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Vagaries of Indian monsoon rainfall and its relationships with regional/global cirulations

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सार – मानसून वर्षा के लक्षण को समझने के लिए प्रयास किए गए हैं जिसके लिए 1871-1988 की अवधि के उत्तम आंकड़ा समुच्चय उपलब्ध हुए हैं। 1894 और 1961 के वर्षों में वर्षा शृंखला में दो असांतत्य (अचानक अथवा तुरन्त परिवर्तन अवधि) पाए गए हैं और देश की वर्षा शृंखला चार विभिन्न कालावधियों से गुजरी है।

परिसंचरण प्राचलों के मुख्यत: तीन वर्ग हैं—(1) भारतीय क्षेत्रों की स्थितियां, (2) हिन्द महासागर क्षेत्र पर पार-विषुवतीय प्रवाह और (3) 1951-80 की अवधि के दक्षिणी दोलन जो कि सारे भारत के मानसून वर्षा (अखिल भारतीय मानसून) से अच्छी तरह से सबन्धित हैं, उसका परीक्षण किया गया और परिणाम प्रस्तुत किए गए हैं। मानसून वर्षा की प्रागुक्ति के लिए इन संबद्धों का प्रयोग किया जा सकता है।

ABSTRACT. Attempts have been made to understand the behaviour of the monsoon rains for which excellent data sets are available covering the period of 1871-1988. There are two discontinuities (sudden or abrupt change periods) noticed in the rainfall series in the years 1894 and 1961 and the country's rainfall series has passed through four different epochs.

Three important families of circulation parameters, mainly (*i*) conditions over Indian region, (*ii*) cross equatorial flow over Indian Ocean region and (*iii*) southern oscillation, which are well associated with all India monsoon rainfall have been examined for the period 1951-80 and results are presented. These associations can be utilized for the prediction of the monsoon rains.

1. Introduction

The seasonal reversals of pressure, temperature and winds across India constitute the monsoons. Monsoons have been the focus of the atmospheric studies carried out in this country for over a century. The large volume of global meteorological data, now available over the tropics, have indicated the linkages of the recent monsoon failures with some of the features of the atmospheric circulation. This study presents certain important features of the all India summer monsoon rainfall series during last one century (1871-1988) and its relationships with regional/global circulation during the period 1951-80.

2. Data details

2.1. *All India summer monsoon rainfall*

The all India summer monsoon rainfall series, prepared by Mooley & Parthasarathy (1984) and Parthasarathy *et al.* (1987) from the year 1871 has been updated to the year 1988. This series has been prepared by area-weighting 306 well-distributed raingauges (one in each district) over the plain regions of the country. The mean ($\bar{R}$), standard deviation (S) and coefficient of variation (CV) of the rainfall for the period 1871-1988 are 849 mm, 85 mm and 10 per cent respectively. The monsoon rainfall has been classified as deficient when the rainfall amount of a year is less than $\bar{R}-S$ and excessive if it is more than $\bar{R}+S$ (Parthasarathy *et al.* 1988). These extreme years are found to be significant in their impact on the total foodgrain production of the country as well as their association with the pre-monsoon regional circulation anomalies. As the rainfall data used in this analysis of relationship with the various factors is for 1951 to 1980, the rainfall mean, standard deviation and CV are 850 mm, 90 mm and 10.5% respectively for the period.

2.2. *Regional circulation parameters*

The summer monsoon of India results from the land-ocean contrast configuration. The region of high temperature and low atmospheric pressure, which gradually builds up over the Indian sub-continent during the pre-monsoon months, is the controlling factor for the following monsoon (for details *see* Parthasarathy *et al.* 1990). Therefore, we considered the area of intense heat source region over India during the summer season which may be a controlling factor for the following monsoon. The averages of pressure and temperature of six stations over west central India (WCI) with respect to all India monsoon rainfall have been examined. The six stations chosen are Jodhpur, Ahmedabad, Bombay, Indore, Sagar and Akola. The arithmetic average of surface air temperaure at these six stations has been suggested by Parthasarathy *et al.* (1990) as a significant thermal factor influencing the monsoon. The seasonal data for the period 1951-80 of WCI temperature and pressure have been examined in detail with respect to all India monsoon rainfall,

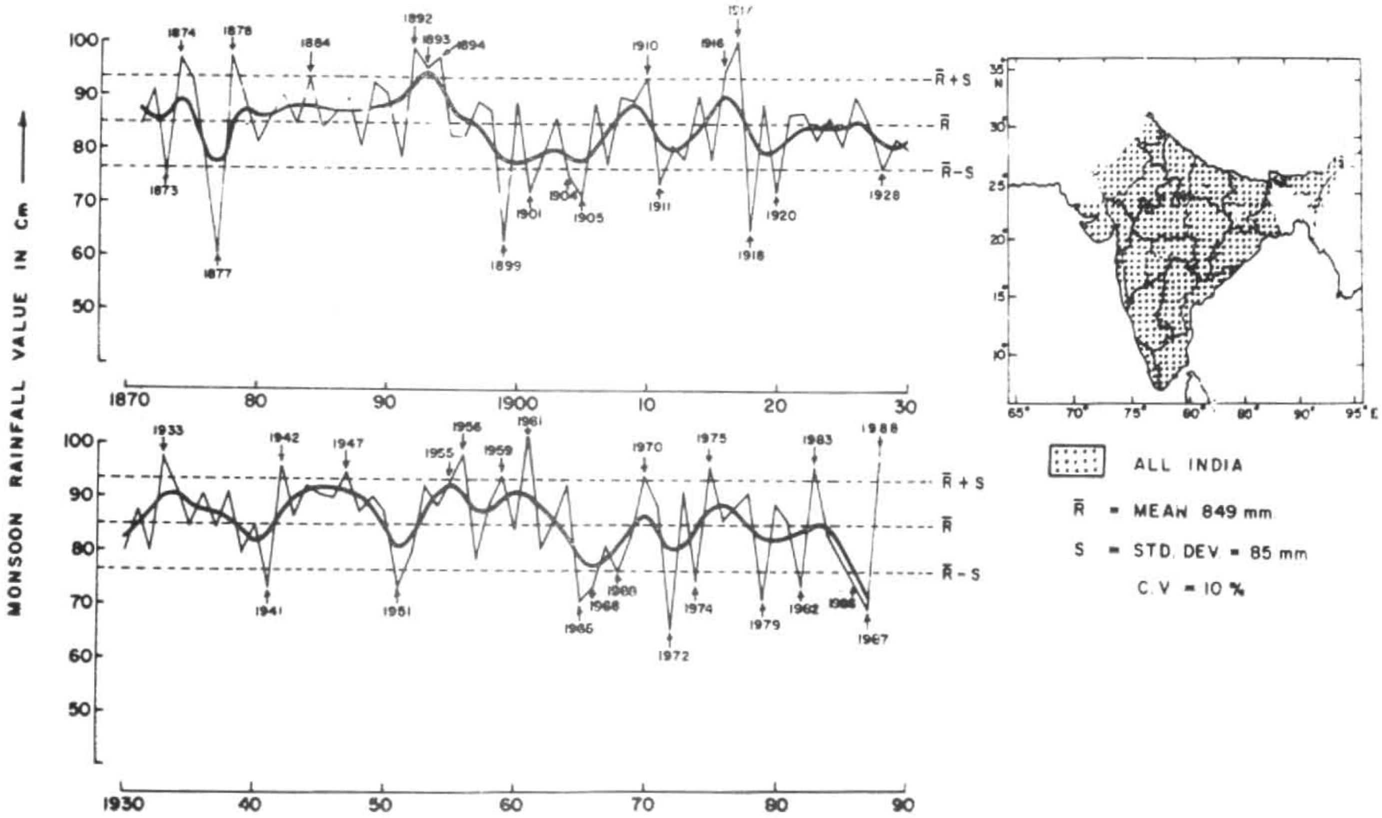


Fig. 1. All India summer monsoon rainfall for the period 1871-1988

TABLE 1

All India summer monsoon (June to September) rainfall (in mm) values (excluding hilly regions, *i.e.*, only 29 sub-divisions considered). The area weightage is given to each of the 306 raingauge stations

Decade	Year 0	1	2	3	4	5	6	7	8	9
1870	—	846	910	754	971	928	776	604	974	894
1880	817	860	901	849	929	842	870	897	810	927
1890	903	789	990	953	969	825	824	890	880	628
1900	885	719	791	858	749	715	883	776	895	889
1910	935	733	804	782	899	780	950	1003	648	885
1920	717	863	867	819	862	803	901	849	766	819
1930	800	877	801	973	913	843	904	843	908	789
1940	850	729	958	866	921	907	901	942	872	902
1950	875	737	792	920	885	930	980	784	886	938
1960	839	1017	807	855	920	707	735	859	754	829
1970	939	886	653	912	747	960	855	881	908	708
1980	883	852	735	955	835	*787*	*747*	*688*	*991*	*866*

Note—Values in italics are approximate calculated on the basis of less number of raingauge stations

We have considered April 500 mb ridge at 75° E over India, which is considered by India Met. Dep., as one of the parameters in the monsoon prediction equation.

2.3. *Global circulation parameters*

Several studies have been shown that meridional pressure gradient or cross-equatorial flow over the Indian Ocean and ENSO are important circulation features for prediction of Indian monsoon rainfall. The m.s.l. pressure over the following areas represents the above two parameters :

(*i*) *Indian Ocean region* — The difference of pressure between sub-tropical high pressure area (Nouvelle) and the equatorial region (Agalega);

(*ii*) *Pacific Ocean region (SO)* — The pressure difference between two centres of action of southern oscillation (Tahiti—Darwin), which are considered in this study for the period 1951-1980.

3. Analysis of data

To understand the temporal characteristics of the relationship between the circulation parameters and the all India monsoon rainfall, the correlation coefficients (CC) of seasonal parameters up to 3 lags on either side of the monsoon season have been calculated. Thus, the all India monsoon (JJAS) rainfall series for the period, 1951-80, has been correlated with seven different seasonal circulation parameters series as : (*i*) the previous autumn season (SON), three seasons prior to monsoon (lag −3); (*ii*) the previous winter season (DJF), two seasons prior to monsoon (lag −2); (*iii*) the spring season (MAM), one season earlier to monsoon (lag −1); (*iv*) summer monsoon season (JJA), concurrent with the Indian monsoon season (lag 0); (*v*) the autumn season (SON), one season after monsoon (lag +1); (*vi*) the succeeding winter season (DJF), two seasons after monsoon (lag +2) and (*vii*) the succeeding spring season (MAM), three seasons after monsoon (lag +3). Besides hese, the seasonal tendency of the parameters between the previous spring and winter (MAM *minus* DJF) has also been taken in view of its importance as demonstrated by Shukla & Paolino (1983), Parthasarathy & Pant (1985) while relating southern oscillation to the Indian rainfall.

The persistence as indicated by the serial correlations of the data series involved is found to be insignificant. We have also calculated composite values of the circulation parameter anomalies for lag −3 to lag +3 and MAM—DJF in deficient/excess rainfall years of all India series for the period 1951-80. During this 30-year period, there were seven deficient (R_i value less than $\bar{R}-S$) years, namely, 1951, 1965, 1966, 1968, 1972, 1974 & 1979 and six excess (R_i value more than $\bar{R}+S$) years 1955, 1956, 1959, 1961, 1970 & 1975. The above anomalies may also be useful for better understanding of the behaviour of extremes.

4. Vagaries of the all India monsoon rainfall

A long homogeneous rainfall data series of the Indian summer monsoon, having areal and temporal representativeness is a useful tool for scientists engaged in general circulation or monsoon studies. Large interannual changes in the release of latent heat over India could affect subsequent circulation patterns over other parts of the globe. Therefore, these rainfall values are tabulated (Table 1) for the period 1871-1988. Fig. 1 presents a plot of these series along with low-pass filter curve which suppresses high frequency waves of length 10 years or less. It is observed from Fig. 1 that there are many negative departures during the periods 1899-1920 and 1962-87. It is also evident from the figure that the country has passed through four major climatic epochs, namely, (*i*) 21 years (1878-1898) of increasing tendency (above normal rainfall); (*ii*) 34 years (1898-1932) of decreasing tendency (below normal rainfall); (*iii*) 32 years (1933-1964) of increasing tendency (above normal) and (*iv*) present 23 years (1965-1987) of decreasing tendency; wherein a large number of deficient years have occurred.

The highest rainfall recorded was 1017 mm in the year 1961 and lowest 604 mm in 1877. The range of all India monsoon rainfall during a period of 118 years is 413 mm which is 49 per cent of the average. It is seen from Fig. 1 that there are 52 negative and 66 positive departures from the average ($\bar{R}$) for the period 1871-1988. There are 21 deficient (less than $\bar{R}-S$) and 18 excess (more than $\bar{R}+S$) rainfall years. There are three cases of consecutive deficient years (1904-05, 1965-66 & 1986-87) and one case of three consecutive excess years, 1892-94. It is observed that there are six cases of deficient rainfall year followed by an excess year : 1873-74; 1877-78; 1941-42; 1974-75; 1982-83 and 1987-88 and there are two cases of an excess year followed by a deficient year : 1910-11 and 1917-18.

5. Relationship between all India rainfall and circulation parameters

The atmospheric circulation over the Asian region undergoes a complete reversal cyclically between summer and winter. In summer the vast Asian land mass gets hotter than the surrounding sea areas to the east and to the south. A deep low pressure develops over India & Pakistan regions and high pressure cells builds upon the North Pacific and the south Indian Oceans. These quasi-permanent pressure systems control the low level circulations. As a result, there is a predominant influx of maritime air from the south and southeast into India and SE Asia. This is the summer monsoon which brings moisture, clouding and widespread rainfall into these regions. Therefore, the performance of seasonal Indian monsoon rainfall seems to depend on (a) conditions over Indian region, (b) meridional pressure gradient and cross-equatorial flow over the Indian Ocean and (c) the southern oscillation. The present study examines these aspects, in detail, to show how the circulation precusors can be used for long-range forecast.

We have selected surface air temperature or m.s.l. pressure of these regions to represent the above circulation features and correlated them with all India monsoon rainfall for the period 1951-80 for lag −3 to lag +3 and pre-monsoon tendency parameter, MAM—DJF. The details of these parameters and their CCs with rainfall are shown in Table 2.

(a) *Conditions over Indian region*

The following parameters over Indian region show good association with all India rainfall for the period 1951-80 under consideration.

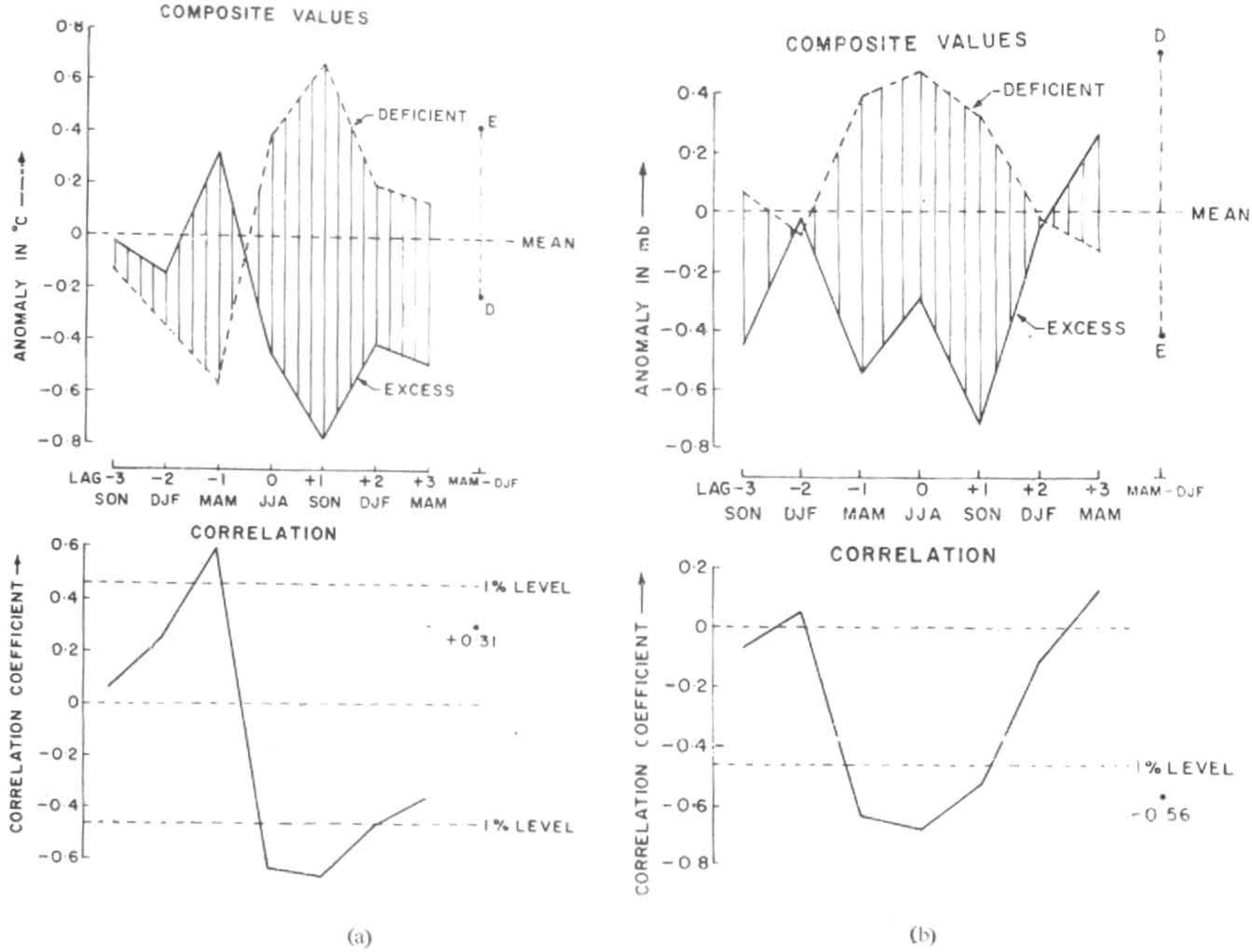


Fig. 2. Relationships between all India summer monsoon rainfall and circulation parameters over Indian region for the three lags on either side of the monsoon season and MAM—DJF for (a) WCI temperature and (b) WCI m.s.l. pressure

TABLE 2

Correlation coefficient between all India summer monsoon rainfall and different circulation parameters for seasons : 1951-80

Parameters	lag −3 SON	lag −2 DJF	lag −1 MAM	lag 0 JJA	lag +1 SON	lag +2 DJF	lag +3 MAM	Pre-monsoon tendency parameter, MAM—DJF
(1) WCI air Temp.	.06	.26	.60†	−.63†	−.66†	−.47**	−.36*	.31
(2) WCI m.s.l. pressure	−.07	.05	−.63†	−.68†	−.53**	−.11	.12	−.56**
(3) Agalega m.s.l. pressure	.24	.29	−.11	−.27	−.11	−.28	.16	−.45*
(4) Nouvelle *minus* Agalega m.s.l. pressure	−.14	−.31	.17	.01	.24	.26	.22	.45*
(5) Darwin m.s.l. pressure	−.01	.39*	−.44*	−.43*	−.53**	−.51**	−.20	−.63†
(6) Tahiti *minus* Darwin m.s.l. pressure	−.14	−.22	.24	.39*	.56**	.53**	.34	.42*

Note—Significant CC * at 5%, ** at 1% and † at 0.1 % levels (*i*) *April 500 mb ridge at 75° E*

Recent studies on prediction of Indian monsoon rainfall, say by Shukla & Mooley (1987) shows that a very important parameter is the latitude position of the April 500 mb ridge axis along 75° E. It has been used by India Met. Dept. for over a decade for forecasting Indian monsoon rainfall. The 500 mb ridge in April is a good indicator of the subsequent planetary-scale circulation of the large-scale vertical motion field over the Indian region. Several recent studies have shown that if the latitudinal position of the 500 mb ridge during April is displaced to the south/north of its normal position, subsequent monsoon rainfall over India tends to be below/above normal. The mean position of ridge for the period 1951-80 is 15.9° N and standard deviation of 1.9°.

The CC between all India rainfall and April 500 mb ridge for the period 1951-80 is +0.70 and composite mean values of position for deficient and excess rainfall years respectively are 12.7° N & 16.4° N. The large difference of 3.7° differentiates the deficient and excess rainfall years.

(*ii*) *WCI temperature*

It is generally known that the development of summer monsoon over Indian region is positively linked to the hottest areas over the Asian/Indian region.

The CCs between all India rainfall and the spatial average of surface air temperature at six stations of west central India, WCI, (Jodhpur, Ahmedabad, Bombay, Indore, Sagar and Akola) have been calculated for the period 1951-80 for lag —3 to lag +3 and MAM—DJF as explained in Sec. 3, and these are shown in Table 2 and in Fig. 2(a). Fig. 2(a) also shows the composite values of temperature for deficient/excess all India rainfall years. The CCs are positive for seasons prior to monsoon (lag —3 to lag —1) and negative for seasons concurrent with and succeeding monsoon (lag 0 to lag +3) and CC is positive for the MAM—DJF temperature tendency. Such change in the CC values as the season advances suggests that the large-scale circulation features of the monsoon system may be undergoing a low frequency transition during the years of markedly high or low monsoon rainfall. During the pre-monsoon season, MAM, (lag —1), the CC is highly positive (0.60) and significant at 1% level suggesting that good monsoon over the country is preceded by strong seasonal heating over WCI region. The composite values of corresponding seasonal temperatures also supports the above inference.

(*iii*) *WCI m.s.l. pressure*

The variations of temperature are, in general, governed by pressure and winds. The m.s.l. pressure over WCI region has been analysed similarly and the results are reported in Fig. 2(b).

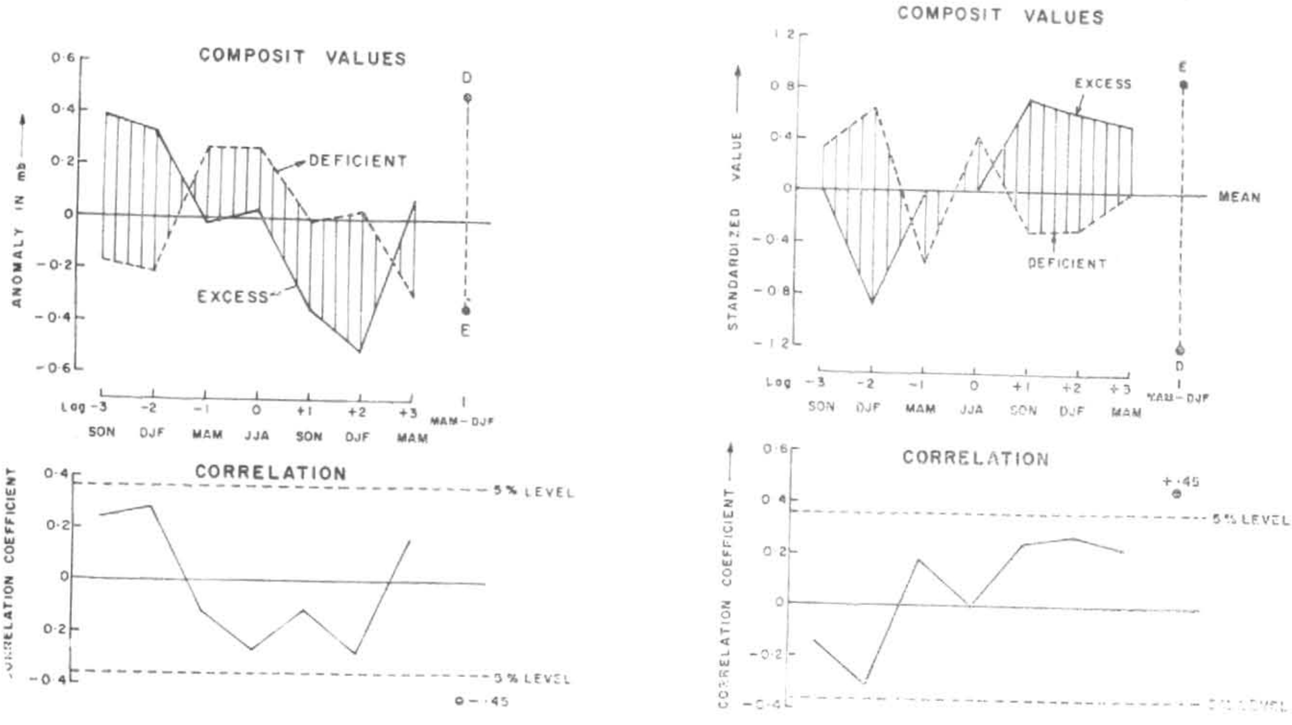
It is observed from the Fig. 2(b) and Table 2 that the CC values show significant association between WCI pressure and all India rainfall after lag —2 to lag +3 indicating strong and systematic signal as the season advances. WCI pressure during spring season has a high negative CC (—.63) with rainfall indicating predictive value. The seasonal tendency (MAM—DJF) of pressure also shows a significant negative CC (—0.56) at 1% level with monsoon rainfall. The composite values of MAM pressure during deficient/excess rainfall years also reflect the high/low anomalies.

(b) *Cross-equatorial flow over Indian Ocean region*

The cross-equatorial flow over the Indian Ocean originating as the southeast trade wind in the southern hemisphere is forming the southwest monsoon flow over Indian sub-continent. The fluctuations of the cross-equatorial flow are reflected in the Indian monsoon rainfall records. It is also pointed out that an abnormal weakening of the southeast trade winds at Mauritus Islands is recognizable in March/April months, well before onset of Indian monsoon, which may provide useful information for foreshadowing the monsoon rainfall. The southern hemispheric high pressure belt shifts north/south during the course of the year. During the months April to June it is located close to Mascarene Islands, known as Mascarene high. The strength of the southeast trades can be determined by the difference of pressures between Mascarene high and equatorial regions. Here we have considered the station : Nouvelle (38° S, 78° E), representing high pressure region, and Agalega (10° S, 57° E) as low pressure region over the Indian Ocean region. We examined the correlation coefficient between all India rainfall and m.s.l. seasonal pressure of (*i*) Agalega representing the equatorial pressure and (*ii*) Nouvelle *minus* Agalega indicating the strength of the southeast trades. The results of correlation analysis and composite values for extreme monsoon rainfall years, from lag —3 to lag +3 and MAM—DJF, are shown in Figs. 3 (a & b). The systematic variation of CCs as the season's advance indicates that the relationship is good. The tendency parameters (MAM—DJF) are significant at 5% level or more, indicating their usefulness for forecasting purposes.

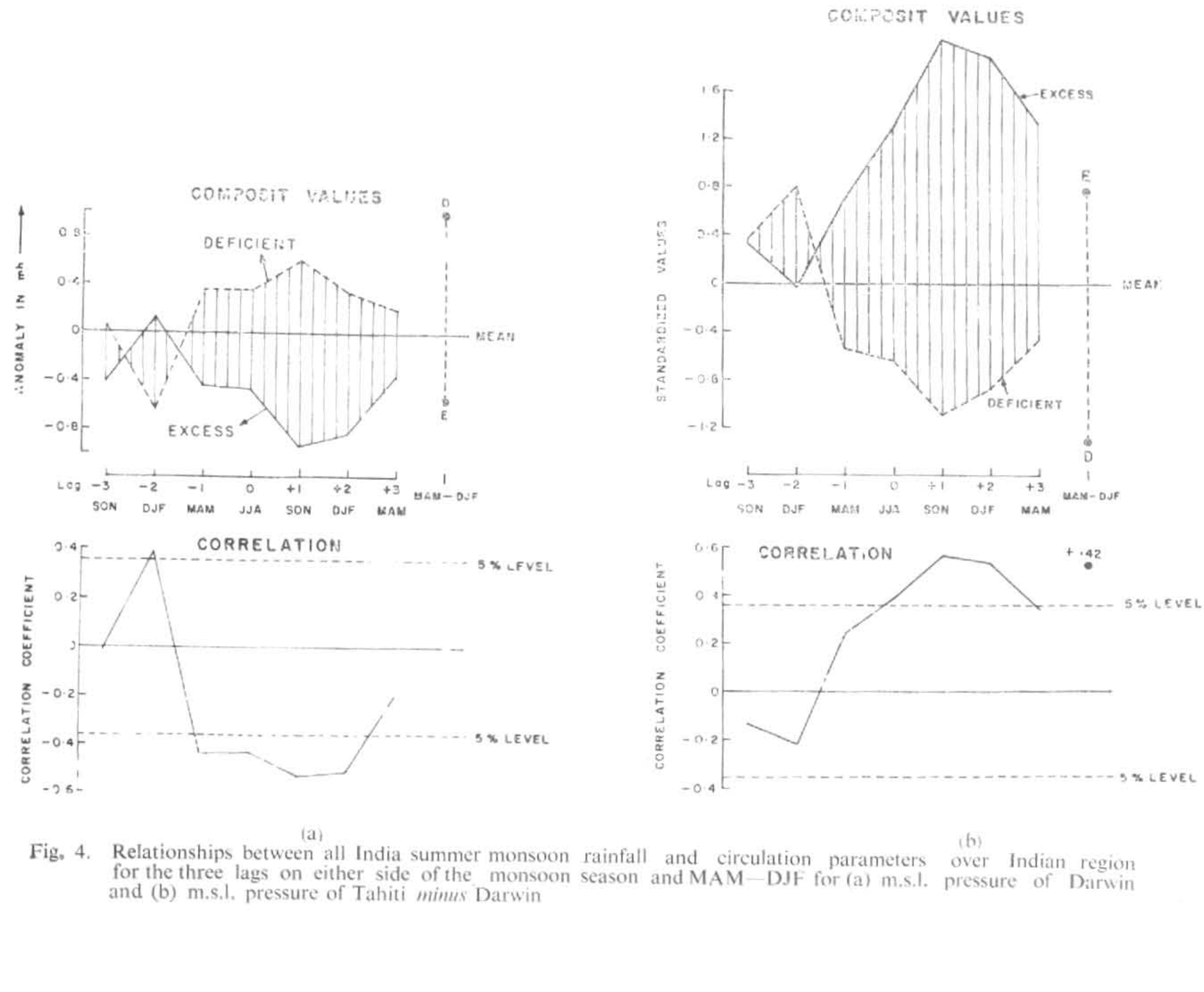
(c) *Southern oscillation*

The southern oscillation (SO) or Walker circulation is an important mode of the tropical atmosphere generally characterised by the exchange of air between the eastern (predominantly land) and western (predominantly ocean) hemisphere. The pressure change occurs in a see-saw fashion, one end of the sea saw being in the Australian-Indonesian region and the other in the southeast Pacific Ocean. A parameter which measures the sea-saw is the difference of pressure between the two core regions represented by the stations : Tahiti (18° S, 150°W) and Darwin (12° S, 131° E), and is used as an index of the SO. Many studies are available bringing out the association between SO and Indian rainfall. Here we examined the CCs between all India rainfall and (*i*) m.s.l. pressure of Darwin representing the eastern core of SO, (*ii*) Tahiti *minus* Darwin indicating the strength of SO. Figs. 4 (a & b) show the details of CC and composite values for extreme monsoon rainfall years for lag —3 to lag +3 seasons and MAM—DJF. It is clearly seen from the Figs. 4 (a & b) that there is a good association between the two parameters. The tendency parameters MAM—DJF of Darwin shows a highly negative correlation (—.63) significant at 0.1% level, indicating a good potential for prediction.



(a) (b)

Fig. 3. Relationships between all India summer monsoon rainfall and circulation parameters over Indian region for the three lags on either side of the monsoon season and MAM—DJF for (a) m.s.l. pressure of Agalega and (b) m.s.l. pressure of Nouvelle *minus* Agalega



(a) (b)

Fig. 4. Relationships between all India summer monsoon rainfall and circulation parameters over Indian region for the three lags on either side of the monsoon season and MAM—DJF for (a) m.s.l. pressure of Darwin and (b) m.s.l. pressure of Tahiti *minus* Darwin

TABLE 3

Inter-correlations among the parameter for the data period, 1951-80

Parameters	All India monsoon rainfall	WCI air tempera-ture (MAM)	WCI m.s.l. pressure (MAM—DJF)	Agalega m.s.l. pressure (MAM—DJF)	Nou—Aga m.s.l. pressure (MAM—DJF)	Darwin m.s.l. pressure (MAM—DJF)	Tah—Dar m.s.l. pressure (MAM—DJF)	500 mb ridge April
(1) All India monsoon rainfall	1.00							
(2) WCI air temperature (MAM)	.60†	1.00						
(3) WCI m.s.l. pressure (MAM—DJF)	—.56**	—.34	1.00					
(4) Agalega m.s.l. pressure (MAM—DJF)	—.45*	—.22	.51**	1.00				
(5) Nouvelle *minus* Agalega m.s.l. pressure (MAM—DJF)	.45*	.25	—.19	—.42*	1.00			
(6) Darwin m.s.l. pressure (MAM—DJF)	—.63†	—.50**	.70†	.55**	—.16	1.00		
(7) Tahiti *minus* Darwin m.s.l. pressure (MAM—DJF)	.42*	.40*	—.62†	—.56**	.23	—.83†	1.00	
(8) April 500 mb ridge	.70†	.49**	—.28	—.28	.36*	—.47**	—47**	1.00

Significant CC* at 5%, **at 1% and †at 0.1% levels.

Table 3 shows the inter-correlations for the period 1951-80 between all the parameters which are highly related with the all India monsoon rainfall.

6. Summary

The detailed examimation of the all India summer monsoon rainfall series for the period 1871-1988 and its relationships with circulation features for the years 1951-80 has brought out the following points :

(a) *Rainfall*

(*i*) There are 52 negative and 66 positive rainfall departures in the series 1871 to 1988, with 21 years of deficient ($\bar{R}$—S) and 18 years of excess ($\bar{R}$+S) rainfall.

(*ii*) There are two discontinuities (sudden or abrupt change) noticed in the years 1894 and 1961 apart from four climatic epochs in the rainfall series of 1871-1988.

(*iii*) The current 25 years period (1962-87) experienced many deficient rainfall years.

(*iv*) There are six cases of deficient monsoon rainfall years followed by excess rainfall : 1873-74; 1877-78; 1941-42; 1974-75; 1982-83 and 1987-88.

(b) *Circulation*

(*v*) The pre-monsoon parameters over Indian region, WCI (west central India) pressure & temperature and April 500 mb ridge position are highly correlated with all India rainfall, the CC varies between 0.6 and 0.7.

(*vi*) For the strength of the cross-equatorial flow indicated by the pressure of Nouvelle *minus* Agalega, the tendency parameter, MAM—DJF has a CC of 0.45 with all India rainfall.

(*vii*) The m.s.l. pressure tendency parameter (MAM—DJF) of Darwin (representing southern oscillation) is negatively related to the all India rainfall with CC of — 0.63.

The above results show good factors while framing the regression formulae for monsoon rainfall prediction.

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