from the normal is more than one standard deviation which is 8.3 cm. Similarly, when the negative departure is more than one standard deviation, it is called sub-normal. Years with departures lying within ± one standard deviation, are considered as normal). This dominance is noticeable generally north of above 10° N. The seasonal mode is generally absent when monsoon is normal or above normal, except just close to the equator.

The variance explained by the seasonal cycle vary within wide limits. However, in the higher latitudes variance explained exceeds generally 40%. The total variance explained by 30-60 days mode ranges between 7% and 55%. Even in these years and in areas where the first harmonic explained a substantial part of the total variance, the contribution of 30-60 days mode remains significantly large. In the years of normal and good monsoon, harmonics of 2nd or higher order are prominent. The 30 to 60 days mode in normal monsoon year explains generally more than 40% of the total variance. When the seasonal rainfall is above normal, periodicities of 10-20 days are prominent and they explain 35% of variance. These were nearly common features in most of the years studied, though year to year variability did exist.

On the basis of above analysis, it may be said that :

(*i*) The 30-60 days cycle appears to be more closely linked to the major active-break monsoon activity than the quasi-biweekly mode.

(*ii*) In the higher latitude in the years of monsoon failure, the seasonal cycle is most predominant.

(*iii*) When the monsoon activity is normal or above normal, the cycle of lower period is predominant. In such years, locations of convectively unstable region march northward with increased frequency.

Significance of amplitude of the harmonics has also been tested as given below :

If there are '*n*' amplitudes, then the largest among them is first tested by making use of Table 5 (given by Brooks and Carruthers 1953).

If this value does not exceed the one given in Table 5 then none of the amplitudes is significant. If it exceeds the table value then that amplitude is considered as significant and the largest among the remaining *n*—1 amplitudes are tested for significance. In this way the process is repeated. Amplitudes of periodicities significant at 5% level are given in Table 2. Since in most of the cases either one or two harmonics had significant amplitudes, in this paper, the modes have been given only for first two significant harmonics. There were, however, a few cases where the amplitude of even 11th harmonic was found significant. These cases occurred when the overall seasonal rainfall was good.

A glance at the table confirmed observations made above from variance analysis that south of 10°N, the modes of period 60 days or less are significant irrespective of whether the monsoon during the year is normal, subnormal or above normal. North of 10° N, while in the year of bad monsoon, the seasonal cycle is predominant (for instance 1982, 1986 etc), in the year of good monsoon, the cylcle of 60 days or less emerge more conspicuously.

TABLE 3

Area weighted mean monsoon rainfall over India

Year	Mean rainfall (mm)	Departure from normal (%)
1982	757.8	—14.6
1983	1003.7	13.1
1984	841.0	—5.2
1985	803.1	—9.5
1986	768.5	—13.4

TABLE 4

Monthly position of ITCB

		1982	1983	1984	1985	1986
Jun	Mean (°N)	13.7	20.5	16.2	17.2	15.8
	SD °Lat.	5.8	5.5	5.9	5.7	6.0
Jul	Mean (°N)	14.8	13.6	13.1	22.8	18.9
	SD °Lat.	6.3	9.0	7.8	4.5	6.0
Aug	Mean (°N)	18.4	16.6	21.4	21.7	18.6
	SD °Lat.	3.5	5.5	4.6	4.3	6.6
Sep	Mean (°N)	14.4	13.5	13.0	15.2	8.2
	SD °Lat.	6.4	7.2	5.6	8.3	6.4

TABLE 5

Significance test for amplitudes

If A' is the largest of n amplitudes computed from a random series of N successive values drawn from a normal population, the 5 per cent point of A' is given by $A'_{.05}=\lambda_A\,\sigma/\sqrt{N}$, where σ is the standard deviation of the N value and

$$\lambda_A = 2\sqrt{\ln(20\,n)}$$

Taking $N=120$ days for $n=8$ to $n=12$, the values of λ_A were obtained as given below :

	n				
	8	9	10	11	12
λ_A	4.50	4.56	4.60	4.64	4.68

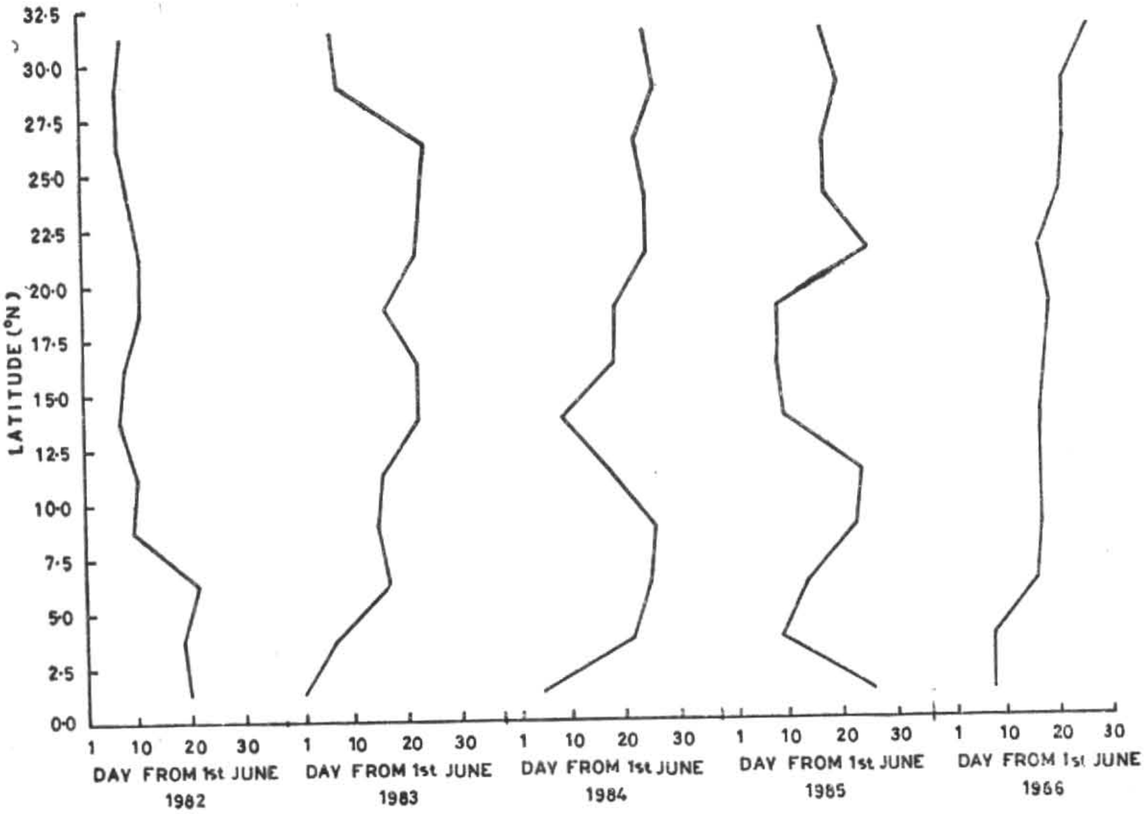

Fig. 1. Northward propagation of 30-40 days mode

4.2. *Northward propagation* — Murakami (1976), by computing the time lag correlations in the cloudiness in the northern summer, found that fields of positive correlations move northwards from equatorial Indian Ocean to the Indian sub-continent with an average speed of about 1° latitude per day. The northward phase speed of about 1° latitude per day was found by Yasunari (1979) who felt that the meridional fluctuations of cloudiness are accompanied by phases of active or break monsoon arising due to the repeatative northward shift of cloudiness from the equatorial Indian Ocean to Himalayas. Sikka and Gadgil (1980) also found that the cloud generated in the equatorial region move northwards and cross over to the monsoon trough zone (north of 15° N). Yasunari (1985) found a northward propagation of 1° to 2° Lat. per day of 500 mb wind anomalies in northern ehmispheric summer.

After having established the presence of 30 and 40-day modes in the zonally averaged cloud, the phase speed of these two modes are then examined. In the average picture for these two modes taken together (Fig. 1) northward propagation of the cloudiness also is generally confirmed. In some years, we found that the propagation is uniform throughout the northern latitudes. However, in other cases it is seen that within some latitudes there is a tendency for the cloud bands to retrograde. Such retrogration in deep convection have been reported by Murakami *et al.* (1984). On an average, it is seen that the northward phase speed is within 1° to 1.8° latitude per day. A northward movement of cloudiness within monsoon zone with speed of 1° Lat. day was observed by Murakami (1976), Yasunari (1980) etc. In zonal westerly flow, Yasunari (1985) observed a phase speed of 1°-2° Lat./day. An analysis of maxima in wind field and relative vorticity in the Indian summer monsoon by Mehta and Ahlquist (1986) revealed a variable phase speed of 0-1° Lat./day in 30-60 day mode The northward propagation of cloud clusters is, perhaps, the result of modulation of the poleward transport of relative angular momentum whose rates of production vary considerably in the tropics (Yasunari 1985), a condition necessary for conservation of angular momentum during the southwest monsoon.

4.3. *Inter-tropical cloud band* — The existence of a narrow band having maximum brightness in the satellite imageries during the monsoon season over India and neighbourhood (equator to 28°N) and its migratory characteristic are now a well documented fact. Sikka and Gadgil (1980) found two maximum cloud zones during the monsoon, located over 15° N to 28° N (called the monsoon MCZ) and equator to 10° N (secondary MCZ). A break in monsoon occurs just prior to the temporary disappearance of monsoon MCZ. The life cycle of the monsoon MCZ is found to be about a month. In this paper, the clouds were averaged as mentioned earlier in 2.5° latitudinal belt. The maximum cloudiness in any latitudinal belt has been termed as Inter-Tropical Cloud Band (ITCB). The location of ITCB for each day was plotted for each year and for some typical years, it is

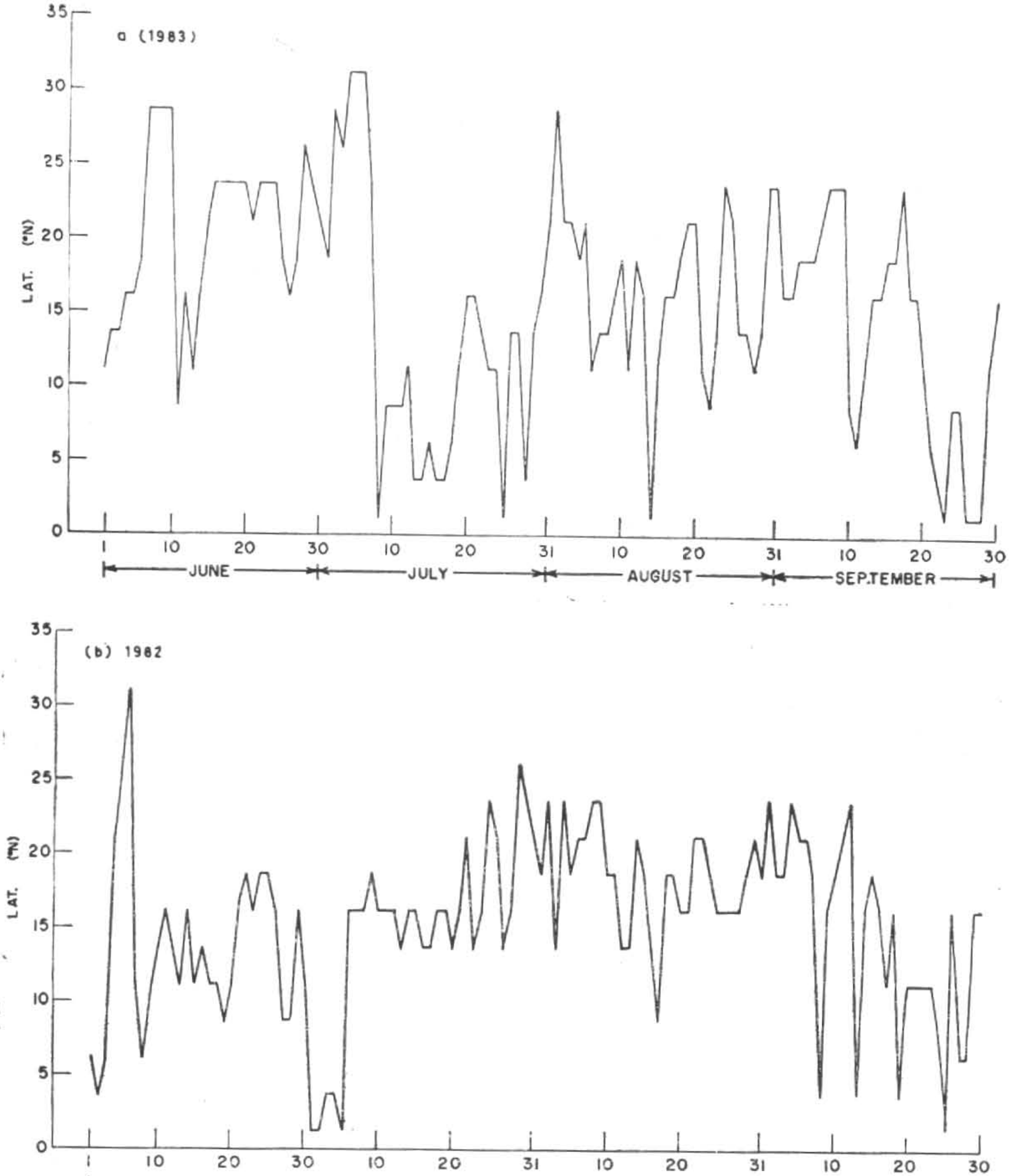

Fig. 2. Time-sections of ITCB : (a) 1983 and (b) 1982

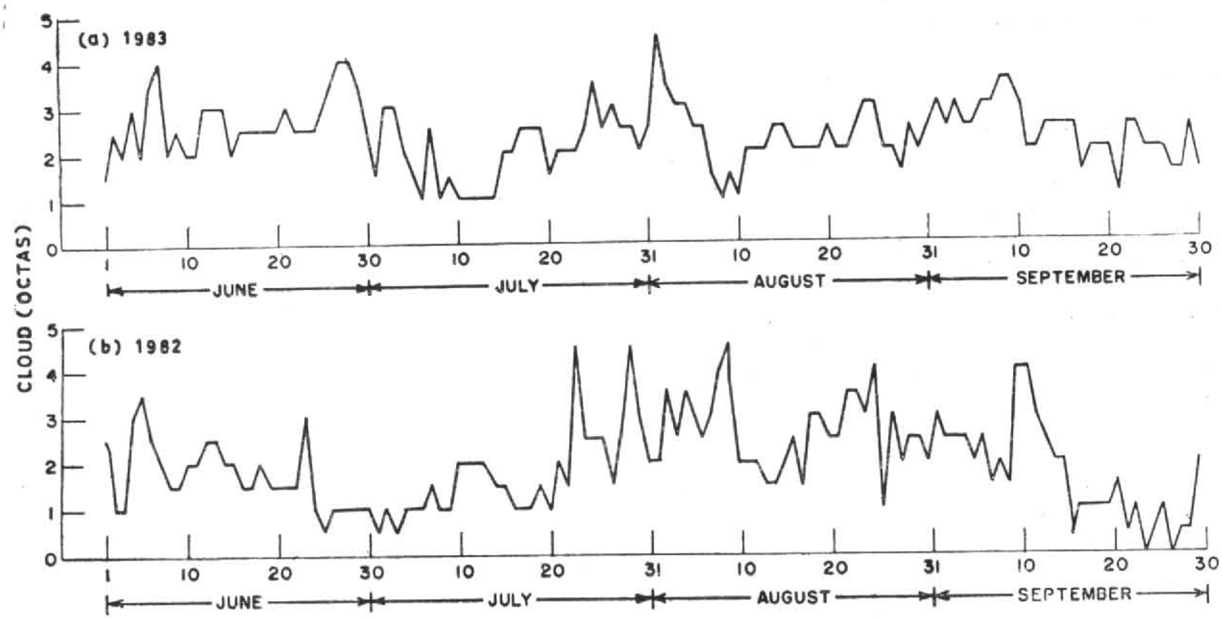

Fig. 3. Mean cloud amount (in octas) in monsoon trough zone (22.5°-27.5°N) for years : (a) 1983 & (b) 1982

illustrated in Fig. 2. A remarkable feature of cloud bands seen during the summer monsoon is their tendency to propagate polewards. This northward movement though continuous is, never uniform and can be related to the development of large cloud clusters within the inter-tropical convergence zone. The first phase of northward march of the ITCB corresponds generally to the onset stage of the Indian monsoon and its further advance. In subsequent period, *i.e.,* after establishment of monsoon over the country northward shift of the ITCB is not continuous and it fluctuates within different latitudes. Even in the sustained rainfall months of July and August, there are fluctuations in the location in the ITCB in association with active-break cycle.

Another feature observed when the locations of ITCB were averaged for each month is that in the ITCB during June, in years of subnormal rainfall is located in latitudes south of 17° N (Table 4). However, when the monsoon rainfall is normal/above normal the mean position during June is north of 20° N. This suggests that the northward march of ITCB in years of good monsoon is quite swift and rapidly covers the whole of the Peninsula though there are years when monsoon onset is late and yet the monsoon rainfall is normal/above normal. Interestingly, during the active monsoon period of July and August, the ITCB, in the mean, occupies rather lower latitudes. Sikka and Gadgil (1980) found high correlation ($\geqslant 0.8$) between monsoon trough at 700 mb and the maximum cloud zone. A lower position of the ITCB would mean a well distributed and heavier rainfall over the country.

The above observation has been supported by another evidence. The mean cloudiness between 22.5°N and 27.5°N can be taken as the clouding in the trough zone when the axis of monsoon trough at the surface, is in normal position. The plot of the mean cloudiness against time in different years are shown for selected years in Fig. 3. During a year of good monsoon, mean cloudiness over this trough zone is comparatively less since maximum cloudiness is located to the south of the axis. As we have seen above, the ITCB is located in the southern latitude in years of normal/above normal monsoon. This would mean that maximum cloudiness prevails in the southern latitudes. On the other hand, a large clouding in the northern latitude in a bad year would suggest that the cloudiness is concentrated in higher latitude only, which may, perhaps, be due to the location of the monsoon trough north of its normal position.

5. Plausible physical explanation

The monsoon circulation is highly influenced by modulations of the ITCB. The ascending motion is taking place in well organised deep convective region within ITCB, transport heat upward and polewards, as a component of localised Hadley cell. Another aspect which contributes to synopic scale disturbances in the summer monsoon is organisation of planetary scale zonal Walker cell with rising motion in 70° E to 140° E and subsidence in Central Pacific. Regional scale modulation of ITCB which give rise to spells of enhanced or suppressed monsoon corresponding to active-break cycle is associated with relative positions of Hadley and Walker circulations and their intensities.

Mainly two types of energy transports affect the summer monsoon, *viz.,* boundary layer sensible heat and moisture and the latent heating during deep convection. The total atmospheric heating which causes the vertical velocity during active spell, depends mainly on the release of the latent heat. During dry spells, however, the contribution of latent heat becomes inconsequential and boundary layer processes dominate. In these phases, the sensible heat and moisture exchange between surface and boundary layer is more significant. At the commencement of the dry spell amplitude of sensible heat is rather small but it increases as the spell prolongs.

As pointed above, the 30 to 60-day and 10 to 20-day oscillations mainly influence intra-seasonal variability in ITCB. The ITCB, perhaps, forms as a result of deep convection in response to warm sea surface temperature anomalies in the equatorial oceanic region. This then propagates northwards and establishes over the monsoon trough region. After remaining in that position for a period of about 30 days, it decays. The decay can largely be attributed to the negative anomaly of the radiative heat flux causing downward motion in the atmosphere (Monin 1972). The sensible heat being basically surface temperature dependent increases, thus increasing the total heating causing destabilisation of the lower troposphere. This process causes regeneration of convection and organisation of ITCB. Perhaps, this mechanism explains the successive zones of vertical motion propagating northwards. From the physical point of view, it appears that the low frequency propagation associated with active-break cycle is produced by cloud-radiative feed-back and hydrology.

6. Conclusions

(i) The variance explained by 30 to 60-day mode is generally significant during monsoon season especially in lower latitudes.

(ii) In good monsoon months lower frequency mode of 10 to 20 days, in general, also explains significant variance in the equatorial region.

(iii) The study confirms presence of interannual variability in the two low frequency modes.

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