Mausam, (1989), **40**, 3, 247-258

551.553.21 : 551.515.1 : 556.124(083.86)

Index of activity of the monsoon trough over India

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(*Received 8 March 1988*)

सार — भारतीय मानसून द्रोणी की दैनिक, मासिक और ऋतुनिष्ठ सक्रियता के लिए पैमानों का विकास किया गया और ग्रीष्म मानसून ऋतु के दौरान भारतीय वर्षा के साथ उनके परिवर्तनों और संबंधों का परीक्षण किया गया।

दैनिक मानसून द्रोणी सक्रियता सूचकांक, दीर्घावधि माध्य से द्रोणी के अन्दर ही दैनिक दाब की असंगति है। सामान्यकृत दैनिक मानसून द्रोणी सक्रियता सूचकांक आवृत्ति 0.1% से ऊपर सार्थकता के स्तर पर भारतीय मानसून के कमी वाले वर्षों की अपेक्षा अच्छे भारतीय मानसून के वर्षों में <-1.0 अधिक रही है। सितम्बर के दिनों में, दैनिक मानसून द्रोणी सक्रियता सूचकांक अच्छे भारतीय मानसून के वर्षों की अपेक्षा कमी वाले भारतीय मानसून के वर्षों में (जैसे द्रोणी पर्याप्त कमजोर) पर्याप्त मात्रा में अधिक रही है।

दैनिक मानसून द्रोणी सक्रियता सूचकांक से व्युत्पन्न मानसून द्रोणी सक्रियता के मासिक मान, जून के अतिरिक्त सभी मानसून महीनों के लिए मासिक वर्षों के साथ महत्वपूर्ण संबंध दर्शाते हैं। सितम्बर के लिए यह संबंध बहुत ही महत्वपूर्ण और स्थिर है।

मानसून द्रोणी सक्रियता के मौसमी मानों में सक्रिय मानसून द्रोणी के साथ दिनों की मौसमी बारंबारता भारतीय मानसून वर्षा के साथ सार्थक रूप में (1 प्रतिशत पर) और स्थिर रूप में संबंधित है।

निम्न दाब प्रणालियां मानसून द्रोणी की सक्रियता में बहुत अधिक मात्रा में वृद्धि करती हुई पाई गई है।

सक्रिय मानसून द्रोणी के साथ ऋतुनिष्ठ बारम्बारता के दिनों का भारत में अप्रैल 500 मि. बार रिज अवस्थान से सार्थक रूप में (1 प्रतिशत पर) और प्रत्यक्ष रूप में संबंध है, यह मार्च-मई से लेकर जून-अगस्त तक पूर्वी भूमध्यरेखीय प्रशांत समुद्र सतही ताप असंगति की प्रवृति पर सार्थक रूप से (1 प्रतिशत पर) और विपरीत है। अतः अप्रैल 500 मि. बार रिज, मानसून ऋतु के दौरान भारत में मानसून द्रोणी सक्रियता का अच्छा सूचकांक है।

ABSTRACT. Measures for the daily, monthly and seasonal activity of the Indian monsoon trough are developed; and their variability and relationships with Indian rainfall during the summer monsoon season are examined.

The daily monsoon trough activity index is the anomaly of the daily pressure within the trough from the long-period mean. The frequency of the normalized daily monsoon trough activity index < -1.0 is higher in years of good Indian monsoon than that in years of deficient Indian monsoon, at a level of significance of above 0.1%. For days in September, the daily monsoon trough activity index is appreciably higher (*i.e.*, trough appreciably weaker) in years of deficient Indian monsoon than that in years of good Indian monsoon.

The monthly measures of the monsoon trough activity, derived from the daily monsoon trough activity index show significant relationship with monthly rainfall for all the monsoon months except June. The relationship for September is highly significant and stable.

Amongst the seasonal measures of the monsoon trough activity, the seasonal frequency of days with active monsoon trough is significantly (at 1%) and stably related to Indian monsoon rainfall.

Low pressure systems are found to add largely to the activity of the monsoon trough.

The seasonal frequency of days with active monsoon trough is related directly and significantly (at 1%) to April 500 mb ridge location over India, inversely and significantly (at 1%) to the eastern equatorial Pacific SST anomaly tendency from MAM to JJA. The April 500 mb ridge thus appears to be a good indicator of the monsoon trough activity over India during the monsoon season.

1. Introduction

The prominent synoptic scale systems over India and neighbourhood during the summer monsoon season (June-September) are, the semi-permanent monsoon trough extending from Pakistan to Burma, and the low pressure systems forming over the Bay of Bengal and the land area north of 15°N and moving generally in a westerly direction. Mooley and Shukla (1987) who examined the formation, location, movement and dissipation of these low pressure systems over the Indian region, found that on about 56.3% of the days during the monsoon season no low pressure system is observed over the Indian region. This brings out that on majority

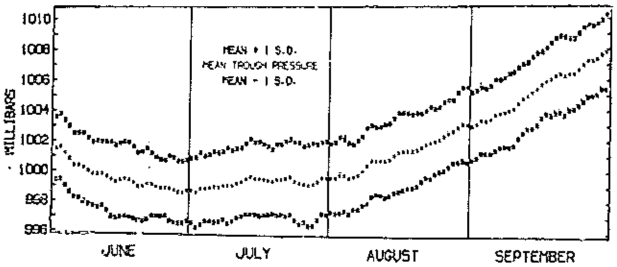

Fig. 1. Mean daily pressure (middle curve) within the monsoon trough during the monsoon season. The upper and lower curves indicate one standard deviation on either side

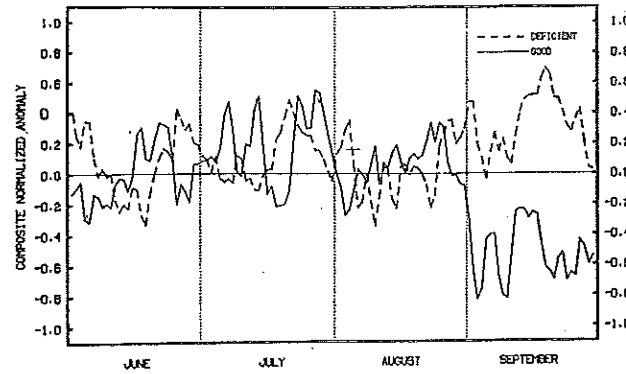

Fig. 2. Composites of daily normalized DMTAI in the monsoo season for years of deficient/good monsoon over India

of the days during the monsoon season, the monsoon trough is the only synoptic scale system contributing to the rainfall. The low pressure systems when present, add to the activity of the monsoon trough. The westerly/northwesterly movement of low pressure systems across the central and adjoining north India results in the maintenance of the activity and normal location of the monsoon trough through the upward vertical transport of heat and moisture over the area of the trough. If the trough shifts northwards to foot-Himalayas, a profound change occurs in the rainfall distribution over the country; rainfall decreases sharply over the plain regions of India and increases substantially over the sub-Himalayan area. Such a change in the trough location and the resulting sharp change in the monsoon activity is referred to as 'break' in the monsoon. When the location of monsoon trough is normal, the distribution of rainfall over the country is generally good. During the monsoon season, the trough undergoes north-south displacements, resulting in changes in rainfall distribution. On a majority of the days, these displacements are small, 2°-4° of latitude. The location of the monsoon trough over India and the variations in its intensity play a very important role in the contribution to the country's water potential and its interannual variability.

According to Koteswaram (1950), the 'breaks' in the Indian monsoon appear to be associated with the westward passage of a weak low pressure system across southern Bay of Bengal. However, Ramaswamy (1958, 1962) has brought out that the 'breaks' are associated with the interaction between the tropical and the mid-latitude circulation systems. Ramamurthy (1969) has studied in detail the 'breaks' in the monsoon in July and August during 1888-1967 and the associated mean circulation and rainfall over India. According to Raghavan (1973), as a result of a tropical low pressure system moving from the plains in a northerly direction towards sub-montane region 'break' in the monsoon follows. However, if there is a low over north Bay and neighbourhood, only the western portion of the monsoon trough may shift to the submontane region and in this situation, a 'break' in the monsoon may not follow. Bhalme and Mooley (1980) showed that the mean number of days of 'break' in the monsoon in July and August in years of drought over India much higher than that in years of flood over Indi Mooley and Parthasarathy (1983) brought out that tl mean of the longest spells of 'break' in the monsoc in drought years is much higher than that in years flood.

Bhalme and Parasnis (1975) who studied the pressu gradient over the Indian area during the monsoc season, found a significant 5-6 day oscillation in tl pressure gradient over north India (Nagpur-Del sector).

While estimating the possible causes of the failure the summer monsoon in 1899 and 1918, Mooley (197 found that the monsoon trough west of 80°E wa in general, substantially weaker than normal in ea of the monsoon months in each of these years. Pa and Sikka (1976) studied the Indian monsoon trou with regard to its location and north-south movemer Krishnamurty and Bhalme (1976) examined t oscillations of the different components of the monsoc system including the monsoon trough in year of norm monsoon rainfall. They found a pronounced qua biweekly oscillation in the surface pressure with the monsoon trough over India and neighbourhoo

For a proper understanding of interannual variabili of the Indian monsoon rainfall it is necessary examine the interannual variations in the activity the monsoon trough, the most important compone of the monsoon system. In this study, it is proposed devise an index of the activity of the Indian monsoc trough, examine the variability of this index and i relationship with the monsoon rainfall.

2. Data used

Preparation of the *Indian Daily Weather Repo* (I.D.W.R.) was commenced by the India Meterorologic Department from 1888. The report included the s level pressure data for the observatory stations ar a map showing analysis of mean sea level pressur After examining the network of observatory statio included in the report, it was found that pressure da for the four stations, Sagar Island, Allahabad, Sag and Jaipur which are fairly close to the normal locatio of the monsoon trough axis and which give the wide longitudinal coverage of the trough are available for the longest possible period of 1888-1983. The pressure data of these four stations were, therefore, proposed to be used for devising an index for estimation of the activity of the Indian monsoon trough. The daily sea level pressure data of these four stations for the morning observational hour for the monsoon season for the period 1888-1983 were collected from the *Indian Daily Weather Report* available in the Library of the National Oceanic Atmospheric Administration (NOAA) at Rockville, MD, U.S.A. Pressure data for June 1902 could not be collected due to non-availability of these I.D.W.R. at the library. From 1949, the hour of observation was changed from 0800 IST (0230 GMT) to 0830 IST (0300 GMT). To maintain the comparability of the post-1948 observations with the earlier observations, a correction of -0.3 mb was applied for diurnal variation to the observations from 1949 onwards. When sea level pressure values were not available in *Indian Daily Weather Report* on some occasions, these were interpolated from the analyzed weather chart contained in *Indian Daily Weather Report*.

Area-weighted monsoon rainfall series for India, north India, central India and south India were prepared from the monthly rainfall data of 306 stations evenly distributed over the country (For details of preparation of the series for India, please see Mooley *et al.* 1981 and Mooley *et al.* 1986), Rainfall data for the period 1888-1983 are used. For the areas north India, central India and south India kindly refer to Mooley and Shukla (1989, p.141, Fig. 4).

3. Basic approach to the problem

There are two approaches to the problem. The first one, the Eulerian approach, is to select a couple of representative stations fairly close to the normal location of the axis of the monsoon trough and to utilize the daily sea level pressure data of these fixed stations for a specific hour of observation to evolve the daily, monthly and seasonal index to assess the activity of the trough over these periods. The second one, the Lagrangian approach, is to select on each day in the monsoon season a couple of representative stations close to the axis of the trough as located on that day and evolve the daily index from the sea level pressure data of the selected stations, and from the daily index evolve the monthly and the seasonal index. Considerable effort is involved in the Lagrangian approach. In addition, when the trough is located over the sub-Himalayan region, it does not become possible to select stations along the trough axis for computation of the daily index. Almost every year, during the monsoon season, the trough is located over the sub-Himalayan region on some days and the number of such days varies from year to year. For such days, no index can be computed if we follow the Lagrangian approach. In the Eulerian approach, the trough index would invariably indicate the general activity of the trough, since the stations selected are fairly close to and around the normal location of the trough axis and the standard deviation of the trough axis is generally small, about 2.5° of latitude (Paul and Sikka 1976). However, in some situations, there may be ambiguity in the interpretation of the index. For example, rather much higher than normal value of the pressure within the trough could be interpreted either as weak trough or shift of the trough to the sub-Himalayan region. Since the influence of the notable weakening of the trough or its shift to the sub-Himalayan region on rainfall distribution over the country is similar, this ambiguity, perhaps, need not concern us. Our main purpose is to evolve an index of the trough activity and to examine its relationship to monsoon rainfall. In the light of these considerations, we decided to follow the Eulerian approach, and hereafter, the mean of the sea level pressures at the four fixed stations within the monsoon trough and close to the normal axis of the trough, will be referred to as pressure within the monsoon trough.

4. Mean daily pressure within the monsoon trough and its variation

The normal monsoon trough over India extends from Head Bay of Bengal to northwest Rajasthan with the trough axis running from Sandheads to Sriganganagar. Sagar Island, Allahabad, Sagar and Jaipur are located fairly close to the normal trough axis and are evenly distributed over the length of the trough axis. The mean monthly pressure data of each of the four stations and for each of the monsoon months were checked against the overall monthly mean to locate any consistently unusual features over any portion of the period 1888-1983. It was found that only the monthly pressures for 1888 at most of the stations were found to be rather too high compared to long-period monthly averages. Hence, pressure data in this study are considered for 1889-1983.

Let P_{ij} be the pressure within the trough on i^{th} day in the j^{th} year. This is the mean of the sea level pressures at the four stations on the i^{th} day of the j^{th} year. $\overline{P_i}$, the mean daily pressure within the trough on the i^{th} day is $\sum_{j=1}^{94} P_{ij}/94$, where i varies from 1 (1 June) to 122 (30 September). Standard deviation (S.D.) of the daily pressure within the trough for the i^{th} day is :

$$\left[\sum_{j=1}^{94} (P_{ij} - \overline{P}_i)^2 / 93 \right]^{\frac{1}{2}}$$

To start with, mean and S.D. of daily pressure within the trough are obtained for each day from day 1 to day 122. The middle curve in Fig. 1, shows the mean daily trough pressure from day 1 to day 122, and the upper and lower curves show respectively limits of 1 S.D. The daily trough pressure falls gradually from day 1 and reaches a minimum around June 29, then rises very slowly up to day 45 (about mid-July). Thereafter, it is almost steady up to day 66. From day 67 (6 August) to day 122 (30 September), the mean daily trough pressure rises progressively from 999.5 mb to 1008 mb. This is the period over which large seasonal variation occurs in the trough pressure. In view of the Gaussian distribution of pressure, the daily monsoon trough pressure is expected to be within one S.D. on either side of the mean on about 68% of the days, be more than one S.D. below or above the mean on about 16% of the days. The S.D. of the daily trough pressure is about 2 mb and shows small variation from one day to another within the monsoon season. A wide variety of patterns of the daily anomaly of the monsoon throug pressure during the monsoon season is possible.

TABLE 1 (a)

Frequency distribution ot normalized DMTAI in years of deficient monsoon over India

Years of deficient monsoon	Frequency of class interval of normalized DMTAI								
	⩽−2.0	>−2.0 but ⩽−1.5	>−1.5 but ⩽−1.0	>−1.0 but ⩽−0.5	>−0.5 but ⩽0.5	>0.5 but ⩽1.0	>1.0 but ⩽1.5	>1.5 but ⩽2.0	>2.0
1899	0	0	0	5	54	27	19	8	9
1901	0	6	8	6	59	17	12	12	2
1904	0	1	3	19	60	27	7	3	2
1905	0	1	6	12	54	27	16	6	0
1911	0	5	9	32	41	14	11	7	3
1918	0	1	1	11	51	34	17	5	2
1920	1	2	7	24	49	18	10	9	2
1928	2	4	10	21	39	29	13	2	2
1941	5	2	10	20	48	15	16	3	3
1951	0	1	4	24	42	21	27	1	2
1965	0	3	10	21	40	25	14	6	3
1966	1	5	9	11	57	22	7	8	2
1968	0	2	7	37	53	16	5	2	0
1972	0	2	13	15	55	23	12	2	0
1974	8	8	8	20	51	19	6	2	0
1979	7	6	7	11	28	22	16	18	7
1982	0	3	13	23	50	20	11	2	0
Mean	1.41	3.06	7.35	18.35	48.88	22.12	12.90	5.65	2.30

TABLE 1 (b)

Frequency distribution of DMTAI in years of good monsoon over India

Years of good monsoon	Frequency of class interval of normalized DMTAI								
	⩽−2.0	>−2.0 but ⩽−1.5	>−1.5 but ⩽−1.0	>−1.0 but ⩽−0.5	>−0.5 but ⩽0.5	>0.5 but ⩽1.0	>1.0 but ⩽1.5	>1.5 but ⩽2.0	>2.0
1892	5	6	11	9	40	22	16	13	0
1893	2	3	5	6	53	24	19	9	7
1894	0	2	8	28	45	15	17	7	0
1910	4	7	11	7	41	23	11	6	12
1916	13	7	16	9	28	19	20	8	2
1917	1	3	16	24	41	21	14	2	0
1933	5	4	9	14	39	22	9	13	7
1942	1	4	14	17	59	10	13	4	0
1947	5	12	15	16	42	14	11	4	3
1956	4	8	8	18	47	22	14	0	1
1959	3	11	24	20	42	16	5	1	0
1961	13	13	21	27	33	4	4	1	6
1970	1	8	20	28	47	10	6	2	0
1975	7	3	16	24	47	11	9	2	3
1983	0	2	11	23	38	21	17	4	6
Mean	4.26	6.20	13.67	18.00	42.80	16.93	12.33	4.67	3.07
Diff. of means*	2.85	3.14	6.32	−0.35	−6.08	−5.19	−0.57	−0.98	0.77

*Mean for good monsoon *minus* mean for deficient monsoon

5. Daily monsoon trough activity index

5.1. *Definition*

Daily monsoon trough activity index (DMTAI) for i^{th} day in the monsoon season is defined as follows:

$$(\text{DMTAI})_i = P_{ii} - \sum_{j=1}^{94} (P_{ij}/94)$$

$(\text{DMTAI})_i$ is thus the anomaly of the pressure within the monsoon trough for the i^{th} day .

The normalized value of the index is $(\text{DMTAI})_i/(\text{SD})_i$ where $(\text{SD})_i$ is the standard deviation of the trough pressure for i^{th} day. DMTAI and its normalized value are computed for day 1 to day 122 for each of the years 1889-1983.

5.2. *Main features*

For each monsoon season, the mean DMTAI and SD are computed. The highest mean DMTAI is 1.4 mb for 1899, and the lowest of −1.4 mb is for 1961. These two years respectively experienced the lowest/highest seasonal rainfall over India during 1889-1983. It is found that the range of DMTAI for 1899 is low, 8.6 mb and that for 1961 is high, 14.2 mb. In 40% of the years, the mean DMTAI is small (within ± 0.3 mb), since in several years, the daily values during the season are symmetrically distributed around zero. Relatively larger numerical values of the mean indicate lack of symmetry around zero.

Standard deviation of DMTAI during the monsoon season varies from year to year by a factor of 2, the lowest (1.6 mb) and the highest (3.1 mb) being in 1968 (deficient monsoon year) and in 1916 (good monsoon year) respectively.

Frequencies of normalized DMTAI are computed for each year for the 12 class intervals: 1(<-3.0), 2(>-3.0 but $\leqslant -2.0$), 3(>-2.0 but $\leqslant -1.5$), 4(>-1.5 but $\leqslant -1.0$), 5(>-1.0 but $\leqslant -0.5$), 6(>-0.5 but $\leqslant 0.0$), 7(>0.0 but $\leqslant 0.5$), 8(>0.5 but $\leqslant 1.0$), 9(>1.0 but $\leqslant 1.5$), 10(>1.5 but $\leqslant 2.0$), 11(>2.0 but $\leqslant 3.0$), 12(>3.0). From these, the mean frequencies are computed for the period 1889-1983. The frequencies are symmetrical about the mean which is zero. Chi-square test for normality of the distribution is applied over 10 class intervals, 3 to 10 as mentioned before and combinations of the class intervals 1 and 2, and of 11 and 12 since frequencies for 1 and 12 are very small. The value of Chi-square is 1.34 (d.f. 7) which is not significant even at 20% level, indicating Gaussian distribution of DMTAI. Kolmogorov-Smirnov (K-S) test also supports this inference.

5.3. *Contrast in years of deficient/good Indian monsoon*

The frequency distribution of normalized DMTAI is examined for years of deficient/good monsoon over India. Years of normalized Indian monsoon rainfall anomaly $\leqslant -1.0/\geqslant 1.0$ are defined as years of deficient/good monsoon over India as done by several research workers. Tables 1(a) and 1 (b) give the frequencies for 9 class intervals of normalized DMTAI for years of deficient and good monsoon years respectively and also the means for these two groups of years. The class intervals are derived from the 12 class intervals as mentioned earlier, by combining 1 & 2, 6 & 7, and 11 & 12, and keeping the remaining six intervals unchanged. Table 1(b) also gives the difference (good *minus* deficient) between the means for the two groups of years. The main point of difference is generally much smaller frequencies for the first three class intervals in deficient monsoon years in comparison to those in good monsoon years, indicating generally weaker monsoon trough in deficient monsoon years. The worst drought year, 1899 and the worst flood year, 1961 show a very large contrast in the frequency distribution of DMTAI. In 1899, there was no day with normalized DMTAI < -1.0 in the whole monsoon season, but in 1961, the number of such days in the season was 47. The monsoon trough was far more active than normal in 1961 and far less active than normal in 1899. The difference between the mean frequencies for good and deficient monsoon years is positive for the first three class intervals (normalized anomaly of DMTAI<-1.0) and negative for class intervals between −0.5 and 2.0. Frequencies of normalized DMTAI<-1.0 and of normalized DMTAI between −0.5 and 2.0 during the monsoon season were tabulated for years of deficient/good monsoon over India and the differences between the means for the two groups of years were tested for significance by Student's t-test (2-tailed). Student's test statistic t in the former case is 3.98 (d.f. 30), significant above 0.1%, and in the latter case, it is 3.0 (d.f.30) significant at 1% . The contrast between the two groups is sharper in respect of the number of days with normalized DMTAI < -1.0 than that in respect of days with normalized DMTAI between −0.5 and 2.0. The number of days with normalized DMTAI <-1.0 is higher during years of good monsoon over India than that during years of deficient monsoon over India at a level of significance of above 0.1% . Mann-Whitney test (1947) also supports this inference at the same level of significance.

We have seen that the frequency distribution of DMTAI shows distinctly different characteristics in years of deficient/good monsoon over India. The question whether DMTAI over any specific portion of the monsoon season shows notable contrast in years of deficient/good monsoon over India has been examined. Mean normalized DMTAI for day 1 to day 122 is computed for years of deficient/good monsoon. The composites for deficient/good monsoon years are shown in Fig. 2. A good contrast is observed for days in September (*i.e.*, from day 93 to day 122). The mean normalised value of DMTAI for each of the days in September is distinctly smaller for years of good monsoon than that for years of deficient monsoon. This indicates higher activity of the Indian monsoon trough during September in years of good monsoon than that in years of deficient monsoon. A further examination is made to find out if the higher activity of the monsoon trough in September is reflected in Indian monsoon rainfall. Indian monsoon rainfall consists of four components— June, July, August and September. Composites of these rainfall components are computed for years of

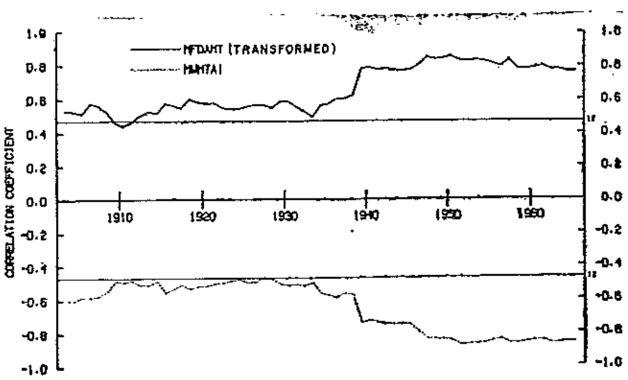

Fig. 3. Variation in correlation coefficient (CC) of Indian rainfall for September with transformed MFDAMT for September (continuous curve) and with MWMTAI for September (discontinuous curve) for sliding 30-year periods

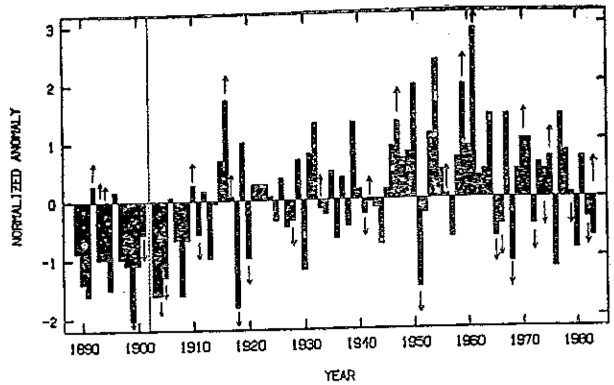

Fig. 4. Normalized anomaly of the Seasonal Frequency of Days with Active Monsoon Trough (SFDAMT) in each year. Period 1889-1983. Mean=19.4 and SD=9.6. Arrows pointing upward/downward indicate good/deficient monsoon over India

TABLE 2 (a)

Spells (of 3 days or more) of activity (normalized DMTAI <−1.0) of the monsoon trough in years of deficient monsoon over India

Year of deficient monsoon	Details of spells from day ....to day..	Total number of spells	Length of longest spell (days)
1899	None		
1901	11-13; 34-37; 67-71	3	5
1904	None		
1905	97-100	1	4
1911	18-20; *115-118*	2	4
1918	None		
1920	52-54	1	3
1928	13-18; 54-56; 90-92	3	6
1941	31-33; 38-40; 70-73; 76-78	4	4
1951	None		
1965	15-18; 56-58; *96-98*	3	4
1966	59-62; *95-100*	2	6
1968	39-41	1	3
1972	42-46; 56-58	2	5
1974	15-17; 42-44; 70-80; 88-90; *120-122*	5	11
1979	24-32; 65-71; *119-121*	3	9
1982	72-74; 82-86; *103-105*	3	5
Total		33 (in 17 years)	
Total (adjusted by the factor 15/17)		29.1	

Note : (*i*) Day 1 is 1 June, Day 31 is 1 July, Day 62 is 1 August, Day 93 is 1 September and Day 122 is 30 September. Details of spells are given in days on scale 1 to 122.

(*ii*) Spells in September are in italics.

TABLE 2 (b)

Spells (of 3 days or more) of activity (normalized DMTAI <−1.0) of the monsoon trough in years of good monsoon over India

Year of good monsoon	Details of spells from day....to day....	Total number of spells	Length of longest spell (days)
1892	9-11; 51-54; *93-96*; *99-104*	4	6
1893	*94-96*; *101-103*	2	3
1894	76-79	1	4
1910	32-35; *95-101*; *120-122*	3	7
1916	4-15; 20-24; *110-122*	3	13
1917	12-14; 49-52; *95-97*; *107-110*	4	4
1933	62-65; *109-115*	2	7
1942	25-27; 60-65	2	6
1947	9-12; 44-52; 91-96; *115-118*	4	9
1956	1-5; 7-9; 63-66; *100-102*; *113-116*	5	5
1959	9-11; 48-50; 64-67; 79-81; *90-97*; *102-107*; *120-122*	7	8
1961	6-9; 30-37; 66-68; 80-83; *102-110*; *113-115*; *117-122*	7	9
1970	40-42; 88-90; *93-98*; *111-114*; *116-118*	5	6
1975	14-19; 69-76; *100-102*; *116-119*	4	8
1983	*108-111*; *118-120*	2	4
Total		55 (in 15 years)	

Note : (*i*) Day 1 is 1 June, Day31 is 1 July, Day 62 is 1 August, Day 93 is 1 September and Day 122 is 30 September. Details of spells are given in days on scale 1 to 122.

(*ii*) Spells in September are in italics.

deficient/good Indian monsoon rainfall, and the differences between composites are tested for significance by Student's t test (2-tailed). The t values are, June: 3.93 (d.f. 28), July: 3.20 (d.f. 28), August: 7.37 (d.f. 28) and September: 9.69 (d.f. 28). Thus, the component for September contributes maximum to the difference between good and deficient Indian monsoon rainfall. The difference in rainfall for September is 2.1 times the standard deviation. August comes next with rainfall difference of 1.8 times S.D. Compared to September and August, the contributions of June and July, though significant at 1% level, are relatively much less. The composites of DMTAI do not show good contrast over August (*i.e.*, from day 62 to day 92) probably because the periods of low values of DMTAI in good monsoon years, as well as the periods of high values of DMTAI in deficient monsoon years show variation. The consistently larger activity of the monsoon trough in September in years of good Indian monsoon in comparison to that in years of deficient Indian monsoon is very well reflected in September rainfall of India in good monsoon years.

Monsoon rainfall is observed to occur in spells. It would be interesting to examine if there are spells of activity of the monsoon trough. Spells of activity of three days or more are considered, and these are defined by the number of consecutive days when normalized DMTAI is <—1.0. Such spells are obtained for deficient/good monsoon years. Tables 2(a) and 2(b) give the details of these spells. The main points of difference are: (*i*) No spells in 4 years (1899, 1904, 1918, 1951) of deficient monsoon, (*ii*) number of spells in 15 years of good monsoon is almost double of that in deficient monsoon, and mean length (6.6 days) of longest spell in good monsoon years is at least 50% more than that (4.1 days) in deficient monsoon years. In Tables 2(a) and 2(b), the spells that occurred in September are indicated. It is observed that while the total number of spells in September in deficient monsoon years is 6, it is 27 in good monsoon years. Thus, the years of good monsoon over India are characterized by a markedly higher frequency of spells of activity of the monsoon trough in September. This, to some extent, could be due to much later wihdrawal of monsoon from northwest India than normal in good monsoon years and much earlier withdrawal of monsoon from northwest India in deficient monsoon years.

6. Monthly monsoon trough activity index

There are two measures of monthly index of monsoon trough activity which can be obtained from DMTAI. The first one is the number of days with normalized DMTAI <—1.0 during the month, to be hereafter referred to as Monthly Frequency of Days of Active Monsoon Trough (MFDAMT). The second one is a weighted index obtained by giving suitable weights to the values of DMTAI during the month. With the daily index assuming positive and negative values, the total of the daily indices for a month would be small. It is expected that in years which depart rather notably from normal rainfall activity, DMTAI may show asymmetry around zero and with a suitable scale of weights it should be possible to obtain a weighted index which would adequately bring out the character of trough activity during the month. In a monsoon month of near-normal activity of the trough, DMTAI would be almost symmetrical around zero and the monthly weighted index for such years would be close to zero. The monthly weighted monsoon trough activity index (MWMTAI) is defined as follows :

$$\text{MWMTAI} = \sum_{i=1}^{n} w_j \times (\text{DMTAI})_i \Big/ \sum_{j=1}^{10} w_j$$

where $(\text{DMTAI})_i$ is the daily index for i^{th} day of the month, i varying from 1 to n, where n is 30 or 31, depending on the month and w_j is the weight which depends on the value of $(\text{DMTAI})_i$. The values of w_j for j=1 to 10 are given below :

$w_1 = w_{10} =$ 0.5, if normalized anomaly of $(\text{DMTAI})_i < -2.0$ or $> +2.0$

$w_2 = w_9 =$ 0.4, if the normalized anomaly of $(\text{DMTAI})_i$ lies between — 2.0 and — 1.5, or between 1.5 and 2.0

$w_3 = w_8 =$ 0.3, if the normalized anomaly of $(\text{DMTAI})_i$ lies between — 1.5 and —1.0 or between 1.0 and 1.5

$w_4 = w_7 =$ 0.2, if the normalized anomaly of $(\text{DMTAI})_i$ lies between —1.0 and —0.5 or between 0.5 and 1.0

$w_5 = w_6 =$ 0.1, if the normalized anomaly of $(\text{DMTAI})_i$ lies between —0.5 and 0.0 or between 0.0 and 0.5

The weights are designed to bring out prominently, the asymmetry of DMTAI in years of deficient and good monsoon. MWMTAI is the total weighted anomaly for the month. MFDAMT and MWMTAI are computed for each monsoon month for each of the years 1889-1983.

6.1. *Monthly frequency of days of active monsoon trough*

Composites of MFDAMT for deficient/good Indian rainfall for June, July, August and September are prepared. The criteria for deficient/good monthly Indian rainfall are, normalized monthly rainfall anomaly $\leqslant -1.0/\geqslant 1.0$. The years of deficient/good monthly Indian rainfall vary from one monsoon month to another. Since the distribution of MFDAMT is not Gaussian it is not possible to use Student's t-test. Hence, the non-parametric Mann-Whitney test is used. The result of the test indicates that MFDAMT for deficient rainfall years is lower than that for good rainfall years at a level of significance of 0.1% for September, 1% for August and 5% for July. For June, the two groups of values of MFDAMT do not differ significantly. The strong contrast for September suggests a highly significant relationship between MFDAMT for September and Indian rainfall for September.

The relationship between monthly Indian rainfall and MFDAMT is examined for each monsoon month. The correlation coefficient (CC) between the two variables is a measure of the relationship between the two variables, provided the two variables are Gaussian-distributed. While the monthly Indian rainfall for monsoon months is Gaussian or near Gaussian, MFDAMT departs rather appreciably from the Gaussian distribution. Hence MFDAMT is transformed to Gaussian distribution by using the transformation $(1+x)^{1/2}$, and CCs for each of the monsoon months are computed between monthly Indian rainfall and the transformed MFDAMT for each of the monsoon months, for the period 1889-1983. These CCs for June, July, August and September are respectively 0.01, 0.36, 0.34 and 0.59. Of these CCs for September is significant well above 0.1% and those for July and August are significant at 0.1%. These relationships are direct.

Table 3 gives the values of MFDAMT for September in years of deficient/good September rainfall over India. The values are zero in several years of deficient September rainfall and generally do not exceed 3 in the remaining years of deficient September rainfall. In contrast, the values in good September rainfall years inveriably are $\geqslant 5$. Thus, the relationship for September is seen to be very strong.

The variation of CC between September Indian rainfall and transformed MFDAMT for September is investigated for sliding 30-year periods, the first 30-year period commencing from 1889 and the period sliding forward by one year at a time. The CC is shown at the centre of the period in Fig. 3. It may be noted that practically for all the 30-year periods, the CC is significant at 1% level. It is found that for all 30-year periods commencing after 1924, the CC exceeds 0.75. The highest observed CC is 0.85 for the period 1936-65.

6.2. *Monthly weighted monsoon trough activity index*

The mean values of MWMTAI are computed for June, July, August and September for deficient/good Indian rainfall in the corresponding months. It is seen that the mean MWMTAI for deficient monthly Indian rainfall is higher (*i.e.*, monsoon trough weaker) than that for good monthly Indian rainfall at a level of significance of above 0.1% for September, above 1% for July and above 5% for August.

These mean values for deficient/good Indian monthly rainfall suggest significant relationship between monthly Indian rainfall and monthly weighted monsoon trough activity index for July, August and September. The CCs between monthly Indian rainfall and MWMTAI are computed. These for July, August and September are respectively —0.38, —0.28 and —0.62, showing highly significant (above 1%) inverse relationship for these three months. The relationship is strongest for September and is significant above 0.1% level. Over such a long period like 90 years (1889-1978), we are not aware of any other CC numerically as high as 0.62 between two atmospheric variables for the same month. This CC is numerically slightly higher than that between Indian rainfall for September and MFDAMT for September.

Fig. 3 also shows the variation of CC between September rainfall of India and MWMTAI for September over sliding 30-year periods. It may be noted that CC is always numerically higher than 0.47 which is significant at 1% level, and particularly for 30-year periods after about 1930, the CC is $\leqslant -0.80$.

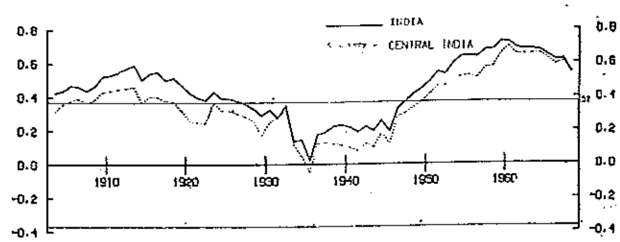

Fig. 5. Variation of the CC between SFDAMT and monsoon rainfall of India (thick continuous curve) and of central India (thin discontinuous curve) for sliding 30-year periods

TABLE 3

Values of MFDAMT for September in years of deficient/good September rainfall over India

Years of deficient rainfall	MFDAMT for Sep (days)	Years of good rainfall	MFDAMT for Sep (days)
1896	1	1891	0
1899	0	1892	10
1901	0	1893	8
1904	0	1900	1
1907	0	1902	2
1912	3	1917	11
1913	4	1924	0
1918	0	1926	9
1920	3	1945	5
1925	2	1947	9
1928	0	1949	16
1929	0	1954	19
1940	0	1955	7
1941	0	1958	8
1951	0	1959	14
1952	1	1961	20
1957	1	1962	8
1968	2	1975	7
1972	2		
1979	3		
1980	0		

Note : Monthly rainfall not available beyond 1980

7. Seasonal monsoon trough activity index

In the previous section, we utilized DMTAI values for each of the monsoon months and obtained two measures of monthly index of monsoon trough activity for each of the monsoon months June, July, August and September. We found that except for June, the relationships between monthly Indian rainfall and these monthly measures of the activity of the monsoon trough are significant for each of the monsoon months.

We now attempt to obtain in a similar manner seasonal measures for the monsoon trough activity. The first seasonal measure is the seasonal frequency of days with DMTAI < -1.0. This will be, hereafter, referred to as Seasonal Frequency of Days with Active Monsoon Trough (SFDAMT). The other measure is the weighted seasonal index obtained from values of DMTAI, using exactly the weights indicated in Sec. 6. This will hereafter, be referred to as Seasonal Weighted Monsoon Trough Activity Index (SWMTAI). Both of these measures have been computed for the season for each of the years 1889-1983.

7.1. *Seasonal frequency of days with active monsoon trough*

The series of SFDAMT for the period 1889-1983 is obtained. The mean and S.D. of the series are 19.4 days and 9.6 days respectively. The auto-correlation coefficient with lag 1 is marginally significant at 5%, suggesting slight persistence. Application of Swed and Eisenhart's (1943) test of runs above and below the median shows that the series has neither significant trend nor significant oscillation. Fig. 4 shows the normalized anomaly of SFDAMT and years of good monsoon (upward-pointing arrow) and of deficient monsoon (downward-pointing arrow) over India. It is seen that the seasonal frequency of days with active monsoon trough was mostly below the long-period mean during the period 1889-1920 and was mostly above the mean during the period 1945-75. During the period 1921-45, SFDAMT is below normal or above normal in about 50% of the years. It may be noted that the lowest and the highest values of SFDAMT of zero and 47 (38.5% of the total number of days during the monsoon season) occurred respectively in 1899, year of the lowest Indian monsoon rainfall, and in 1961, the year of the highest Indian monsoon rainfall.

The distribution of SFDAMT is tested for normality by applying Chi-square and K-S tests. For Chi-square test, the 8 class-intervals considered are < 5 days, 5-9, 9-14, 14-19, 19-24, 24-29, 29-33 and >33 days. The value of Chi-square is 2.85 (5 d.f.) which is not significant even at 20% level. For K-S test, the maximum absolute value of the difference between observed cumulative distribution and the Gaussian cumulative distribution is 0.02 which is also not significant even at 20% level. Both the tests clearly bring out the Gaussian distribution of SFDAMT.

The CCs between SFDAMT and monsoon rainfall over India, north India, central India and south India are computed for the period 1889-1983. These are respectively 0.41, 0.08, 0.36 and 0.41 which except that for north India are significant above 0.1% level. The low CC for north India suggests no relationship.

These relationships are further examined by testing for significance the difference between the means of SFDAMT for deficient/good monsoon years, and the difference in mean rainfall in years of low/high SFDAMT, by Student's *t*-test (2-tailed). Years of low/high SFDAMT are defined by the criteria, normalized anomaly of SFDAMT$\leqslant -1.0/\geqslant 1.0$. It is found that the difference between the two means of SFDAMT is significant above 0.1% for India, at 1% for south India and at 5% for central India. The difference between the two means of rainfall is significant at 0.1% for India, above 0.5% for central India and at 1% for south India. Considering the significance of both the sets of differences, we find that the relationship is best for India. Amongst the three divisions of India, the relationship is best for south India and next best, for central India. For north India, monsoon rainfall is not related to this measure of the activity of the monsoon trough.

Fig. 5 shows the variation of CC between SFDAMT and monsoon rainfall for India and central India for sliding 30-year periods. Similar variation for south India and north India (not shown) is also examined. It is found that the relationships are generally stable and good for India, south India and central India. Stability for south India appears to be somewhat better than that for India. However, for 30-year periods centred on the years between 1925 and 1945, the CCs are not significant. The lowest 30-year CC is observed for the period centred on 1935. Thus, the two variables appear to have got delinked during the period 1921-50. During this period, monsoon rainfall over India was deficient in 1928 and 1941 and good in 1933, 1942 and 1947. In these five years, SFDAMT deviations from the mean (19.4 days) were small except in 1947 when it was rather large, 12.6 days. Hence, during the period 1921-50 the contribution to the covariance by deficient/good monsoon rainfall years for India was small. The reasons for this delinking of the variables during this period are not clear.

7.2. *Seasonal weighted monsoon trough activity index*

The mean value of SWMTAI for the period 1889-1983 is $+0.2$ mb and S.D. is 8.1 mb. It is observed that SWMTAI was mostly above normal during the period 1889-1920 and mostly below normal during 1945-75. A slow decreasing tendency from about 1900 to about 1960, and a slow increasing tendency after 1960 are observed. These tendencies could be part of long period oscillation or long period trend. Correlation coefficient with lag 1 and Swed and Eisenhart's (1943) test show trend in SWMTAI at 1% level. However, it is observed that after 1935 there is no trend. Application of Swed and Eisenhart's test to the series for the period 1936-83 shows neither significant trend nor significant oscillation even at 20% level. The highest normalized anomaly of SWMTAI occurred in 1899, the year of lowest Indian monsoon rainfall, and the lowest occurred in 1961, the year of highest Indian monsoon rainfall, during the period of study. The distribution of SWMTAI was tested for normality by Chi-square and K-S tests and was found to be Gaussian.

The CCs between SWMTAI and monsoon rainfall over India, north India, central India and south India are respectively, —0.32, —0.12, —0.29 and —0.28. The relationships are inverse and significant at 1% level for India, central India and south India. A further examination of the relationship is made to find out if the contrast in the mean of SWMTAI for years of deficient/good monsoon rainfall, and the contrast in the mean monsoon rainfall for low/high values of SWMTAI are significant on the basis of Student's t-test (2-tailed). Years with normalized anomaly of SWMTAI $\leqslant -1.0$ / $\geqslant 1.0$ are considered as years with low/high values of SWMTAI. The contrast between the means of SWMTAI for years of deficient/good monsoon over India, central India and south India are near 5% level significance and that none of the contrasts between the means of monsoon rainfall for these three areas for low/high values of SWMTAI is significant at 5% level. It is clear from these results that these relationships between SWMTAI and monsoon rainfall over India, central India and south India over the whole period are not good. A further examination of these relationships for sliding 30-year periods shows that although there is no significant relationship for 30-year periods prior to 1935, after 1935, significant and stable relationship is observed between SWMTAI and monsoon rainfall over India, central India and south India. During the last 30 years the relationships are highly significant.

It may be noted that the relationships of SFDAMT to monsoon rainfall of India, central India and south India are much better that those of SWMTAI to the monsoon rainfall of India, central India and south India.

8. Seasonal monsoon trough activity with and without low pressure systems

We obtained SFDAMT as a measure of the seasonal activity of the monsoon trough when the season included both the days with low pressure systems (LPS) and days with no LPS over the Indian region. The days with LPS and the days with no LPS during the season varied from one year to the other. We now estimate the mean values of the seasonal measure of the activity of the monsoon trough in two types of situations under certain assumptions. The two types of situation are: (*i*) all days in the monsoon season are LPS days and (*ii*) all days in the monsoon season are without LPS. The assumptions are, the mean proportion of days with active monsoon trough, *i.e.*, days with normalized DMTAI < -1.0, found within LPS days prevails throughout the season, and likewise, the mean proportion of days with active monsoon trough found within non-LPS days prevails throughout the season. For each year of the period 1889-1983, a_i, the number of LPS days in the season, b_i, the number of non-LPS days in the season, c_i and d_i the numbers of days of active monsoon trough within the set of LPS days and the set of non-LPS days respectively, are obtained. Next, $\bar{a}$, $\bar{b}$, $\bar{c}$, and $\bar{d}$, the means of a_i, b_i, c_i and d_i respectively, are computed for the period 1889-1983.

TABLE 4

Correlation coefficients between SFDAMT and SOI tendency/SST tendency/April 500 mb ridge/mean May minimum temperature over southwest Madhya Pradesh and adjoining Gujarat State

Variables	Period	CC	Significant at %
SFDAMT & SOI tendency from DFJ to MAM	1939-1983	—0.09	
SFDAMT & SOI ten- from MAM to JJA	1939-1983	—0.25	10%
SFDAMT & SST tendency from DJF to MAM	1939-1983	—0.20	
SFDAMT & SST tendency from MAM to JJA	1939-1983	—0.41	1%
SFDAMT & April 500 mb ridge	1939-1983	0.45	Above 1%
SFDAMT & May minimum temp. over southwest Madhya Pradesh and adjoining Gujarat State	1939-1975	0.26	10%

The computed values of $\bar{a}$, $\bar{b}$, $\bar{c}$ and $\bar{d}$ are respectively 56.4, 65.6, 14.0 and 5.4 days. With the assumptions as indicated above, x, the mean number of days with active monsoon trough when all days within the season are LPS days is, 122 $\bar{c}/\bar{a}$ =30.3, and y, the mean number of days with active monsoon trough when all days within the season are non-LPS days is 122 $\bar{d}/\bar{b}$=10.0. Thus, in the mean, in a season with LPS on all days, the seasonal monsoon trough activity would be about 3 times of that in a season without LPS on any day. The LPS thus largely add to the activity of the monsoon trough. This brings out the importance of LPS (primarily lows and depressions) during the monsoon season. During the period 1889-1983 the number of non-LPS days varied from 43 to 90. This variation leads to the variation in the activity of the monsoon trough during the season.

9. Relationship of the seasonal frequency of days with active monsoon trough with other variables

Indian monsoon rainfall is significantly related to SOI tendency from DJF to MAM season (Shukla and Paolino 1983; Bhalme *et al.* 1983; Parthasarathy and Pant 1985; Shukla and Mooley 1987), to SST over eastern equatorial Pacific (Angell 1981; Mooley and Parthasarathy 1984; Khandekar and Nerala 1984), to April 500 mb ridge over India (Banerjee *et al.* 1978; Mooley *et al.* 1986) and to areal mean May minimum temperature over southwest Madhya Pradesh and adjoining portion of Gujarat State (Mooley and Paolino 1988). Since the monsoon trough along with the lows which move generally westnorthwestwards across the area of the trough is the prominent synoptic system which contributes to the rainfall over India during the monsoon season, it is proposed to examine the relationship of the seasonal measure of the trough activity, *viz.*, SFDAMT, to the SOI tendency from DJF to MAM as well as MAM to JJA, eastern equatorial Pacific (0-10° S, 80°W-180° W) SST tendency from DJF to MAM as well as from MAM to JJA, April 500 mb ridge in the wind field over India and mean May minimum temperature over southwest Madhya Pradesh and adjoining Gujarat State. CCs between SFDAMT and these variables are computed. These CCs are given in Table 4. The relationships with the ridge and SST tendency from MAM to JJA are highly significant (1% level). The relationship with ridge is direct but that with SST tendency is inverse. These relationships suggest a basis for the linkage been ween Indian monsoon rainfall and the ridge/ eastern equatorial Pacific SST tendency. The relationships with SOI tendency from MAM to JJA and the May minimum temperature over southwest Madhya Pradesh and adjoining Gujarat State show significance at 10% level only, suggesting weak relationships. The ridge SFDAMT relationship has some predictive value.

10. Conclusions

The daily, monthly and seasonal measures of the activity of the Indian monsoon trough are derived from the pressure data of 4 representative stations located within the trough. The following conclusions can be drawn in respect of these measures.

(*i*) *Daily measures*

The daily monsoon trough activity index, DMTAI is Gaussian-distributed. The frequency of normalized DMTAI < -1.0 in years of good Indian monsoon rainfall is significantly (above 0.1% level) higher than that in years of deficient Indian monsoon rainfall. For days of September, DMTAI in years of deficient Indian monsoon is appreciably higher (*i. e.*, monsoon trough appreciably weaker) than that in years of good Indian monsoon.

(*ii*) *Monthly measures*

Both the monthly measures, *viz.*, monthly frequency of days of active monsoon trough (MFDAMT), and monthly weighted monsoon trough activity index (MWMTAI), which are obtained from DMTAI, show significant relationships with monthly rainfall for the monsoon months except June. The relationship for September is highly significant (above 0.1%) and is stable.

(*iii*) *Seasonal measures*

The seasonal frequency of days of active monsoon trough (SFDAMT) is highly significantly (0.1%) related to Indian monsoon rainfall and this relationship is direct and is stable. Low pressure systems which form over north and central Bay, and over central and north India, and move in a westerly direction add largely to the activity of the Indian monsoon trough.

While the relationship between the seasonal weighted monsoon trough activity index, SWMTAI, and Indian monsoon rainfall is not good over the whole period, it is found to be good and stable over the last 40 years.

It is found that SFDAMT is related directly and significantly (at 1%) to the location of April 500 mb ridge over India and inversely and significantly (at 1%) to eastern equatorial Pacific SST tendency from MAM to JJA season. These relationships suggest a basis for linkage between Indian monsoon rainfall and the ridge/eastern equatorial Pacific SST tendency.

Acknowledgements

We are grateful to Mr. D. A. Paolino for computational assistance, to the National Oceanic Atmospheric Administration for making available to us the *Indian Daily Weather Report* and to Dr. J. K. Angell for the SST data for eastern equatorial Pacific Ocean. We thank Mrs. Marlene Schlichtig for typing the manuscript.

The research was supported under the auspices of the Science and Technology Initiative (STI) to foster United States-India collaboration on monsoon research through NSF grant ATM-8414660, and NASA's Global Weather Program (NASA-NAGW-558).

References

Angell, J.K., 1981, *Mon. Weath. Rev.*, **109**, 230-243.

Banerjee, A.K., Sen, P.N. and Raman, C..R.V., 1978, *Indian J. Met. Hydrol. Geophys.*, **29**, pp. 425-431.

Bhalme, H.N. and Parasnis, S.S., 1975, *Indian J. Met. Hydrol. Geophys.*, **26**, pp. 77-80.

Bhalme, H.N. and Mooley, D.A., 1980, *Mon. Weath. Rev.*, **108**, 1197-1211.

Bhalme, H.N., Mooley, D.A. and Jadhav, S.K, 1983, *Mon. Weath. Rev.*, **111**, 86-94.

Khandekar, M.K. and Nerala, V.R., 1984, *Geophys. Res. Letters*, **11**, 1137-1140.

Koteswaram, P., 1950, *Indian J. Met. Geophys.*, **1**, pp. 162-164.

Krishnamurty, T.N. and Bhalme, H.N., 1976, *J. atmos. Sci.*, **33**, 1937-1954.

Lilliefors, H.W., 1967, *J. Amer. Stat. Association*, **62**, 399-402.

Mann, H.B. and Whitney, D.R., 1947, *The Annals of Math. Stat.*, **18**, 50-60.

Mooley, D.A., 1976, *Proc. Indian Nat. Sci. Acad.*, **42**, Pt. A, 1, 34-43.

Mooley, D.A., Parthasarathy, B., Sontakke, N.A. and Munot, A.A., 1981, *J. Climatology*, **1**, 167-186.

Mooley, D.A. and Parthasarathy, B., 1983, Proc. Symp. on "*Variations of the global water budget*', (Eds.) A.S. Perrot, M. Beran and R. Ratcliffe, D. Reidel Publishing Co., 239-252.

Mooley, D.A. and Parthasarathy, B., 1984, *Atmosphere-Ocean*, **22**, (1), 23-35.

Mooley, D.A., Parthasarahy, B. and Pant, G.B., 1986, *J. Climate appl. Met.*, **25**, 633-640.

Mooley, D.A. and Shukla, J., 1989, Main features of the westward-moving low pressure systems which form over the Indian region during the summer monsoon season and their relation to monsoon rainfall, *Mausam*, **40**, 2, pp. 137-152.

Mooley, D.A. and Paolino, D.A., 1988, *Mon. Weath. Rev.*, **116**, 256-264.

Paul, D.K. and Sikka, D.R., 1976, Extended range forecasting—Categorization of weather charts. Part I : Monsoon Sea Level Pressure Field. Project Report No. ERF/1 of Indian Institute of Tropical Meteorology, Pune, 34 pp.

Parthasarathy, B. and Pant, G.B., 1985, *J. Climatology*, **5**, 369-378.

Raghavan, K., 1973, *Mon. Weath. Rev.*, **101**, 33-43.

Ramamurty, K., 1969, Forecasting Manual, Part IV, India Met. Dep., 57 pp.

Ramaswamy, C., 1958, *Geophysica*, **6**, 455-477.

Ramaswamy, C., 1962, *Tellus*, **14**, 337-349.

Shukla, J. and Paolino, D.A., 1983, *Mon. Weath. Rev.*, **111**, 1830-1837.

Shukla, J. and Mooley, D.A., 1987, *Mon. Weath. Rev.*, **115**, 695-703.

Swed, F.S. and Eisenhart, C., 1943, *The Annals of Math. Stat*, **14**, 66-87.