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Development of monsoon breaks due to heat source over northwest India

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सार – मानसून द्रोणी क्षेत्रों के पश्चिमी भागों में भारी वर्षा की अनियमितता की घटनाओं का पता लगाने और देश के मध्य भागों में बाद की तीन पंचदिवसावधियों में वर्षा के वितरण में हुए परिवर्तन का अध्ययन करने के लिए दक्षिणी पश्चिमी मानसून वर्षा ऋतु में भारत के 52 खंड़ों में 1901 से 1980 तक के वर्षों में हुई वर्षा की पंचदिवसावधियों की अनियमितताओं व सिनॉप्टिक जलवायविक विश्लेषण किए गए। यह विश्लेषण भिड़े (1997) द्वारा किए गए नैदानिक अध्ययन के परिणामों के आधार पर है। इस विश्लेषण से मानसून द्रोणी क्षेत्र के पश्चिमी भाग में संवहनी भारी वर्षा और उसके बाद 1979 की मानसून वर्षा ऋतु के दौरान वर्षा के कम अथवा विरल अवस्था की घटना के कारण डायबैटिक उष्मा स्रोत के विकास की घटना का पता चला है।

मानसून द्रोणी (एस.ए.) के पश्चिमी भाग के टी.ए. परीक्षण क्षेत्र में वर्षा की पंचदिवसावधियों की सकारात्मक अनियमितताओं की घटना को सिनॉप्टिक घटना के रूप में समझाया गया है। एस.ए. को सी. 1 से सी. 5 वाले पाँच वर्गों वाले –1 और 9 के बीच की श्रेणियों में वर्गीकृत किया गया है। बाद की तीन पंचदिवसावधियों में हुई वर्षा की अनियमितता में आए परिवर्तन का अध्ययन किया गया है। एस.ए. के अधिकतम मान वाली सी. 5 की वर्षा की अनियमितता के पैटर्नों से भारत में विरल अवस्था के विकास का पता चलता है और यह वर्ष 1979 के मानसून के पहले किए गए प्रेक्षणों की पुष्टि करता है। सी. 4 वर्ग से कमज़ोर अवस्था के विकास का पता चलता हे।

ABSTRACT. A synoptic climatological analysis of pentad rainfall anomalies for 52 blocks over India for southwest monsoon season for the years 1901 to 1980 has been carried out to identify events of anomalous heavy rainfall over the western part of the monsoon trough area and study the change in rainfall distribution over central parts of the country in subsequent three pentads. This analysis is based on the results of a diagnostic study by Bhide *et al*. (1997) which showed that the events of development of diabatic heat sources due to convective heavy rainfall over the western part of the monsoon trough area were followed by the occurrence of a weak or break phase during monsoon 1979.

An event of positive pentad rainfall anomaly (SA) for a test area TA on the western part of the monsoon trough is considered as a basic synoptic event. SA is categorised into five classes C1 to C5 having ranges between –1 and 9. The change in rainfall anomalies for subsequent three pentads is studied. The pattern of rainfall anomalies for class C5, having the largest values of SA indicates development of a break phase over India and confirms the earlier observation for monsoon 1979. The development of a weak phase is indicated for class C4.

Key words – Monsoon rainfall, Secondary heat sources, Monsoon breaks.

1. Introduction

Recent results of MONEG (Monsoon Experiment Group - Sub period of TOGA) integration have shown that the simulation of average rainfall over India is feasible through the atmospheric boundary conditions (Palmer *et al*. 1992). However, the General Circulation Models are not able to simulate the intraseasonal variability correctly. Hence, any diagnostic work on intraseasonal variability *viz*. the evolution of active to break spells of monsoons can serve as a useful aid in medium/extended range weather forecasting. This paper is an attempt in this particular direction.

The monsoon circulation sets in due to the differential heating of the Eurasian land mass and the Indian Ocean caused by solar radiation. Cumulus convection causes release of very large amounts of latent heat in the atmosphere and leads to development of secondary diabatic heat sources in the atmosphere. Such heating takes place within a very short period and can change the thermal distribution over an area and hence it is expected to affect the circulation. Bhide *et al*. (1997) brought out detailed distribution of the diabatic heat sources over the monsoon trough area using FGGE MONEX 1979 data. Using the *x-t* diagram of heating and drying rates at 500 hPa along 22.5° N, the central latitude

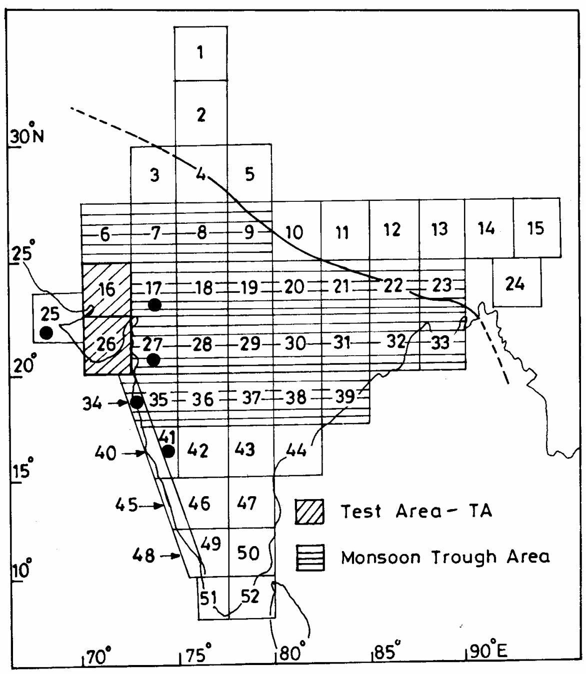


Fig. 1. Map showing the 52 blocks (each 2.5° Lat. × 2.5° Long.) over India. Axis of monsoon trough between 75° to 90° E is represented by the thick line

for trough area, they have shown that the east-west differential heating gradient over the monsoon trough reversed during the later days of the active phases during monsoon 1979 as compared to the normal heating gradient from west to east observed by Das (1962) for the month of July. Such a reversal was followed by break situations in monsoon 1979. They showed that the vertically integrated heat source and moisture sink moved coherently with convective rainfall in presence of transient synoptic scale systems over the monsoon trough area. The average heating rates were very large of the order of 8 to 11 K/day in the mid-troposphere at 500 hPa. An intense diabatic heat source developed at 500 hPa over the western part of the monsoon trough area during the active phase due to very heavy rainfall and associated release of latent heat. The heavy rainfall was associated with synoptic scale disturbances which either formed *in situ* over the western part of the trough area or moved there after their formation over north Bay of Bengal.

This relationship between the development of a diabatic heat source over the western trough area and the subsequent evolution of break over India for monsoon 1979 brought out by Bhide *et al.* (1997, hereafter referred to as Base Reference-BR) prompted us to analyse pentad rainfall data over India in the past records. The objective of the present study is to see whether monsoon evolved into break phase over India in a way, similar to monsoon 1979 or otherwise. The details of data and methodology are given in section 2. The results of this analysis are discussed in section 3. The conclusions from this study appear in section 4.

2. Data and methodology

Pentad rainfall (R) data for 52 blocks over India (Fig. 1) for June to September 1901 to 1980 is used for this study. For this purpose the daily rainfall data of 365 stations uniformly spread over the country were obtained from the India Meteorological Department. From these station data the spatial averages have been prepared for the 52 blocks covering the contiguous country. Each block is of the size, 2.5° latitudes x 2.5° longitudes. On an average there are about 6-8 stations for each block. More details are available in Singh *et al.* (1992) and Kripalani *et al.* (1991). These pentad rainfall data are considered to be most suitable for this analysis since the rainfall activity associated with synoptic scale monsoon disturbances, which have a time scale of 5 to 7 days, is reflected in the pentad rainfall over any part of India. Monsoon season rainfall shows very large variations from western to eastern parts of monsoon trough area. Hence, pentad rainfall anomaly ratio, S for the different blocks are used for this study. S for each block and each pentad is obtained as , S(I,Y,K) = [R(I,Y,K) – RBAR(I,K)] / RBAR (I,K)

where, Y stands for years, 1901 to 1980, I stands for the blocks, 1 to 52 and K stands for pentads, 1 to 24. RBAR (I, K) is the mean rainfall for I^{th} block and K^{th} pentad based on the 80-yr data.

In this analysis the test area 'TA' is selected to find out events of anomalous heavy rainfall over the western part of the monsoon trough. TA comprises of two blocks viz. 16 and 26 located on the northern and southern side of 22.5 ° N which is identified as the central latitude (BR). S-values for 52 blocks for the subsequent three pentads represent evolution of rainfall activity over India. TA extends from 20° and 25° N and 70.0° and 72.5° E. Average anomaly ratio, SA for the test area is obtained as,

SA(Y,K) = [S(16,Y,K) + S(26,Y,K)]/2.0

Normally, the monsoon advances over the entire country by 15 July and is found to withdraw from the central parts of the country after 15 September. Hence the data for pentads K = 10 to 21 covering the period from 16 July to 19 September of each season has been used for identifying the events of heavy rainfall over TA. The range of SA-values is from -1.0 to 8.5 and the classification of

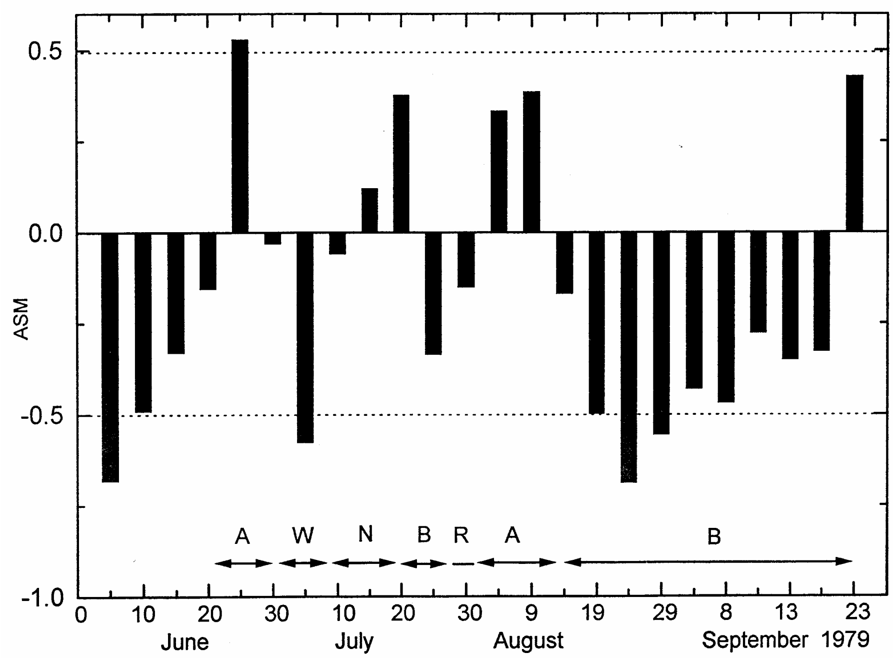


Fig. 2. Time series of average pentad rainfall anomaly ratio (ASM) for trough area excluding TA for monsoon 1979. [The periods of Active(A), Normal(N), Break(B) and Revival(R) phases are marked]

SA is done into five classes, C1 to C5 with the ranges from -1 to 0.99, 1 to 2.99, 3 to 4.99, 5 to 6.99 and 7 to 8.99 respectively. Suppose, there are N number of cases with anomalous heavy rainfall activity such that SA is lying between 3 to 4.99 in class C3. Then for each case the set of S-values for 52 blocks in the pentad say, PN in the Y^{th} year is identified as set A1 for pentad 1. The sets of S-values for pentads PN+1, PN+2 and PN+3 in the same year are identified as sets A2, A3 and A4 for pentads 2 , 3 and 4 respectively representing evolution.

In this way, S-values for the 52 blocks from A1, A2, A3 and A4 provide the data on evolution of rainfall anomalies for one case in class C3. The mean anomaly ratio, SM for each block is obtained from S-values from the N sets of A1, A2, A3 and A4 to prepare four maps, MP1 to MP4 for four pentads P1 to P4 respectively to prepare the mean pattern of evolution of rainfall activity of class C3. Similar procedure is repeated for the remaining classes. For class C1, data from 1971 to 1980 only are used to make the sample size small and comparable to other classes.

Average pentad anomaly ratio, ASM is obtained for each class and each pentad from SM values for blocks within the monsoon trough area from 17.5° to 27.5° N and 70° to 90° E and excluding blocks near the foot hills of Himalayas following BR. TA is also excluded from the trough area while obtaining ASM. The rainfall activity of the mean patterns is described by comparing it with ASM obtained for the 24 pentads of monsoon 1979.

Correlation coefficient, *r* is obtained between S for each block and SA for TA, using the data for 1971 to 1980 for pentads K=10 to 21. The statistical significance for the difference between ASM for class C5 and for C1, C2, C3 and C4 is tested by the *t*-test (Anderson, 1984).

Data of Daily Latitudinal Anomaly (DLA) from the normal position of the axis of the monsoon trough at mean sea level chart is used to prepare time series at 75° and 85° E for examining the oscillations of the monsoon trough in relation to evolution of rainfall activity. The data of the daily latitudinal position of the axis of trough at mean sea level at each 2.5° longitude between 75° and 90° E over India for July-August 1958 to 1990 has been collected from the daily surface charts, prepared at Weather Central, Pune (India Meteorological Department) for 0300 UTC. The daily data of DLA for different cases is obtained using the normal based on the 33-yr data.

3. Results and discussion

Fig. 1 shows the monsoon trough area following BR, and Test area, TA selected for the present analysis. Large positive anomaly ratios between 10 and 21 are observed

TABLE 1

Average pentad rainfall anomaly ratio, ASM for the monsoon trough area excluding TA. The blocks close to the foot hills of Himalayas with the area extending from 25° to 27.5° N and 80° to 90° E are excluded following BR

Class	Range of SA	Period	N	ASM			
				P1	P2	P3	P4
C1	-1 to 0.9	1971-80	105	-0.07	-0.05	-0.03	0.01
C2	1 to 2.9	1901-80	119	0.45	0.28	0.16	-0.04
C3	3 to 4.9	1901-80	35	0.52	0.18	0.00	0.06
C4	5 to 6.9	1901-80	5	0.58	0.18	-0.10	0.33
C5	7 to 8.9	1901-80	2	0.11	-0.56	-0.72	-0.67

for blocks 3, 6, 7, 16, 25 and 26 located on the western part of the trough. Particularly for blocks 16 and 26 the largest S-values are 11.75 and 13.86 respectively. Blocks having correlation coefficient, *r* larger than 0.5 with TA are indicated by large dots drawn below the block number in the figure. The events of anomalous heavy rainfall seem to cover an area larger than TA which is affected simultaneously by synoptic systems. TA, thus, can represent the western part of the monsoon trough in this analysis.

Fig. 2 presents the pentad rainfall scenario of the monsoon 1979 from 1 June to 29 September in terms of ASM, the average rainfall anomaly ratio for monsoon trough outside TA. The periods of Active (A), Normal (N), Weak (W), Break (B) and Revival (R) phases of monsoon 1979 are marked in the same figure following BR. ASM is between 0.3 to about 0.6 for pentad 5 in the first active phase in June and for pentad 13 and 14 of the second active phase in August. These pentads cover the initial part of the two active phases. Pentads 6 and 15 from the later part of these active phases have low negative ASM. This shows that the rainfall is reduced outside TA substantially in the later days of active phases of 1979. The normal phase in July shows a different behaviour with an increase of ASM from initial to final part. During the weak and break phases of monsoon 1979, ASM is found to be less than –0.3.

Table 1 shows that out of 960 pentads analysed from the 80-yr period, 161 pentads show large SA values corresponding to class C2 to C5. The table also shows a drastic reduction of N from C3 to C5 and indicates that events of anomalous very heavy rainfall over TA are rare. The ASM is near zero for all the four pentads for C1. This suggests that rainfall activity continues to be normal subsequent to events of near normal rainfall over TA.

For C2, C3 and C4, the ASM is greater than 0.4 and this indicates active phase in the first pentad similar to 1979. There is a substantial decrease of ASM in pentad P1 from class C4 to C5. The reason for such a decrease in ASM can be seen from the first map of the mean pattern for C5 (Fig. 4) which shows that the large positive anomalies are restricted to western trough only. The *t*-statistics for the ASM values for P1, P2, P3 and P4 is presented in the Table 2. It can be seen that for P1, the mean for class C5 is significantly different from that for class C4 (C3) at 97% (95%) level. For the following three pentads of evolution also ASM for C5 differs from that for C4 and C3 at more than 90% level of significance. This shows that the rainfall activity for class C5 is significantly different from that for class C4 and C3.

ASM shows a decrease from P1 to P2 and then to P3 for C2 to C4. For P4 in case of class C3 and C4 there is an increase in ASM. For class C5, however, the ASM-values are -0.56, -0.72 and -0.67 for P2, P3 and P4 respectively. These values are similar to the values of ASM for break phases in monsoon 1979 (Fig. 2). Large negative ASM is found to persist for 3 pentads and this suggests an evolution of a break over India in mean pattern for class C5. Due to large differences of ASM between class C4 and C5 the mean patterns of SM-distribution for these two classes only are discussed in detail in the following sub-sections.

3.1.1. *SM-distribution for class C4*

For class C4, the anomaly ratio, SA is between 5 and 7 and there are 5 cases. Out of these, 3 are from the years 1937, 1953 and 1958 of pentads 21, 16 and 21 respectively. Remaining two cases are from 1970 from pentads 18 and 20. Maps for the mean pattern of SM-values for this class are shown in Fig. 3. SM-values are of the order of 4 to 6 over TA and surrounding area in map MP1 and these are decreasing fast as we go eastwards to Head Bay of Bengal indicating normal rainfall over the eastern trough. SM is large over the west coast and over northwest India, northward of TA. Very low negative

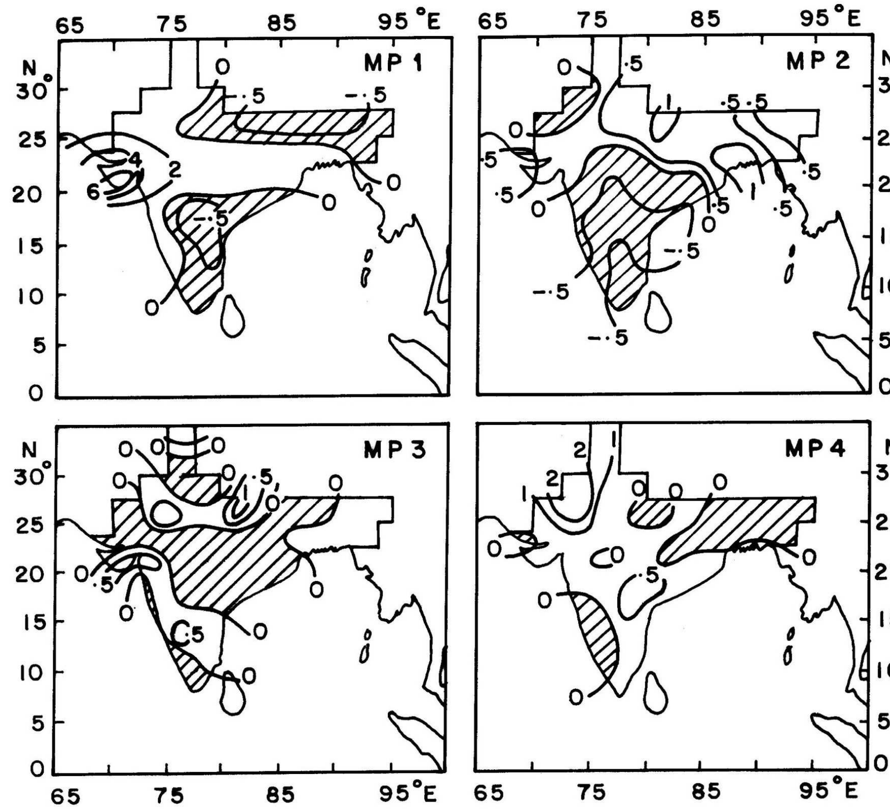


Fig. 3. Maps of pentad mean rainfall anomaly ratio, SM for pentad P1 to P4 for class C4. Shaded area shows negative values

TABLE 2

***t*-statistic for ASM for class C5 and C1, C2, C3 and C4. Ls shows level (%) at which '*t*' is significant**

Class	Degrees of freedom	P1		P2		P3		P4	
		t	Ls	*T*	Ls	*T*	Ls	*T*	Ls
C1	105	0.804	65	1.555	90	2.010	97	1.922	95
C2	119	1.507	90	2.647	99	2.080	97	1.675	95
C3	35	1.762	95	2.237	97	2.309	97	1.566	90
C4	5	3.828	97	2.695	97	1.881	90	1.548	90

anomalies are seen centred around 17.5° N, 77.5° E and these are surrounded by negative values of smaller intensity over most parts of peninsula except on west coast. Near the foot hills of Himalayas, north of about 27° N also, very low negative SM-values are seen. Positive anomalies extending northward from TA suggests presence of normal monsoon condition at the western end of the axis of the monsoon trough which normally runs from Ganganagar to Calcutta *via* Allahabad and then to Head Bay of Bengal.

A substantial decrease in anomalies is seen over TA from MP1 to MP2. There is an increase in the area of negative anomalies northward from peninsula in MP2. Positive anomalies north of this area show an increase as compared to MP1. From MP2 to MP3 and then to MP4 anomaly pattern shows a change from positive to negative type and *vice versa* over different parts. The positive anomalies over eastern peninsula and northwest India in MP4 seem to be associated with movement of some disturbance from west central Bay across the country towards northwest India. Large positive anomalies in the northern parts of the trough in different pentads are variable in space and time from P1 to P4. A reduction of rainfall anomalies over the trough for class C4 for two pentads subsequent to the event of large positive anomaly

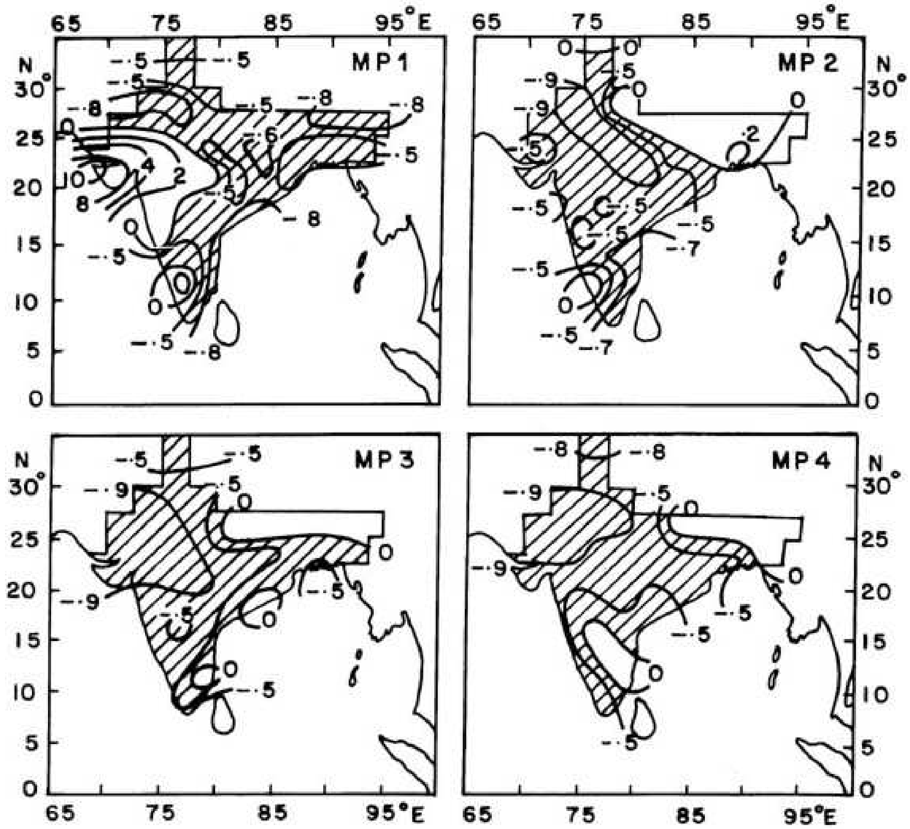


Fig. 4. Same as Fig. 3 except for class C5

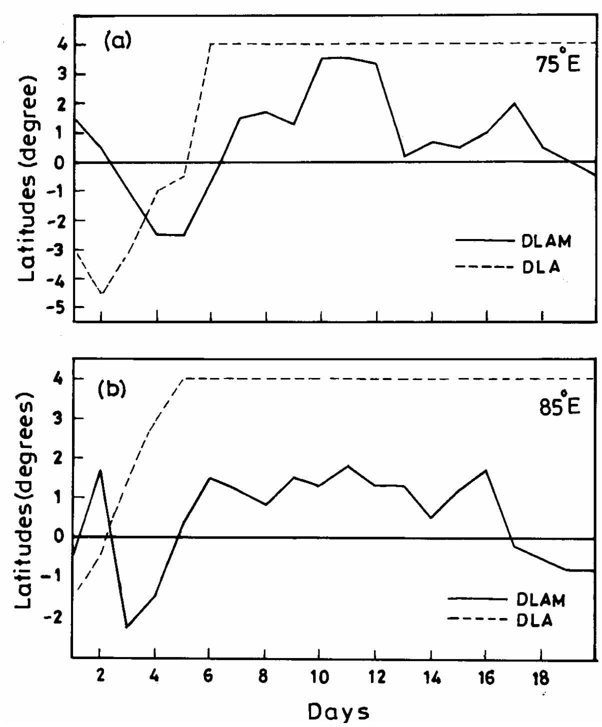
over TA in P1 indicates development of a weak phase. The rainfall anomalies for pentad P4 indicate recovery of rainfall activity over India.

3.1.2. *SM-distribution for class C5*

SA-values for the class C5 are between 7 and 9. One case of pentad 12 from the year 1905 and the other of pentad 15 from the year 1979 have contributed to the mean pattern. The SM-distribution for this class shown in Fig. 4 is typical and different from class C4. In pentad P1 all the positive large SM-values are concentrated over TA and the surrounding area west of about 75°E. South of TA on west coast and nearby rain shadow area east of western ghats, positive SM-values are observed north of 15° N. Outside this area, large negative anomalies of the order -0.5 and less than that are remarkable. Very large negative SM-values are observed over the east coast. These are slightly reduced as we move inside. The north eastern parts of India and areas close to the foothills of Himalayas show positive SM-values in maps MP2 to MP4. An area having very low negative anomalies from north western parts of the country is seen in different maps. Most of the remaining parts of India have large negative anomalies. This is indicative of a large deficiency of rainfall over central parts and the west coast similar to what is observed during the break monsoon conditions. In the pentad P4, small positive SM-values are observed over southeast peninsula surrounded by small negative values in map MP4 indicating shift of rainfall zone from monsoon trough area toward south peninsula. Change in the SM-distribution, for class C5, shows the evolution of break phase over India. This confirms the results for monsoon 1979.

3.2. *Oscillation of the monsoon trough over India*

The position of the monsoon trough is observed to control the rainfall activity over central parts of the country on day to day scale. Presence of transient synoptic scale disturbances within the trough leads to changes in its intensity and enhances the rainfall. The monsoon trough is observed close to foothills of Himalayas during the break phase over India. Normal position of the axis of monsoon trough between 75^o to 90^o E (Fig. 1) is based on its daily location at each 2.5^o longitude interval during July-August for 1958 to 1990. The daily latitudinal anomalies of the axis of the monsoon trough from its mean position at



Figs. 5(a&b). Time series of Daily Latitudinal Anomaly of the axis of the monsoon trough at 75° and 85° E for class C4 and C5

75° and 85° E have been studied to find out whether the oscillations of the trough show any difference with respect to the evolutions corresponding to C4 and C5.

Fig. 5 shows the time series of the Daily Latitudinal Anomaly Mean (DLAM) of the trough axis from its normal position for a 20-day period covering pentads P1 to P4 along the longitudes 75° and 85° E. The DLAM series is obtained from the daily average of data for the three cases of class C4, *viz.*, from pentad no. 21 of monsoon 1958 and pentad no. 18 and 20 from monsoon 1970. The DLA series for one case of class C5, from pentad no. 15 of 1979 is also shown in the same figure. Daily rainfall over an area is considered to result from the synoptic situation observed during the previous 24-hr period. Considering this the appropriate 20-day time series of trough anomaly is used for the study. The time series for 75° E and 85° E in the figure represent the oscillations of the western and the eastern parts of the trough axis respectively. The location of TA is very close to 75° E. A positive daily anomaly of 4° latitudes in the long data series represents shifting of the monsoon trough to the foothills of Himalayas during break phases.

DLA series shows that there is a southward anomaly of larger than 4° latitudes on day-2 [Fig.5(a)]. Such a southward location of the trough is responsible for the anomalous very heavy rainfall over TA as observed in the map MP1 (Fig. 4) for pentad P1. Following this, the trough shifted northward and is observed close to foothills of Himalayas from day-6 till the last day. This shows a northward movement of the trough through about 8° latitudes within four days. This also implies development of a zone of higher pressure over the western part of the trough. The DLAM series [Fig. 5(a)] shows that the southward anomaly on day-4 and day-5 is smaller as compared to that on day-2 for DLA for the case of 1979. For individual cases the southward anomaly of the trough is as large as that observed for the case of monsoon 1979 represented by DLA here. Such southward location of the trough has contributed to the large positive anomaly over TA for class C4. The northward extension of the positive rainfall anomaly zone is the result of the near normal location of the monsoon trough on remaining days of the first pentad. DLAM also shows a northward shift of the trough from day-6 and is found to be very close to the foothills within next five days. Unlike the case of 1979 a couple of days later the DLAM indicates a southward shift of the trough towards its normal position and finally is found to be slightly southward of the normal at the end. It can be noted that both the DLAM and DLA series show that the event of anomalous heavy rainfall over TA is followed by a shift of the monsoon trough towards the foothills of Himalayas on the western part and this implies development of a zone of higher pressure as compared to the normal on the western part.

Small negative anomalies are observed from DLA series for first two days at 85° E [Fig.5(b)] and following this the trough is close to the foothills from day-5 till the end of the period. The behaviour of DLAM is different and it shows small positive and negative anomalies in the initial five days. Following this the trough is seen to be located slightly to the north of the normal from day-6 and has small oscillations. Finally from day-16, it shows a southward movement till the end of the period. On the eastern side the positive anomaly of 4° latitudes for DLA series means shifting of the trough to the foothills of Himalayas and this implies development of a zone of higher pressure on eastern side also for the case of 1979. Thus DLA series for class C5 indicates more or less simultaneous development of a zone of higher pressure over the entire trough at the beginning of the break and its further continuation during the break phase. The reduction in rainfall over the trough as observed from maps MP2, MP3 and MP4 (Fig. 4) confirms the development of such a zone of higher pressure. Absence of such a development for class C4 on the eastern part has resulted into evolution of a weak phase having variable rainfall anomalies over

India as observed from maps MP2, MP3 and MP4 (Fig. 3) during pentads P2 to P4.

Thus, DLAM and DLA series for class C4 and C5 clearly show presence of monsoon trough close to TA over the western part in the initial days of the time series and this situation caused the observed large positive rainfall anomalies in the first pentad. Subsequent to this, during the period of evolution, the monsoon trough is found to shift close to the foothills of Himalayas for both the classes. Such a change is for a long period for the case of 1979 from C5 while remains for a shorter duration for class C4. These sequences suggest that the large positive rainfall anomalies and the associated development of an anomalous heat source over TA caused northward movement of the trough axis and development of a zone of high pressure over the western part. Simultaneous change of this type on the eastern part caused development of a zone of high pressure over the entire trough and led to the break phase during monsoon 1979.

4. Conclusions

The synoptic climatological analysis of pentad rainfall anomaly data for 52 blocks over India for an 80-year period from 1901 to 1980 for the established phase of the southwest monsoon season is carried out to identify the events of anomalous heavy rainfall in a pentad over the western part of the monsoon trough area represented by the test area TA and study the change in rainfall activity subsequent to such events. Average anomaly ratio, SA for the test area is categorised into five classes *viz*., C1 to C5 with the range of values from -1 to 0.9, 1 to 2.9, 3 to 4.9, 5 to 6.9 and 7 to 8.9 respectively. The results show that the events of anomalous heavy rainfall over TA are not restricted to TA alone but such events cover a larger area which is affected simultaneously by synoptic systems. For class C4, the event of anomalous heavy rainfall is followed by a weak phase while evolution of a break phase is observed over India for class C5. This is similar to what was observed for monsoon 1979 by Bhide *et al*. (1997) and the earlier results are confirmed.

DLAM and DLA time series for class C4 and C5 clearly show that the observed positive heavy rainfall anomalies and the associated development of the heat source over TA and surrounding area have caused northward movement of the monsoon trough towards foothills of Himalayas and development of a zone higher pressure over the western part of the trough. Simultaneous northward shift of the trough to the foothills of Himalayas and development of a zone of higher pressure over the eastern part led to the development of a break for the case of monsoon 1979 from class C5.

Out of 960 pentads analysed from the 80-yr period for the established phase of monsoon over India. The actual number of breaks observed during this long period is large. Whereas only few cases could be identified under class C4 and C5 for which evolution of a weak/break phase has been observed. This might be due to the limitation of the analysis which is based on the intensity of the rainfall anomaly over TA alone.

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