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Homogeneous Indian Monsoon rainfall: Variability and prediction

B PARTHASARATHY, K RUPA KUMAR and A A MUNOT

Climatology & Hydrometeorology Division, Indian Institute of Tropical Meteorology, Pune 411 008, India

Abstract. The Indian summer monsoon rainfall is known to have considerable spatial variability, which imposes some limitations on the all-India mean widely used at present. To prepare a spatially coherent monsoon rainfall series for the largest possible area, fourteen subdivisions covering the northwestern and central parts of India (about 55% of the total area of the country), having similar rainfall characteristics and associations with regional/global circulation parameters are merged and their area-weighted means computed, to form monthly and seasonal Homogeneous Indian Monsoon (HIM) rainfall series for the period 1871–1990. This paper includes a listing of monthly and seasonal rainfall of HIM region. HIM rainfall series has been statistically analysed to understand its characteristics, variability and teleconnections for long-range prediction.

HIM rainfall series is found to be homogeneous, Gaussian distributed and free from persistence. The mean ($\bar{R}$) rainfall is 757 mm (87% of annual) and standard deviation (S) 119 mm, with a Coefficient of Variation (CV) of 16%. There were 21 dry ($R_i \leqslant \bar{R} - S$) and 19 wet ($R_i \geqslant \bar{R} + S$) years during 1871–1990. There were clusters of frequent negative departures during 1899–1920 and 1965–1987 and positive departures during 1942–1961. The recent three decades show very high rainfall variability with 10 dry and 6 wet years. The decadal averages were alternatively positive and negative for three consecutive decades, viz., 1871–1900 (positive); 1901–1930 (negative); 1931–1960 (positive) and 1961–1990 (negative) respectively. Significant QBO and autocorrelation at 14th lag have been found in HIM rainfall series.

To delineate the changes in the climatic regime of the Indian summer monsoon, sliding correlation coefficients (CCs) between HIM rainfall series and (i) Bombay msl pressure, (ii) Darwin msl pressure and (iii) Northern Hemisphere surface air temperature over the period 1871–1990 have been examined. The 31-year sliding CCs showed the systematic turning points of positive and negative CCs around the years, 1900 and 1940. In the light of other corroborative evidences, these turning points seem to delineate 'meridional' monsoon regime during 1871–1900 and 1940–1990 and 'zonal' monsoon regime during 1901–1940. The monsoon signal is particularly dominant in many regional and global circulation parameters, during 1951–1990.

Using the teleconnections of HIM series with 12 regional/global circulation parameters during the recent 36-year period 1951–86 regression models have been developed for long-range prediction. In the regression equations 3 to 4 parameters were entered, explaining upto 80% of the variance, depending upon the data period. The parameters that prominently enter the multiple regression equations are (i) Bombay msl pressure, (ii) April 500 mb Ridge at 75°E, (iii) NH temperature, (iv) Nouvelle minus Agalega msl pressure and (v) South American msl pressure. Eleven circulation parameters for the period 1951–80 were subjected to Principal Component Analysis (PCA) and the PC's were used in the regression model to estimate HIM rainfall. The multiple regression with three PCs explain 72% of variance in HIM rainfall.

Keywords. Indian summer monsoon; monsoon rainfall; climate change; long range prediction; homogeneous monsoon area; teleconnections.

1. Introduction

The summer and winter monsoons of south Asia constitute the most spectacular manifestation of regional anomalies in the general circulation of the atmosphere resulting from land-sea contrasts and geographical features. The monsoons of southern Asia which includes India, Pakistan and Bangladesh are described as 'ideal monsoons'. The monsoon system of the Indian sub-continent differs considerably from that of the rest of Asia. The centres of action, air mass involved and the mechanism of precipitation of Indian monsoon are altogether different from other monsoon systems. The main reason for this very strong development of monsoons is the vast size of the Indian sub-continent and adjacent seas: Indian Ocean to south, Pacific Ocean to the east and a vast landmass extending from the Pacific to Atlantic Ocean. The very high and extensive mountain system of the Himalayas to the extreme north of the sub-continent is another favourable factor.

India, with a population of 15 percent of the world (850 million) is located in the central portion of south Asia and the summer monsoon (also known as southwest monsoon) contributes about 70% of the annual rainfall over most parts of the country. The country's agriculture, power generation and industrial production substantially depend on these rains. Despite much progress in industrialization since independence, the national economy is still heavily dependent on agriculture and food production for feeding the large and growing population which has doubled since independence.

Many recent studies in understanding or prediction of the seasonal rainfall behaviour over India are mainly focussed on the country as one unit i.e., All-India. Though All-India is too large an area for practical purposes, it provides an overall view of the rainfall fluctuations and abnormalities which are helpful to the planners and scientists studying general circulation and changes therein. For a country as vast as India, with inherent spatial variability of monsoon rainfall, there would almost always be some areas of deficient rains even in the best monsoon years (or some areas of flood even in worst monsoons). However, there are certain regional differences in the monsoon rainfall variability which are of important consequence. For instance, the rainfall of meteorological sub-divisions in the northeastern parts of the country is poorly or negatively correlated with the rest of the country (Parthasarathy 1984b). Walker (1924), Shukla (1987a) and Gregory (1989) suggested that rainfall over several sub-divisions of India should be grouped together to define areal averages for large homogeneous regions. They further showed that the consideration of local distribution characteristics of seasonal rainfall in dividing the country into homogeneous regions yielded better formulae for forecasting than when India was treated as one unit.

An effort has been made here to analyze the sub-divisional monsoon rainfall series of India and to group them into homogeneous macro-regional units with similar rainfall characteristics and association with global/regional circulation parameters, in order to obtain the better forecast formulae. An attempt has also been made here to delineate a Homogeneous Indian Monsoon (HIM) region of India based on the above criteria and to study its monsoon rainfall characteristics during 1871–1990.

2. Past studies

The need to predict the summer monsoon rainfall over India sustains much of the interest in the study of possible relationships between the amount and distribution

Table 1. Studies dealing with teleconnections/long-range prediction of Indian summer monsoon rainfall.

1. Indian (Asian) region	2. Indian Ocean region	3. ENSO
Banerjee *et al* (1978)	Ramesh Babu *et al* (1981)	Khandekar (1979)
Verma (1980)	Ranjit Singh (1983)	Sikka (1980)
Joseph *et al* (1981)	Joseph and Pillai (1987)	Pant and Parthasarathy (1981)
Thapliyal (1982)	Hastenrath (1986, 1987)	Angell (1981)
Dey and Bhanu Kumar (1982)	Fu and Fletcher (1988)	Keshavamurty (1982)
Dickson (1984)	Kusuma Rao and Goswami (1988)	Rasmusson and Carpenter (1982, 1983)
Raj *et al* (1985)		Nicholls (1983)
Mooley *et al* (1986)		Mooley and Parthasarathy (1983, 1984b)
Bhalme *et al* (1986)		Bhalme *et al* (1983, 1984)
Mooley and Paolino (1988)		Bhalme and Jadhav (1984)
Verma (1982, 1990)		Parthasarathy and Pant (1984, 1985)
Sunder (1990)		Mooley *et al* (1985)
Parthasarathy *et al* (1990b, 1991a, 1991b, 1992b)		Shukla and Mooley (1987)
Krishna Kumar *et al* (1992)		Ropelewski and Halpert (1987, 1989)
		Gregory (1988)
		Parthasarathy and Sontakke (1988)
		Bhalme *et al* (1990)

4. Other global parameters	5. Diagnostics	6. Review/Appraisals
Mukherjee *et al* (1981)	Parthasarathy (1984a)	Walker (1924)
Verma *et al* (1985)	Hastenrath (1986, 1991)	Savur (1931)
Das and Datta (1985)	Mooley and Shukla (1987)	Montgomery (1940)
Rupa Kumar and Hingane (1986)	Shukla (1987b)	Normand (1953)
Bhalme *et al* (1987)	Elliot and Angell (1987)	Rao (1965)
	Meehl (1987)	Raghvendra and Robert (1973)
	Pant *et al* (1988)	Rao (1976)
	Parthasarathy *et al* (1988, 1990a)	Ananthakrishnan (1977)
	Thapliyal (1987, 1990)	Bell (1977)
	Gowariker *et al* (1989, 1991)	Joseph (1983)
	Kiladis and Sinha (1991)	Ananthakrishnan and Parthasarathy (1984)
	Yasunari (1991)	Parthasarathy (1984a)
	Prasad and Singh (1988, 1992)	Das (1986)
	Prasad (1992)	Hastenrath (1991)
	Srivastava and Singh (1993)	Yasunari (1991)

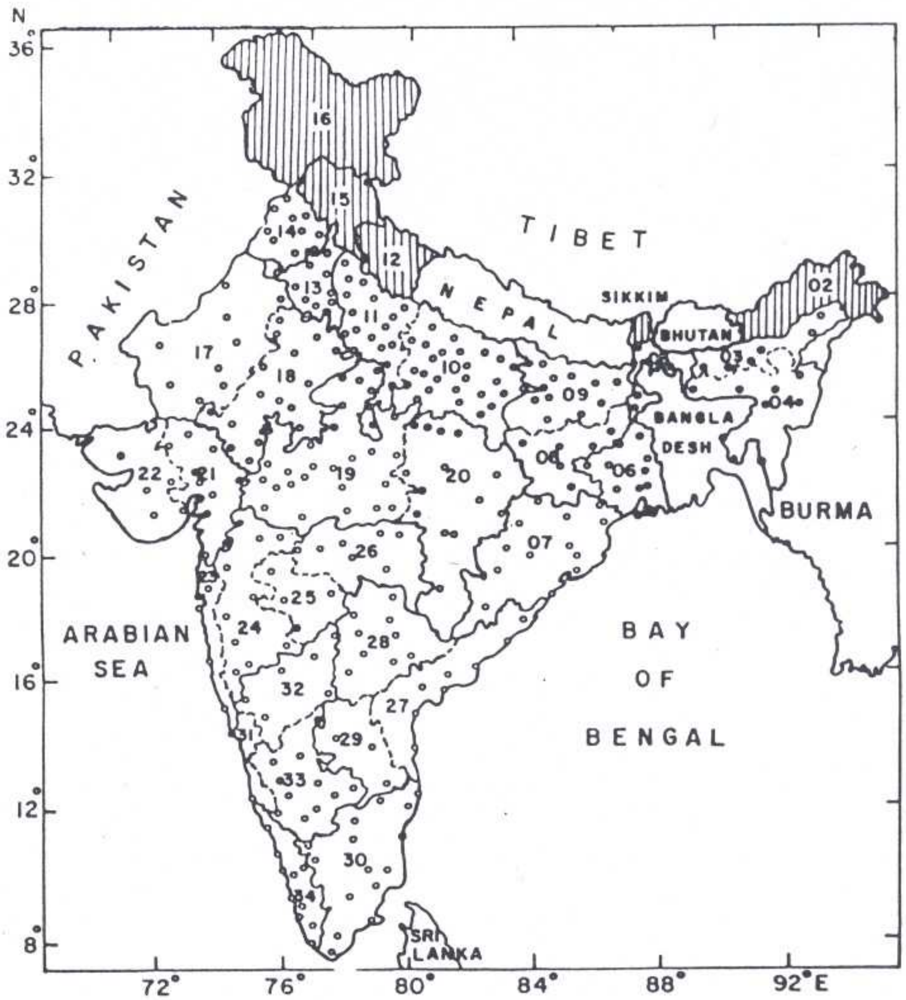
of Indian rainfall and antecedent regional and global circulation features. It is also in view of increased observations from the tropical regions in general and the monsoon regime in particular, that the interest in the study of monsoon has increased with emphasis on its spatial and temporal variations, interaction of monsoon with large-scale circulations and prediction of monsoon rainfall. A large body of literature exists documenting the observational evidence of the interannual variability of the monsoon circulation and rainfall and its possible relationships with the regional and global atmospheric circulation features. All these studies have been reviewed periodically, notably by Savur (1931); Montgomery (1940); Normand (1953); Jagannathan (1960); Rao (1965); Raghavendra and Robert (1973); Rao (1976); Parthasarathy (1984a); Das (1986); Shukla (1987a, b); Thapliyal (1987) and Hastenrath (1991). Some of the recent important studies on the teleconnections of Indian monsoon rainfall are classified into six groups depending upon the nature of circulation considered, and tabulated in table 1.

Almost all the above studies have used All-India (India taken as one unit) monsoon rainfall. Though this may be quite relevant to the large-scale circulation studies, India as one unit is perhaps too large an area for practical purposes. Moreover, the correlation coefficients (CCs) between All-India rainfall and different sub-divisional rainfall are significantly positive ($> 0{\cdot}6$) over central and northwestern parts of India while they are very small or even negative over northeastern and southernmost peninsular India (Parthasarathy 1984b). The inter-correlations between the sub-divisional rainfall have also brought out that two Assam sub-divisions are negatively or poorly related with the rest of the sub-divisions except with Bihar plains, Rayalaseema and Tamilnadu. The CCs of Bengal, Orissa, Bihar and UP State sub-divisions are poorly related with other regions. However the sub-divisions of northwestern, central and part of peninsular India are highly related amongst themselves. Subbaramayya and Naidu (1992) identified west central India and northeast India as two regions having opposite rainfall tendencies. Hastenrath and Arnold (1983) and Gregory (1989) found similar areal homogeneities from isocorrelation charts. Shukla (1987a), on the basis of principal components analysis, argues that the two regions, north western and part of peninsular India can be treated as a single homogeneous area. In view of such spatial patterns, it will be more appropriate and realistic to group the sub-divisions having similar characteristics to form a homogeneous Indian monsoon rainfall series rather than including all the sub-divisions of India. This will make the monsoon signal stronger and spatially more coherent. It is reasonable to expect that the nature of the interannual variability of the seasonal averages will depend upon the spatial and temporal domains for which the averages are calculated.

3. Details of data

3.1 *Indian summer monsoon rainfall*

All-India (India taken as one unit) and the 29 different meteorological sub-divisional mean summer monsoon (June through September) rainfall data sets have been prepared by properly area-weighting the rainfall at 306 well distributed raingauges over plain regions. Figure 1 shows the contiguous meteorological sub-divisions considered in this study. Parthasarathy (1984a), Parthasarathy *et al* (1987, 1990a)



2. Arunachal Pradesh
3. North Assam
4. South Assam
5. Sub-Himalayan West Bengal
6. Gangetic West Bengal
7 Orissa
8 Bihar Plateau
9 Bihar Plains
10 East Uttar Pradesh
11 West Uttar Pradesh Plains
12 West Uttar Pradesh Hills
13. Harayana
14. Punjab
15. Himachal Pradesh
16. Jammu and Kashmir
17. West Rajasthan
18 East Rajasthan
19 West Madhya Pradesh
20 East Madhya Pradesh
21 Gujarat
22 Saurashtra & Kutch
23 Konkan & Goa
24. Madhya Maharashtra
25. Marathwada
26. Vidarbha
27. Coastal Andhra Pradesh
28. Telangana
29 Rayalseema
30 Tamil Nadu
31 Coastal Karnataka
32 North Karnataka
33 South Karnataka
34 Kerala

Figure 1. Latest meteorological subdivisions of India with locations of raingauges considered. Hatched hilly subdivisions are not considered.

provide a detailed discussion of preparing these data sets and listing of data from the year 1871 onwards. Recently, Parthasarathy *et al* (1992a) have updated these data to the year 1991.

3.2 *Circulation parameters*

Earlier studies of Hastenrath (1987) and Parthasarathy *et al* (1988) on the relationships between Indian monsoon rainfall and regional/global circulation parameters indicated that a data length of about 20 to 30 years is necessary and sufficient to establish a stable correlation for prediction purposes. Also, a period of 30 years is generally considered adequate for establishing climatic normals. In the present study we have mainly considered the data period 1951–1980 for which excellent data sets on various parameters related to Indian monsoon are available.

In the present study the data of the relevant circulation parameters are obtained from the World Weather Records, Monthly Climatic Data for the World and India Meteorological Department (IMD), Pune.

4. Methodology

To study the association between the Indian summer monsoon rainfall and circulation parameters and to develop prediction equations, the following approach has been used:

- Simple correlation analysis,
- composite of circulation parameter anomalies during the wet and dry years of the regional rainfall,
- consistency of significant CCs over long periods using sliding windows of different widths,
- Principal Component Analysis (PCA) of circulation parameters and
- stepwise multiple regression analysis.

5. Grouping of sub-divisions for Homogeneous Indian Monsoon (HIM) region

Among the 29 sub-divisions those comprising the HIM region have been identified by the following criteria:

- Contiguity of area,
- contribution of monsoon seasonal rainfall to the annual amount,
- inter-correlations of sub-divisional and All-India monsoon rainfall and
- relationships between sub-divisional monsoon rainfall and regional/global circulation parameters.

5.1 *Monsoon contribution to annual subdivisional rainfall*

Contribution of monsoon rainfall to the annual amount has been tabulated for the 29 sub-divisions for the period 1871–1978 by Parthasarathy (1984b). There are 18 sub-divisions over central, northeastern and northwestern regions whose monsoon rainfall accounts for more than 80% of annual. The monsoon rainfall accounts for less than 60% of the annual rainfall over a small area of south peninsula.

5.2 *Inter-correlation of subdivisional monsoon rainfall*

The CCs between All-India summer monsoon rainfall and the 29 sub-divisional rainfall series for the period 1871–1978 have been presented by Mooley and Parthasarathy (1983). The CCs are positive in 27 sub-divisions and significant at 1% level over 22 sub-divisions over northwest, central, peninsular and northern sub-divisions. Interestingly, six contiguous subdivisions of Bihar, Bengal and Assam states do not show significant CCs, and the CCs over the two sub-divisions of Assam are even negative.

The intercorrelations of 29 sub-divisional monsoon rainfall series are discussed by Parthasarathy (1984b) and Subbaramayya and Naidu (1992). These studies show that neighbouring sub-divisions are in general, highly positively related. However two sub-divisions of Assam state are negatively related with rest of the sub-divisions. The CCs of west Bengal, Orissa, Bihar and UP state sub-divisions are not significantly correlated with other sub-divisions. The sub-divisions of northwestern, central and part of peninsular India are strongly related among themselves.

5.3 *Regional/global teleconnections of subdivisional monsoon rainfall*

The correlation analysis between various circulation parameters and 29 sub-divisional rainfall series has been studied by Parthasarathy *et al* (1990b, 1991b, 1992b). For a comprehensive view of the spatial preferences of these parameters, the CCs during 1951–80 for twelve parameters considered as important are given in table 2. The CCs are presented for (i) winter, DJF (lag-2), (ii) spring, MAM (lag-1) and (iii) winter-to-spring tendency, MAM-DJF, (lag-1 minus lag-2) as used by Shukla and Paolino (1983), immediately preceding the monsoon season and directly relevant to the long-range prediction of monsoon rainfall.

Bombay msl pressure tendency (MAM-DJF) shows generally negative CCs with sub-divisional rainfall, which are significant at 10% level, over 20 sub-divisions of northwest and central Indian regions (Parthasarathy *et al* 1991b). The April 500 mb ridge at 75°E (Mooley *et al* 1986) which is one of the leading parameters in the forecasting scheme of Indian monsoon rainfall, shows significant positive CCs with the monsoon rainfall of 20 sub-divisions over northwestern, central and part of peninsular India. The average surface air temperature of six stations, Jodhpur, Ahmedabad, Bombay, Indore, Sagar and Akola, representing as west central India (WCI – Parthasarathy *et al* 1990b) for MAM season shows positive CCs with the monsoon rainfall of a major part of India and significantly at 10% level for 16 sub-divisions north of 15°N and west of 80°E.

The cross-equatorial flow over the Indian Ocean, originating as the southeast trade wind in the Southern Hemisphere, is believed to be the basic flow of southwest monsoon over the Indian sub-continent. The CCs between sub-divisional rainfall and MAM-DJF pressure tendency of Agalega (10°S, 57°E) are mostly negative and are significant at 10% for 12 sub-divisions over west coast and central Indian regions (Parthasarathy *et al* 1990a). Meridional gradient of seasonal pressure tendency (MAM-DJF) over the Indian Ocean, i.e., Nouvelle (38°S, 78°E) minus Agalega, representing changes in cross-equatorial flow shows generally positive CCs with the sub-divisional monsoon rainfall. There are 13 sub-divisions showing significant CCs, mainly over northwest

Table 2. The Correlation Coefficients between sub-divisional monsoon rainfall and the circulation parameters for the period 1951–80.

Details of subdivisions	Indian region: Bombay msl Pressure MAM–DJF	Indian region: 500 HPa ridge at 75°E April	Indian region: WCI Temp MAM	Indian Ocean region: Agalega msl Pressure MAM–DJF	Indian Ocean region: Nouvelle minus Agalega MAM–DJF	Indian Ocean region: SST of Indian Ocean reg.III MAM	Pacific Ocean region: Darwin msl Pressure MAM–DJF	Pacific Ocean region: Tahiti minus Darwin MAM–DJF	Pacific Ocean region: SST of Pacific Ocean reg.III MAM–DJF	Other global parameters: N.H. air TEMP J+F	Other global parameters: South American msl Pressure MAM–DJF	Other global parameters: 10 HPa westerly (zonal) Balboa wind DJF (1958–87)	No. of significant parameters
No. Subdivision	1	2	3	4	5	6	7	8	9	10	11	12	13
3 North Assam	·20	−·16	·01	·05	−·30†	−·21	·08	−·21	·09	·05	·15	·01	01
4 South Assam	−·05	−·15	−·11	·20	−·26	−·19	−·01	−·04	·06	−·17	·31†	−·30†	02
5 S.H. West Bengal	·01	·22	·21	−·08	−·28	−·11	−·27	·20	−·23	·14	·06	−·08	00
6 Gan. West Bengal	−·31†	·09	·24	−·08	·22	·05	−·13	·26	−·02	−·06	·06	·14	01
7 Orissa	−·25	·37*	·35†	−·01	·47§	·25	−·22	·06	−·26	·20	−·21	·41*	04
8 Bihar Plateau	−·28	·34†	·42*	−·13	·33†	·08	−·20	·18	−·04	·24	·03	·35†	04
9 Bihar plains	−·26	·35†	·37*	−·10	·04	·00	−·22	·19	−·02	·18	−·09	·01	02
10 East UP	−·31†	·52§	·36*	−·12	·00	·29	−·30†	·10	−·28	·44*	−·45§	·47§	07
11 West UP plains	−·22	·51§	·16	−·29	·36*	·22	−·19	·14	−·22	·38*	−·24	·48§	04
13 Harayana**	−·32†	·58§	·13	−·38*	·30†	·24	−·31†	·36*	−·26	·46§	−·04	·35†	08
14 Punjab**	−·30†	·52§	·30†	−·13	−·09	·26	−·38*	·34†	−·34†	·49§	−·05	·34†	08
17 West Rajasthan**	−·58§	·44*	·26	−·37*	·41*	·25	−·43*	·27	−·36*	·51§	−·20	·29	07
18 East Rajasthan**	−·58§	·53§	·47§	−·45§	·56§	·39*	−·56§	·49§	−·46§	·50§	−·17	·40*	11
19 West MP**	−·53§	·54§	·61§	−·31†	·43*	·51§	−·54§	·45§	−·49§	·38*	−·15	·55§	11
20 East MP**	−·33†	·38*	·49§	−·26	·51§	·36*	−·28	·10	−·32†	·34†	−·37*	·58§	09
21 Gujarat**	−·57§	·59§	·50§	−·46§	·44*	·36*	−·62§	·44*	−·47§	·45*	−·27	·29	10
22 Sau. & Kutch**	−·39*	·28	·30†	−·43*	·42*	·38*	−·27	·21	−·23	·25	−·44*	·05	06
23 Konkan Goa**	−·42*	·52§	·46§	−·17	·11	·36*	−·49§	·21	−·40*	·42*	−·36*	·30†	09
24 Madhya Maha**	−·41*	·73§	·34†	−·35†	·30†	·34†	−·46§	·47§	−·28	·15	−·17	·03	08
25 Marathwada**	−·53§	·43*	·36*	−·46§	·07	·44*	−·62§	·37*	−·44*	·51§	−·51§	·17	10
26 Vidarbha**	−·59§	·37*	·46§	−·46§	·20	·68§	−·57§	·38*	−·59§	·51§	−·46§	·23	10
27 Coastal AP	−·45§	·39*	·08	−·07	·04	·26	−·28	·14	−·27	·26	−·29	·16	02
28 Telangana**	−·59§	·50§	·24	−·36*	·20	·30†	−·44*	·33†	−·38*	·38*	−·44*	·17	09
29 Rayalseema	−·49§	·41*	·18	−·33†	·15	·37*	−·38*	·38*	−·32†	·31†	−·06	−·01	08
30 Tamilnadu	−·04	·00	−·24	·02	−·03	·02	−·08	−·05	−·02	·15	·17	·16	00
31 Coastal Karnataka	−·50§	·24	·24	−·37*	·06	·26	−·32†	·23	−·21	·37*	−·36*	·30†	06
32 North IK**	−·52§	·56§	·32†	−·22	·34†	·17	−·30†	·28	−·31†	·15	−·21	·06	06
33 South IK	−·39*	·13	·36*	−·25	·07	·44*	−·39*	·30†	−·41*	·20	−·20	·12	06
34 Kerala	−·24	·04	·03	−·24	·03	·19	−·12	·14	·00	·07	−·12	·11	00
No. of significant sub-divisions	20	20	16	12	13	12	16	11	13	15	9	12	169

** These subdivisions are merged to form homogeneous Indian region.
† Significant at 10 percent.
* Significant at 5 percent.
§ Significant at 1 percent.

and central regions. Parthasarathy *et al* (1988) found that the MAM sea surface temperatures (SST) over Indian Ocean region III (2°–14°S; 100°–124°E) show generally positive CCs with the subdivisional monsoon rainfall, which are significant for 12 sub-divisions over the Rajasthan, Madhya Pradesh and Gujarat.

Tahiti (18°S, 150°W) and Darwin (12°S, 131°E) pressures are most commonly used to relate El Niño-Southern Oscillation (ENSO) and Indian monsoon (Parthasarathy and Pant 1985). Darwin msl pressure tendency (MAM-DJF) shows negative CCs with the monsoon rainfall of all sub-divisions, out of which 16 sub-divisions over northwest, central and some parts of peninsular India show significant CCs at 10% level. Tahiti minus Darwin pressure tendency (MAM-DJF) shows positive CCs with 11 sub-divisions mainly over northwest and central Indian regions. The redistribution of tropical rainfall during El Niño years alters the heating pattern over the Pacific Ocean region and plays an important role in Indian monsoon variability (Angell 1981; Parthasarathy and Sontakke 1988). Parthasarathy *et al* (1988) showed that the seasonal tendency (MAM-DJF) of SST averaged over the tropical Pacific Ocean Region III (14°N to 10°S; 148°W to 100°W) shows significant CCs with the monsoon rainfall of 13 sub-divisions over northwest and central Indian regions.

Verma *et al* (1985) has brought out the significant association between the Indian monsoon rainfall and Northern Hemispheric (NH) surface winter (J + F) temperature by using the Jones *et al* (1986) data. This parameter shows significant positive CCs with the monsoon rainfall of 15 sub-divisions mainly over northwest, central and some peninsular Indian regions. Parthasarathy *et al* (1988) found that the south American msl pressure tendency (MAM-DJF), average of Cardoba (31°S, 64°W) and Buenos Aires (35°S, 58°W) shows significant negative CCs with the sub-divisional monsoon rainfall over west coast and central India. Bhalme *et al* (1987) identified the significant association between 10 mb zonal winds of Balboa (9°N, 80°W) and the Indian monsoon rainfall using data for the period 1958–87. This parameter shows significant positive CCs with the monsoon rainfall of 12 sub-divisions over Bihar, UP, Rajasthan, Orissa, Madhya Pradesh and Maharashtra.

The above results of correlation analysis between sub-divisional rainfall and 12 different circulation parameters can be summarized as follows: There are twelve sub-divisions covering about 50% area of India, lying north of 14°N and west of 85°E, having highly significant association with 70% of the circulation parameters (8 or more out of 12). About nine sub-divisions adjoining the above region show moderate relationships with the circulation parameters (4 to 7 out of 12). The remaining sub-divisions (eight) show poor association with circulation parameters.

5.4 *The Homogeneous Indian Monsoon* (*HIM*) *region*

A comprehensive view of the above discussion in the light of the criteria for delineating the HIM region listed above suggests that there are 14 sub-divisions (Haryana, Punjab, west and east Rajasthan, east and west Madhya Pradesh, Gujarat, Saurashtra, Konkan, Madhya Maharashtra, Marathwada, Vidarbha, Telangana and north Karnataka), which can be grouped to form a unit. These are contiguous sub-divisions covering central and northwestern parts of India. The monsoon rainfall of these sub-divisions is more than 80% of annual amount, the series are highly interrelated and their relationships with regional/global circulation parameters are also identical. Therefore, it will be quite appropriate to group these sub-divisions into a homogeneous Indian Monsoon (HIM) region for further analysis.

Table 3. Monthly, seasonal and annual rainfall (in mm) series of Homogeneous Indian Monsoon (HIM) region for the year 1871–1990.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	J + F	MAM	J − S	OND	Annual
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1871	19·4	6·4	·8	4·4	26·4	194·2	236·3	130·4	133·9	11·2	11·8	3·2	25·8	31·6	694·8	26·2	778·4
1872	2·8	3·4	3·4	13·1	6·4	153·1	276·2	239·4	154·9	29·5	·8	16·2	6·2	22·9	823·6	46·5	899·2
1873	3·4	10·1	4·9	4·1	26·1	84·1	237·0	204·7	176·5	15·7	5·7	6·2	13·5	35·1	702·3	27·6	778·5
1874	4·1	3·7	3·9	3·1	18·1	194·7	305·6	220·9	157·0	21·8	2·1	·7	7·8	25·1	878·2	24·6	935·7
1875	1·5	12·5	2·8	5·3	14·5	160·6	321·9	162·5	226·0	31·2	·8	5·6	14·0	22·6	871·0	37·6	945·2
1876	·2	1·0	6·9	3·2	9·3	74·6	303·4	168·7	146·9	7·9	·9	·0	1·2	19·4	693·6	8·8	723·0
1877	27·8	17·9	11·4	28·8	26·6	129·8	118·1	120·0	107·5	79·0	7·1	31·7	45·7	66·8	475·4	117·8	705·7
1878	6·6	8·4	2·8	19·2	29·3	96·7	310·6	336·9	173·8	49·4	9·8	1·5	15·0	51·3	918·0	60·7	1045·0
1879	·6	10·0	1·8	1·6	39·4	171·5	147·9	340·2	110·6	52·9	7·5	2·4	10·6	42·8	770·2	62·8	886·4
1880	·3	5·0	1·7	2·6	8·5	138·6	261·8	118·3	203·3	54·8	18·3	3·6	5·3	12·8	722·0	76·7	816·8
1881	·3	3·1	22·6	9·3	11·5	124·8	325·0	229·1	107·2	22·9	17·4	1·6	3·4	43·4	786·1	41·9	874·8
1882	8·6	2·6	·9	5·8	16·4	208·0	365·0	128·2	162·1	16·5	26·9	·6	11·2	23·1	863·3	44·0	941·6
1883	13·7	·1	9·9	2·0	23·6	171·0	251·6	149·2	217·9	58·7	8·5	·2	13·8	35·5	789·7	67·4	906·4
1884	8·7	5·2	2·1	4·2	5·4	135·9	350·1	225·8	265·9	38·2	·6	25·8	13·9	11·7	977·7	64·6	1067·9
1885	10·1	5·1	5·8	11·3	33·0	159·6	253·4	232·2	78·1	52·2	13·0	43·5	15·2	50·1	723·3	108·7	897·3
1886	4·2	·6	9·5	2·0	28·7	177·0	302·7	170·8	61·1	109·2	5·6	15·0	4·8	40·2	711·6	129·8	886·4
1887	13·3	·1	·6	6·1	9·6	148·3	341·7	249·2	131·3	54·0	22·4	3·9	13·4	16·3	870·5	80·3	980·5
1888	20·9	12·8	3·7	3·4	10·3	101·9	247·3	246·6	84·1	14·1	32·8	·6	33·7	17·4	679·9	47·5	778·5
1889	4·6	8·7	2·6	10·8	18·7	149·6	259·6	291·3	112·7	65·2	1·1	·1	13·3	32·1	813·2	66·4	925·0
1890	·4	·3	6·2	9·5	4·1	181·4	260·3	192·9	136·4	17·4	28·2	16·4	·7	19·8	771·0	62·0	853·5
1891	11·8	6·8	18·8	8·7	12·9	35·3	284·9	188·9	238·2	29·6	·7	·0	18·6	40·4	747·3	30·3	836·6
1892	7·1	6·2	·2	6·4	14·1	128·4	307·5	289·1	251·2	71·2	4·2	6·0	13·3	20·7	976·2	81·4	1091·6
1893	23·0	17·6	43·0	4·1	43·9	223·2	206·3	239·5	204·4	55·6	38·6	1·2	40·6	91·0	873·4	95·4	1100·4
1894	14·0	7·6	6·1	4·3	5·6	206·3	333·6	186·2	198·0	79·4	15·4	13·7	21·6	16·0	924·1	108·5	1070·2
1895	10·7	8·5	8·7	12·8	5·2	173·9	209·1	207·9	106·6	42·0	4·5	1·7	19·2	26·7	697·5	48·2	791·6
1896	·8	2·1	1·6	3·2	5·8	183·7	298·4	264·8	27·6	3·2	25·4	10·0	2·9	10·6	774·5	38·6	826·6
1897	10·4	4·9	3·5	13·9	10·0	85·9	246·6	275·9	155·7	48·0	·7	·2	15·3	27·4	764·1	48·9	855·7
1898	·3	31·4	1·4	7·4	10·6	134·7	316·2	170·9	147·9	19·4	8·2	6·2	31·7	19·4	769·7	33·8	854·6

(*Continued*)

Table 3. (Continued).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	J + F	MAM	J – S	OND	Annual
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1899	·3	2·8	·8	18·1	15·1	149·9	94·5	88·7	52·4	4·9	·0	·2	3·1	34·0	385·5	5·1	427·7
1900	9·3	2·0	2·2	12·4	10·8	70·5	232·3	305·5	219·2	15·2	2·3	8·6	11·3	25·4	827·5	26·1	890·3
1901	20·9	24·2	11·1	16·7	15·8	78·5	215·5	248·5	73·2	25·4	2·0	·8	45·1	43·6	615·7	28·2	732·6
1902	3·8	1·9	·7	7·4	8·7	58·6	234·0	168·1	179·2	29·3	17·1	18·0	5·7	16·8	639·9	64·4	726·8
1903	4·7	1·7	3·0	2·2	32·5	70·7	313·1	236·8	166·4	75·8	6·7	2·7	6·4	37·7	787·0	85·2	916·3
1904	2·8	5·6	21·3	2·5	21·8	127·6	194·2	150·4	118·8	42·4	2·2	6·2	8·4	45·6	591·0	50·8	695·8
1905	10·6	8·2	7·6	9·9	10·4	49·4	225·3	123·2	152·7	18·8	1·5	·8	18·8	27·9	550·6	21·1	618·4
1906	8·4	25·3	14·6	·4	5·3	162·1	271·0	191·9	162·7	17·2	4·8	12·3	33·7	20·3	787·7	34·3	876·0
1907	4·1	33·3	8·7	33·1	4·2	102·8	207·0	322·9	52·3	1·3	4·0	2·3	37·4	46·0	685·0	7·6	776·0
1908	10·4	9·4	4·6	5·3	7·7	92·5	328·3	319·7	136·6	7·2	·7	1·3	19·8	17·6	877·1	9·2	923·7
1909	5·6	5·4	2·2	35·0	11·4	158·8	302·3	168·8	141·1	7·1	·7	23·2	11·0	48·6	771·0	31·0	861·6
1910	3·8	·6	·9	3·7	7·8	191·6	185·5	266·7	193·7	47·8	27·6	·1	4·4	12·4	837·5	75·5	929·8
1911	13·5	·4	20·0	2·0	5·4	139·2	120·3	182·3	131·8	30·8	25·6	1·8	13·9	27·4	573·6	58·2	673·1
1912	7·1	18·9	·8	8·3	7·8	62·0	327·2	234·4	82·0	19·2	29·6	·9	26·0	16·9	705·6	49·7	798·2
1913	·5	21·9	7·3	4·6	30·0	183·9	251·3	157·6	88·5	17·2	1·9	12·1	22·4	41·9	681·3	31·2	776·8
1914	1·1	4·9	9·5	14·7	20·5	156·0	321·4	188·5	180·8	11·5	9·7	4·7	6·0	44·7	846·7	25·9	923·3
1915	16·9	22·0	32·3	11·7	12·4	127·4	185·8	163·0	138·1	81·3	9·5	4·6	38·9	56·4	614·3	95·4	805·0
1916	·8	8·2	·3	3·8	23·4	158·7	226·6	293·3	188·7	98·3	35·9	·0	9·0	27·5	867·3	134·2	1038·0
1917	3·0	28·0	11·1	12·1	54·7	180·7	228·4	293·4	272·6	129·6	10·2	1·1	31·0	77·9	975·1	140·9	1224·9
1918	4·5	1·4	5·5	5·5	51·5	117·1	99·8	170·2	61·6	3·0	14·0	6·4	5·9	62·5	448·7	23·4	540·5
1919	36·9	12·6	9·3	7·6	21·6	150·5	247·4	300·6	108·1	46·2	25·7	5·0	49·5	38·5	806·6	76·9	971·5
1920	19·1	2·8	5·5	8·3	29·3	109·6	250·5	121·6	68·8	7·9	·1	·0	21·9	43·1	550·5	8·0	623·5
1921	13·7	·6	·2	5·6	·8	135·0	250·3	171·0	174·4	20·1	9·4	1·0	14·3	6·6	730·7	30·5	782·1
1922	23·2	4·0	·1	5·9	10·1	123·9	256·0	131·2	182·0	16·9	39·6	5·5	27·2	16·1	693·1	62·0	798·4
1923	4·0	14·2	15·4	5·7	12·0	29·9	317·7	240·5	145·5	15·4	·9	5·3	18·2	33·1	733·6	21·6	806·5
1924	14·5	4·6	2·9	7·6	7·8	60·4	246·5	207·3	200·5	47·0	21·0	10·5	19·1	18·3	714·7	78·5	830·6
1925	·8	·0	1·0	6·3	38·1	167·4	253·7	169·6	74·2	34·2	28·5	2·3	·8	45·4	664·9	65·0	776·1
1926	25·6	2·6	24·7	15·5	30·0	37·0	251·5	345·4	210·7	25·2	1·4	·9	28·2	70·2	844·6	27·5	970·5

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1927	1·7	12·7	9·3	3·4	9·8	130·9	327·7	194·9	99·5	42·4	47·3	12·6	14·4	22·5	753·0	102·3	892·2
1928	3·3	20·0	6·4	4·3	4·6	112·4	266·2	182·5	127·8	63·8	5·4	16·0	23·3	15·3	688·9	85·2	812·7
1929	7·0	15·9	·6	13·7	6·6	129·6	277·5	182·9	107·4	32·4	1·3	17·7	22·9	20·9	697·4	51·4	792·6
1930	4·6	2·9	2·4	14·0	13·2	146·4	275·8	140·9	137·8	49·7	20·3	3·0	7·5	29·6	700·9	73·0	811·0
1931	3·1	8·5	6·0	4·7	12·4	73·4	263·2	310·1	148·2	114·2	28·1	5·0	11·6	23·1	794·9	147·3	976·9
1932	·9	9·3	8·7	7·4	11·4	75·6	350·1	168·6	154·6	44·3	17·6	2·8	10·2	27·5	748·9	64·7	851·3
1933	4·7	19·6	8·4	16·4	63·9	177·0	234·3	298·8	219·6	45·0	13·0	10·6	24·3	88·7	929·7	68·6	1111·3
1934	5·0	·0	7·8	8·3	2·3	162·0	226·9	310·7	172·4	18·5	26·8	3·5	5·0	18·4	872·0	48·8	944·2
1935	13·3	6·7	1·6	20·1	2·2	105·7	327·3	158·3	154·8	31·8	2·2	5·1	20·0	23·9	746·1	39·1	829·1
1936	4·9	24·5	11·7	4·7	22·6	208·7	188·0	187·9	152·9	30·6	56·5	4·8	29·4	39·0	737·5	91·9	897·8
1937	·2	30·2	12·1	40·6	5·2	136·9	365·5	125·7	160·9	54·1	·5	9·3	30·4	57·9	789·0	63·9	941·2
1938	9·8	9·0	8·8	5·2	24·2	226·7	256·0	192·8	117·7	72·1	2·8	·3	18·8	38·2	793·2	75·2	925·4
1939	4·4	14·1	17·8	6·3	·6	89·7	221·2	235·4	98·4	31·2	5·6	·3	18·5	24·7	644·7	37·1	725·0
1940	11·0	10·9	10·2	11·1	21·4	146·8	274·5	268·6	66·1	49·3	13·6	7·6	21·9	42·7	756·0	70·5	891·1
1941	17·8	11·1	6·1	3·2	10·5	90·5	218·0	175·9	96·6	19·2	·7	1·7	28·9	19·8	581·0	21·6	651·3
1942	11·9	30·7	1·6	10·6	9·9	137·0	350·4	275·8	130·5	7·8	·7	14·7	42·6	22·1	893·7	23·2	981·6
1943	32·2	1·8	1·2	9·1	32·1	122·4	300·7	137·7	187·7	64·7	3·9	·0	34·0	42·4	748·5	68·6	893·5
1944	12·4	23·2	43·3	9·0	8·1	96·9	375·4	320·8	111·1	64·2	6·6	1·3	35·6	60·4	904·2	72·1	1072·3
1945	19·9	1·0	·6	19·6	8·4	147·2	331·5	212·3	202·1	28·6	3·0	·3	20·9	28·6	893·1	31·9	974·5
1946	·0	11·1	1·1	13·3	16·1	192·7	251·3	291·5	102·4	17·5	64·8	10·9	11·1	30·5	837·9	93·2	972·7
1947	15·4	10·4	6·6	14·8	6·7	62·3	256·2	309·7	236·2	24·6	3·0	11·7	25·8	28·1	864·4	39·3	957·6
1948	27·4	9·2	6·6	7·9	5·9	113·6	253·3	233·1	161·3	27·9	65·1	1·0	36·6	20·4	761·3	94·0	912·3
1949	1·4	5·8	1·3	4·6	31·0	95·2	279·7	184·8	228·3	62·7	1·9	·4	7·2	36·9	788·0	65·0	897·1
1950	4·5	12·6	15·6	1·6	9·7	60·6	352·3	170·7	195·4	18·9	4·9	4·8	17·1	26·9	779·0	28·6	851·6
1951	4·3	1·8	22·6	14·5	17·4	100·8	222·9	194·4	82·8	49·2	14·3	·0	6·1	54·5	600·9	63·5	725·0
1952	1·2	9·7	5·4	7·9	17·4	117·8	289·0	207·7	71·2	28·4	·2	3·0	10·9	30·7	685·7	31·6	758·9
1953	15·6	1·2	·0	12·3	2·5	113·4	252·3	302·1	132·2	55·9	·0	·6	16·8	14·8	800·0	56·5	888·1
1954	5·6	12·8	7·1	5·5	6·3	95·4	285·6	193·0	279·1	22·5	·3	2·8	18·4	18·9	853·1	25·6	916·0
1955	13·9	1·3	3·7	7·1	17·1	156·0	160·9	333·9	221·9	119·0	3·0	·2	15·2	27·9	872·7	122·2	1038·0
1956	4·9	3·6	6·2	4·2	44·1	139·5	388·8	235·6	135·3	102·2	29·3	4·6	8·5	54·5	899·2	136·1	1098·3
1957	14·8	2·6	31·3	14·4	18·6	105·4	245·2	261·8	81·4	38·6	8·9	2·1	17·4	64·3	693·8	49·6	825·1
1958	4·4	6·0	7·8	11·0	14·7	86·4	308·0	244·9	214·1	59·5	19·6	3·1	10·4	33·5	853·4	82·2	979·5
1959	12·7	3·6	·8	8·9	21·5	123·8	357·7	255·4	234·8	76·4	9·8	·3	16·3	31·2	971·7	86·5	1105·7
1960	13·1	·0	19·0	5·5	20·7	131·4	232·6	234·7	98·8	44·6	4·5	3·0	13·1	45·2	697·5	52·1	807·9

Table 3. (Continued).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	J + F	MAM	J − S	OND	Annual
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1961	12·8	13·1	2·2	8·2	30·7	143·4	328·1	249·0	265·5	85·5	5·9	4·5	25·9	41·1	986·0	95·9	1148·9
1962	4·3	7·1	11·9	18·3	20·0	55·4	258·5	194·1	208·3	20·8	13·7	32·9	11·4	50·2	716·3	67·4	845·3
1963	1·9	5·6	8·7	13·2	13·5	112·7	207·0	310·3	126·9	51·7	12·0	1·1	7·5	35·4	756·9	64·8	864·6
1964	·7	3·0	3·1	4·4	10·6	125·5	267·8	275·8	164·4	36·3	5·5	1·3	3·7	18·1	833·5	43·1	898·4
1965	7·3	3·2	7·1	10·7	8·8	67·8	270·4	148·7	110·9	8·7	2·4	7·4	10·5	26·6	597·8	18·5	653·4
1966	9·2	4·8	3·9	4·6	26·8	102·4	232·3	157·8	122·9	11·4	27·8	10·0	14·0	35·3	615·4	49·2	713·9
1967	·8	·5	53·1	7·6	5·9	124·4	297·3	230·4	145·2	16·4	1·6	53·7	1·3	66·6	797·3	71·7	936·9
1968	11·6	12·1	16·1	9·6	5·5	69·9	256·1	169·5	113·8	31·2	4·8	2·1	23·7	31·2	609·3	38·1	702·3
1969	3·8	2·1	2·5	6·0	19·2	75·2	288·1	211·5	167·5	14·8	24·1	2·5	5·9	27·7	742·3	41·4	817·3
1970	13·8	12·3	10·7	6·7	21·1	196·3	192·6	330·0	187·8	23·6	·1	·0	26·1	38·5	906·7	23·7	995·0
1971	7·5	5·7	5·2	9·7	38·0	196·0	225·4	210·6	137·0	55·9	·3	·0	13·2	52·9	769·0	56·2	891·3
1972	1·0	5·8	·8	6·4	6·7	96·8	150·0	215·8	73·2	15·3	21·7	1·7	6·8	13·9	535·8	38·7	595·2
1973	2·2	9·4	1·0	2·5	10·5	85·3	294·8	333·8	164·1	79·9	2·4	4·2	11·6	14·0	878·0	86·5	990·1
1974	·3	2·8	2·3	4·9	31·9	72·3	205·2	203·6	82·0	94·3	3·3	2·8	3·1	39·1	563·1	100·4	705·7
1975	5·9	7·3	7·9	1·8	10·5	149·4	260·0	273·1	228·7	100·8	2·6	·1	13·2	20·2	911·2	103·5	1048·1
1976	6·2	4·3	3·9	10·1	11·8	125·3	287·3	273·3	125·1	3·1	39·2	·8	10·5	25·8	811·0	43·1	890·4
1977	6·7	3·0	4·9	14·8	27·3	178·7	291·8	225·7	134·8	34·2	42·5	3·5	9·7	47·0	831·0	80·2	967·9
1978	6·8	20·3	14·6	11·9	15·0	174·3	276·7	277·4	100·7	23·6	23·0	14·4	27·1	41·5	829·1	61·0	958·7
1979	16·9	27·8	6·2	3·8	26·3	123·6	179·6	230·9	103·6	16·0	68·6	3·6	44·7	36·3	637·7	88·2	806·9
1980	3·4	1·6	6·1	9·2	6·0	202·0	235·8	252·9	94·9	7·9	3·6	19·4	5·0	21·3	785·6	30·9	842·8
1981	12·3	2·0	15·5	4·8	16·1	111·2	253·9	211·8	177·1	29·4	26·2	5·4	14·3	36·4	754·0	61·0	865·7
1982	24·1	6·9	14·8	17·9	39·8	79·6	219·1	249·1	89·0	32·4	39·9	2·8	31·0	72·5	636·8	75·1	815·4
1983	5·7	5·1	2·1	20·4	25·1	118·3	266·7	302·2	227·0	59·0	1·4	4·7	10·8	47·6	914·2	65·1	1037·7
1984	13·6	13·7	2·6	10·8	2·5	95·4	217·4	265·5	104·5	40·1	1·0	1·3	27·3	15·9	682·8	42·4	768·4
1985	11·2	2·1	2·1	11·1	12·3	97·9	230·8	201·1	90·2	90·3	2·2	3·7	13·3	25·5	620·0	96·2	755·0
1986	9·2	29·8	5·7	8·0	16·2	163·4	221·1	197·2	55·2	16·4	10·9	13·0	39·0	29·9	636·9	40·3	746·1
1987	12·9	10·3	8·2	2·4	28·0	83·3	157·8	210·5	71·9	62·5	30·1	14·1	23·2	38·6	523·5	106·7	692·0
1988	2·5	7·0	6·3	12·0	6·2	115·8	320·9	226·8	206·2	25·9	1·6	5·0	9·5	24·5	869·7	32·5	936·2
1989	5·3	·1	18·1	2·4	6·6	150·1	232·5	232·8	109·9	9·4	2·0	9·7	5·4	27·1	725·3	21·1	778·9
1990	1·2	17·4	4·9	2·6	66·6	155·4	227·6	323·3	176·7	64·7	6·4	7·9	18·6	74·1	883·0	79·0	1054·7
Mean	8·6	8·8	8·0	9·0	17·2	127·0	260·3	223·9	146·0	40·2	13·0	6·3	17·4	34·3	757·2	59·5	868·3
Per Ann	1·0	1·0	·9	1·0	2·0	14·6	30·0	25·8	16·8	4·6	1·5	·7	2·0	3·9	87·2	6·9	100·0
STD	7·52	8·16	9·01	6·72	12·82	44·27	57·75	60·43	55·49	28·25	15·07	8·55	11·25	16·86	118·96	31·29	132·06
COV	87·8	92·4	112·3	74·4	74·5	34·9	22·2	27·0	38·0	70·3	115·6	135·9	64·6	49·2	15·7	52·6	15·2

Table 4. Inter-correlation (R*100) between HIM and sub-divisional summer monsoon rainfall for the period 1871–1990.

Region/Sub-division	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 Homogeneous India	100														
2 Haryana	61$^{\$}$	100													
3 Punjab	57$^{\$}$	72$^{\$}$	100												
4 West Rajasthan	74$^{\$}$	50$^{\$}$	54$^{\$}$	100											
5 East Rajasthan	80$^{\$}$	65$^{\$}$	56$^{\$}$	71$^{\$}$	100										
6 West Madhya Pradesh	79$^{\$}$	46$^{\$}$	41*	52$^{\$}$	73$^{\$}$	100									
7 East Madhya Pradesh	57$^{\$}$	28	18	28	42*	57$^{\$}$	100								
8 Gujarat	78$^{\$}$	43*	39*	65$^{\$}$	63$^{\$}$	50$^{\$}$	28	100							
9 Saurashtra and Kutch	63$^{\$}$	32†	34†	49$^{\$}$	41*	26	16	74$^{\$}$	100						
10 Konkan and Goa	67$^{\$}$	39*	31†	40*	42*	47$^{\$}$	16	48$^{\$}$	36*	100					
11 Madhya Maharashtra	65$^{\$}$	30†	30†	36*	36*	41*	06	54$^{\$}$	48$^{\$}$	63$^{\$}$	100				
12 Marathwada	65$^{\$}$	37*	41*	41*	39*	36*	10	41*	35*	65$^{\$}$	71$^{\$}$	100			
13 Vidarbha	75$^{\$}$	38*	34†	44*	43*	55$^{\$}$	36*	55$^{\$}$	50$^{\$}$	51$^{\$}$	57$^{\$}$	59$^{\$}$	100		
14 Telangana	54$^{\$}$	26	38*	40*	32†	22	09	40*	38*	46$^{\$}$	48$^{\$}$	59$^{\$}$	51$^{\$}$	100	
15 North Karnataka	58$^{\$}$	29	34†	38*	31†	22	08	40*	43*	60$^{\$}$	72$^{\$}$	67$^{\$}$	41*	59$^{\$}$	100

†Significant at 10 percent level.
*Significant at 5 percent level.
$^{\$}$Significant at 1 percent level.

The monthly HIM rainfall for the period 1871 to 1990 is obtained by the area weighted average of the rainfall of the 14 sub-divisions. Rainfall data at 151 well distributed and constant network of stations throughout the data period constitute the basic data involved in these calculations (Parthasarathy *et al* 1987, 1992a). It may be noted that, the rainfall data of all the individual raingauge stations used in this analysis have been earlier found to be homogeneous, Gaussian distributed and free from persistence during the period 1871–1978 (Parthasarathy 1984a). A listing of the monthly and seasonal rainfall series of HIM region is presented in table 3 along with the basic statistical details, for the benefit of further research. It may be noted that July and August are the wettest and seven months November through May are driest for the HIM region.

Table 4 shows the inter-correlations between HIM rainfall and the 14 sub-divisional series which are involved in preparation of this time series, for the period 1871–1990. All 14 sub-divisional series are highly correlated (CCs) with homogeneous series and also among themselves, clearly supporting their grouping. Almost all the CCs are significant at 0·1% level or above.

The HIM rainfall series has been subjected to various statistical analysis to understand its characteristics, variability and teleconnections.

6. Salient features of HIM rainfall variability

Figure 2 shows HIM rainfall series expressed as percentage departures from the long-term mean, along with a low-pass filter curve (binomial low-pass filter; see Tyson *et al* 1975 and Mooley and Parthasarathy 1984a) with dry/wet years marked on the bars of the diagram. This figure also includes a map showing the areas of sub-divisions considered in preparation of this series along with necessary statistical details. A monsoon rainfall year has been classified as excess (wet) when $R_i \geqslant \bar{R} + S$ and deficient (dry) when $R_i \leqslant \bar{R} - S$, where R_i is the rainfall of the ith year, $\bar{R}$ the mean and S the standard deviation of the series. This classification is considered to be rational for the tropical regions with high spatial and temporal variations of rainfall, with the crop growth and water requirement and management tuned to the local conditions (Parthasarathy *et al* 1992c). The statistical analysis of the series indicates that the series is homogeneous, Gaussian distributed and free from persistence. The mean ($\bar{R}$) rainfall is 757 mm (87% of annual amount) and standard deviation (S) 119 mm with a CV of 16%. The highest rainfall was 986 mm in the year 1961, the lowest was 386 mm in 1899 and the range is 79% of the mean. There were 21 dry and 19 wet years in the series and their occurrence is randomly distributed. Table 5 shows the details of dry and wet years during 1871–1990. Further, it is observed that there were relatively more frequent dry years during the periods 1899–1920 and 1965–1987, but wet years were rather well distributed through out the data period. There was one instance of three consecutive dry years (1985, 1986 and 1987), two instances of two consecutive dry years (1904 and 1905 and 1965 and 1966) and one instance of two consecutive wet years (1944 and 1945). There were four instances of a dry year followed by a wet year (1877–1878; 1941–1942; 1982–1983 and 1987–1988) and one instance of a wet year followed by a dry year (1917–1918). There was also an alternating sequence of dry and wet: 1972–1973–1974–1975. It is noticed that, during the dry years corresponding to HIM rainfall, 95% or more of the 14 sub-divisions comprising

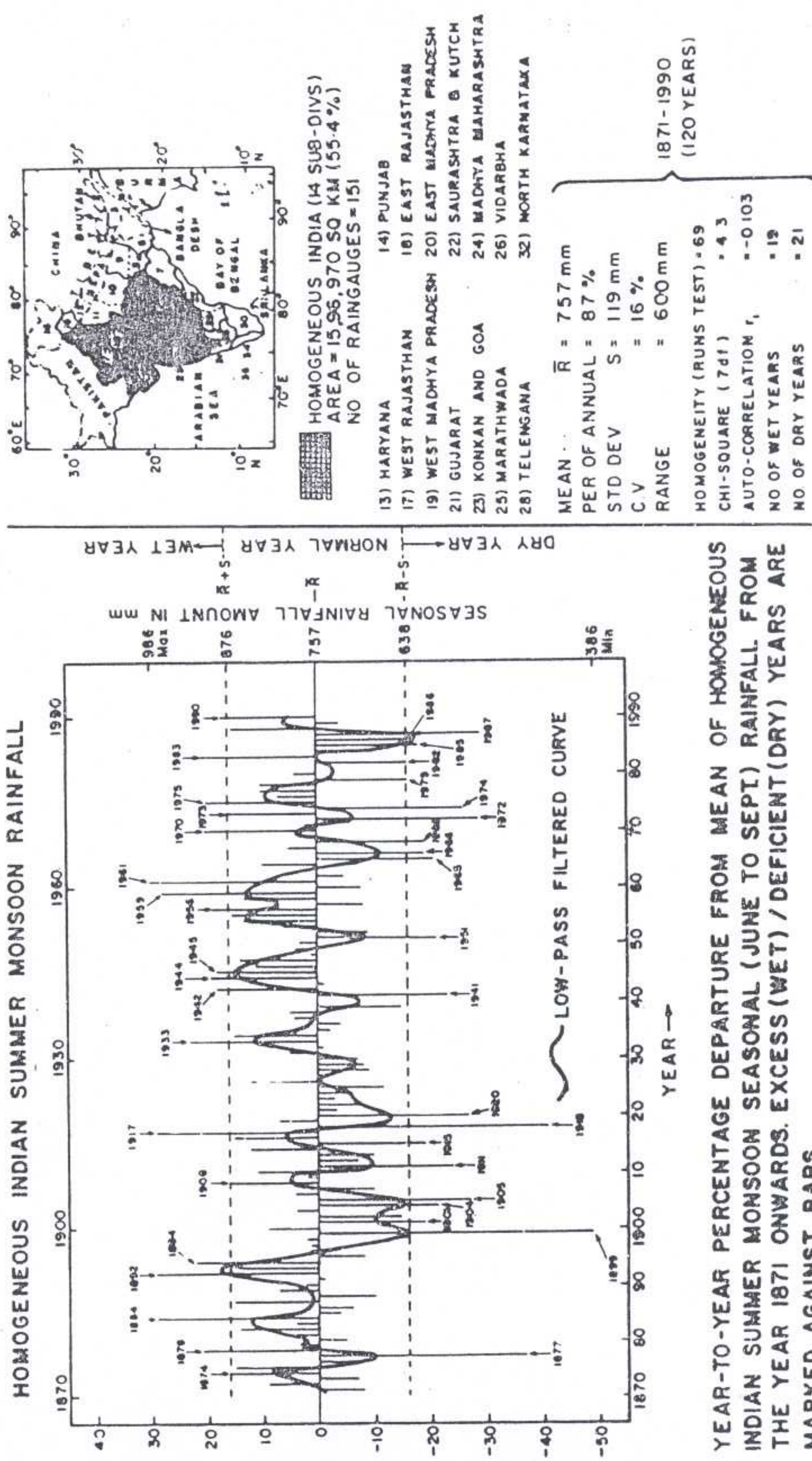

Figure 2. Year-to-year percentage departure from mean of homogeneous Indian monsoon (June to Sept) rainfall from 1871 to 1990. Wet/dry years are marked against the bars. Statistical details and sub-divisions merged with HIM are also shown in the diagram.

Table 5. Statistical details of dry and wet rainfall years of HIM during the period 1871–1990.

	Dry years					Wet years				
No.	Year	Rainfall mm	Dep from mean (%)	Standardised value	Rank	Year	Rainfall mm	Dep from mean (%)	Standardised value	Rank
1.	1877	475·6	−37·2	−2·378	3	1874	878·4	16·0	1·022	17
2.	1899	385·7	−49·1	−3·137	1	1878	918·2	21·2	1·358	8
3.	1901	615·8	−18·7	−1·195	17	1884	978·0	29·1	1·863	2
4.	1904	591·3	−21·9	−1·401	11	1892	976·2	28·9	1·847	3
5.	1905	550·9	−27·3	−1·742	7	1894	924·3	22·0	1·409	7
6.	1911	573·7	−24·2	−1·550	9	1908	877·3	15·8	1·013	19
7.	1915	614·4	−18·9	−1·206	15	1917	975·3	28·8	1·840	4
8.	1918	448·9	−40·7	−2·603	2	1933	930·0	22·8	1·458	6
9.	1920	550·7	−27·3	−1·744	6	1942	893·8	18·0	1·152	14
10.	1941	581·2	−23·3	−1·487	10	1944	904·4	19·4	1·241	12
11.	1951	600·9	−20·7	−1·320	13	1945	893·3	18·0	1·148	15
12.	1965	597·9	−21·1	−1·346	12	1956	899·3	18·7	1·198	13
13.	1966	615·5	−18·7	−1·197	16	1959	971·8	28·3	1·810	5
14.	1968	609·5	−19·5	−1·248	14	1961	986·3	30·2	1·933	1
15.	1972	535·9	−29·2	−1·869	5	1970	906·9	19·8	1·263	11
16.	1974	563·2	−25·6	−1·639	8	1973	878·2	16·0	1·020	18
17.	1979	637·8	−15·8	−1·009	21	1975	911·3	20·3	1·300	10
18.	1982	636·9	−15·9	−1·016	19	1983	914·3	20·7	1·325	9
19.	1985	620·1	−18·1	−1·158	18	1990	883·2	16·6	1·062	16
20.	1986	637·1	−15·9	−1·015	20					
21.	1987	523·6	−30·9	−1·973	4					

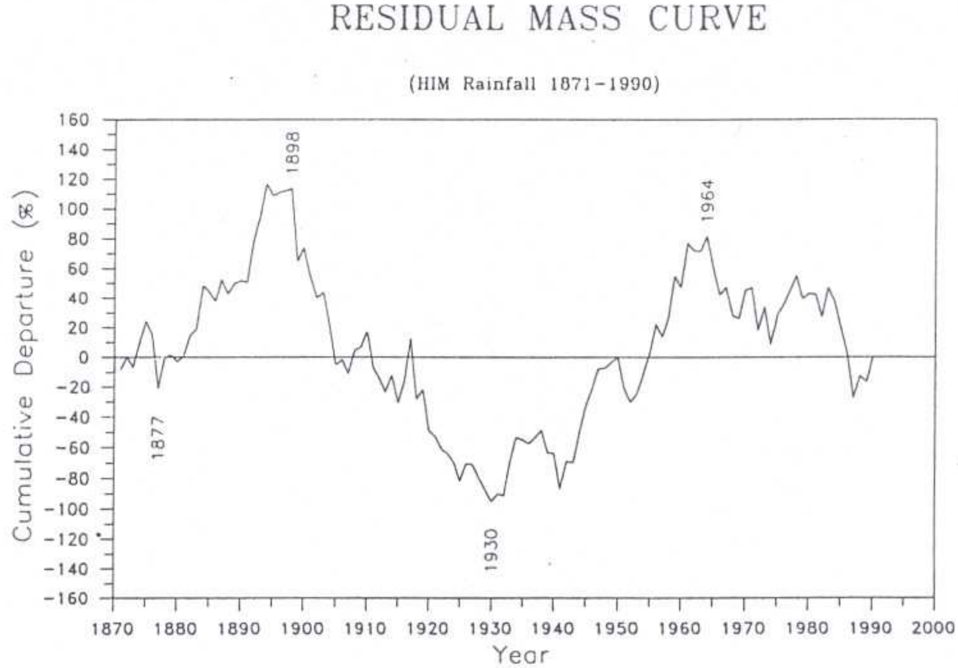

Figure 3. Residual mass curve of HIM rainfall for the period 1871–1990.

the HIM region also had dry years or negative rainfall departures, while during HIM wet years about 90% of sub-divisions had wet years or positive rainfall departures. This further supports the spatial representativeness of the monsoon signal contained in HIM rainfall series.

The binomial low-pass (Mitchell *et al* 1966; Tyson *et al* 1975) filtered curve in figure 2 indicates the slow variations in HIM rainfall series. It is generally below the normal rainfall during the period 1899–1930 and 1962–1987 and above during 1874–1894 and 1942–1961. It also shows an increasing tendency from 1899 to 1961. Thus, low-pass filter curve of HIM rainfall series indicates distinct epochs. However, Kraus (1955) and Reynolds (1956) have pointed out that abrupt changes, if any, in rainfall may not show up well in simple time series plot. Such changes can be more effectively brought out by the residual mass curve technique. The residual mass curve analysis involves cumulation of the percentage rainfall departures from long term averages; thus the curve begins and ends with a zero value. From the residual mass curve analysis of HIM rainfall series for 120-year period, 1871–1990 (figure 3), four climatic epochs can be delineated, two with above average rainfall and increasing tendency (1877–98 and 1931–64) and two with below average rainfall and decreasing tendency (1899–1930 and 1965–90). The curve indicates sharp turning points from increase to decrease in the rainfall around the years 1894 and 1961.

Decadal averages and coefficients of variations for the twelve decades (1871–1990) are shown in figure 4. It can be noticed that the decadal averages were above and below the long-term average alternately for the three consecutive decades, showing systematic turning points around the years 1900, 1930 and 1960. It is interesting to note that low decadal averages of rainfall are associated with high CV and vice versa, except for the decade 1921–30 when the mean and CV were both low, with no dry or wet year. Further, the decade, 1891–1900 with high decadal average and high CV has been noticed. The five decades 1901–10, 1911–20, 1961–70, 1971–80 and

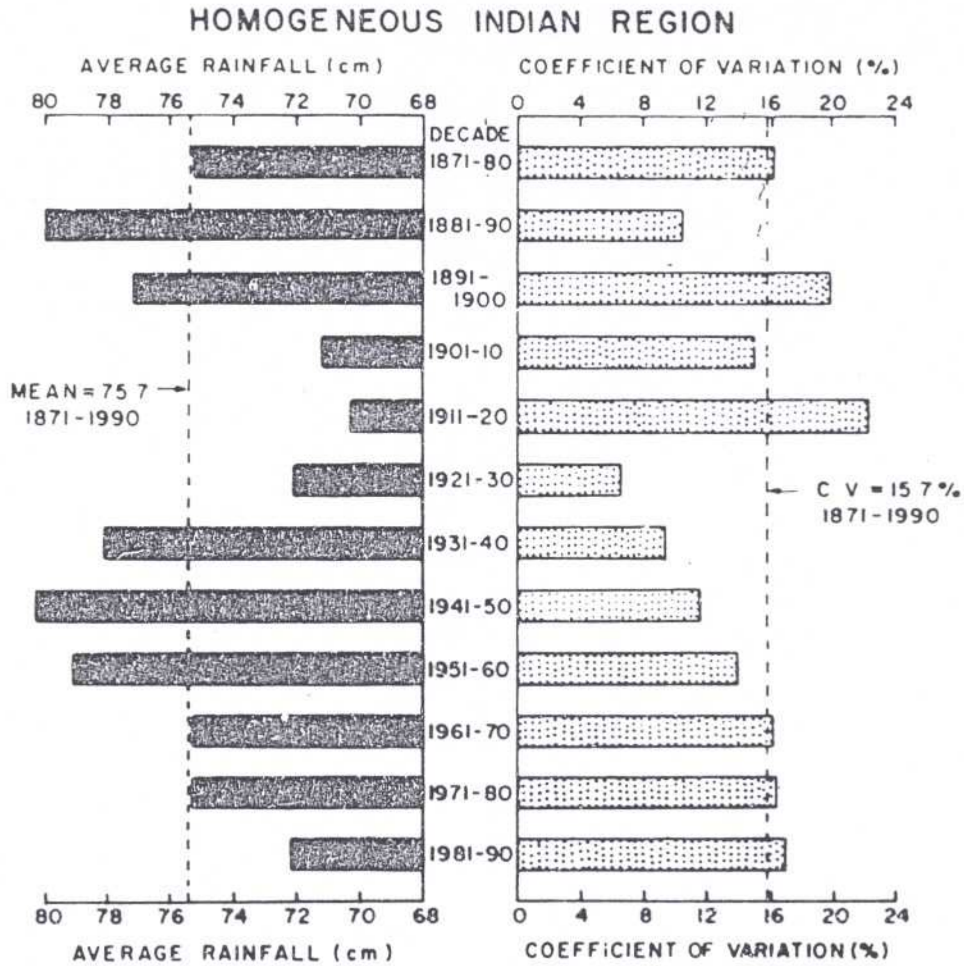

Figure 4. Decadal averages and coefficient of variations for HIM rainfall for the period 1871–1990.

1981–90 experienced relatively more dry years. The present three decades (1961–90) constitute the longest spell of below-normal average with higher CVs during the data period. During this 30-year (1961–90) period, the country experienced 10 dry and 6 wet years. Thus, it can be seen that the country has been passing through a critical rainfall epoch in the current 30-year period.

The HIM rainfall series has been subjected to power spectrum analysis following the Blackman-Tukey algorithm (Mitchell *et al* 1966) to identify significant periodicities. The 14th auto-correlation is significant at 5% level indicating the presence of 14-year cycle in the series. The power spectrum showed only one peak significant at 5% level, corresponding to Quasi-Biennial-Oscillation (2–3 years). However this cycle accounts for only about 10% of the total variance and therefore is of limited practical application.

7. Regional and global teleconnections of HIM rainfall series

Correlation Coefficients between the various regional/global circulation parameters and HIM rainfall were computed for the period 1951–80 (table 6). Their statistical

Table 6. Inter correlation (R*100) among the parameters (regional/global circulation) and HIM rainfall for the data period 1951–1980.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Parameters	HIM	$\times_1$	$\times_2$	$\times_3$	$\times_4$	$\times_5$	$\times_6$	$\times_7$	$\times_8$	$\times_9$	$\times_{10}$	$\times_{11}$	$\times_{12}$
1 Homogeneous India (HIM)	100												
Condition over Indian region													
2 Bombay pressure MAM-DJF: $\times_1$	$-67^{\$}$	100											
3 500HPa ridge at 75E April: $\times_2$	$67^{\$}$	$-46^{\$}$	100										
4 WCI temperature MAM: $\times_3$	$59^{\$}$	$-49^{\$}$	$49^{\$}$	100									
Cross equatorial flow over Indian Ocean													
5 Agalega pressure MAM-DJF: $\times_4$	-42^{*}	$51^{\$}$	-17	-22	100								
6 Nouvelle-agalega MAM-DJF: $\times_5$	$-51^{\$}$	$-30^{\dagger}$	35^{*}	26	-25	100							
7 SST of Indian ocean MAM: $\times_6$	$53^{\$}$	$-51^{\$}$	$32^{\dagger}$	$51^{\$}$	-23	22	100						
El Nino and southern oscillation													
8 Darwin pressure MAM-DJF: $\times_7$	$-62^{\$}$	$79^{\$}$	$-47^{\$}$	$-51^{\$}$	$55^{\$}$	-14	$-55^{\$}$	100					
9 Tahiti-Darwin MAM-DJF: $\times_8$	44^{*}	$-73^{\$}$	$46^{\$}$	43^{*}	$-52^{\$}$	22	40^{*}	$-83^{\$}$	100				
10 SST of Pacific Ocean MAM-DJF: $\times_9$	$-54^{\$}$	$48^{\$}$	-41^{*}	$-66^{\$}$	$32^{\dagger}$	-18	$-63^{\$}$	$59^{\$}$	-44^{*}	100			
Other related parameters													
11 NH temperature J + F: $\times_{10}$	$54^{\$}$	$-50^{\$}$	$34^{\dagger}$	$30^{\dagger}$	$-49^{\$}$	00	$54^{\$}$	$-63^{\$}$	37^{*}	-44^{*}	100		
12 S. American pressure MAM-DJF: $\times_{11}$	-39^{*}	$32^{\dagger}$	-10	-29	$46^{\$}$	-04	-42^{*}	22	03	29	-40^{*}	100	
13 10HPa Balboa wind DJF: $\times_{12}$ (1958–1987)	$45^{\$}$	-16	24	$31^{\dagger}$	-18	$33^{\dagger}$	43^{*}	$-47^{\$}$	$33^{\dagger}$	-39^{*}	06	-26	100

† Significant at 10 percent level.
* Significant at 5 percent level.
$^{\$}$ Significant at 1 percent level.

significance was evaluated after taking into account the serial correlation (or persistence) of the series involved, and adjusting the number of degrees of freedom (Quenouille 1952). All the 12 parameters show very high and significant CCs with the HIM rainfall, as expected. However, it is worth noting here that these parameters are also highly inter related among themselves (table 6).

The lead-lag associations of these parameters with the HIM rainfall were examined by computing CCs of the parameters with three seasonal lags (lag − 3 to lag + 3) on either side of the monsoon season and also MAM-DJF tendency. Their respective composites for dry and wet years were examined to have an idea about the strength of signal. Figures 5 to 8 show the results for four parameters representing the four

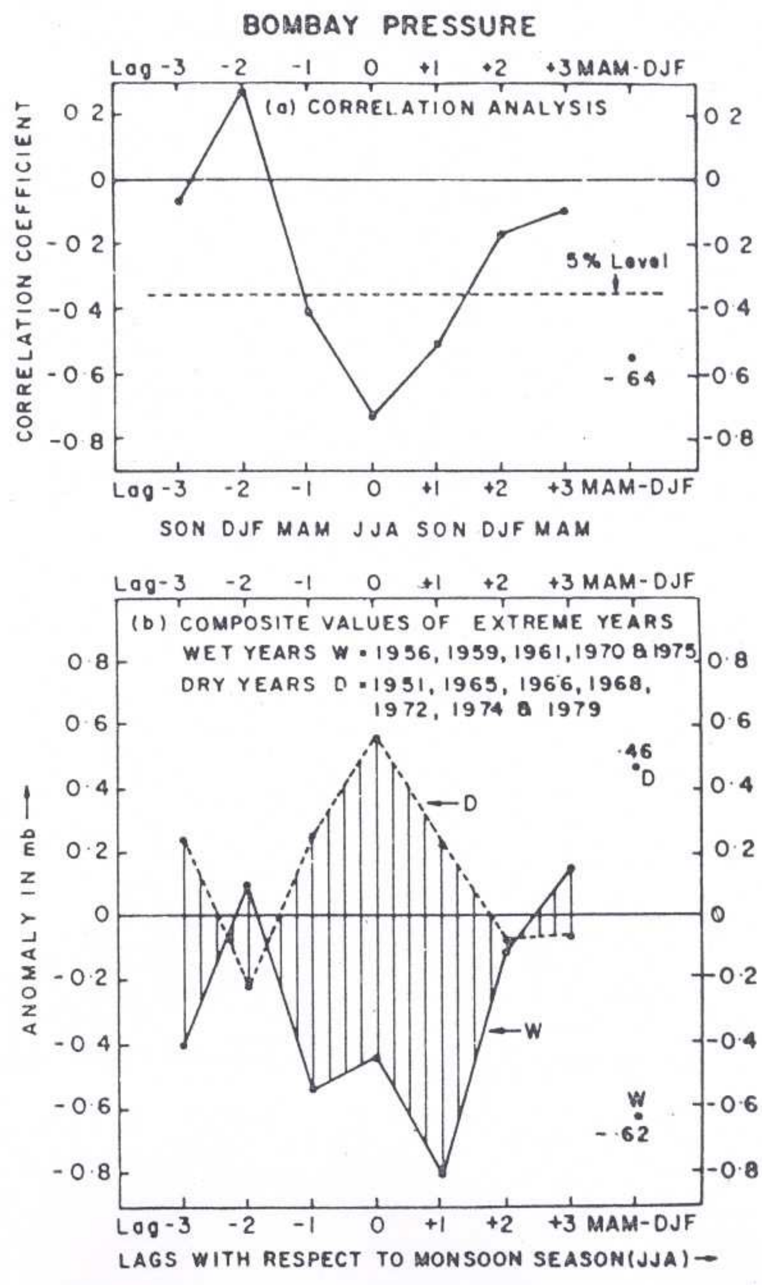

Figure 5. Relationships between HIM rainfall and msl pressure of Bombay for different seasons during the period 1951–80.

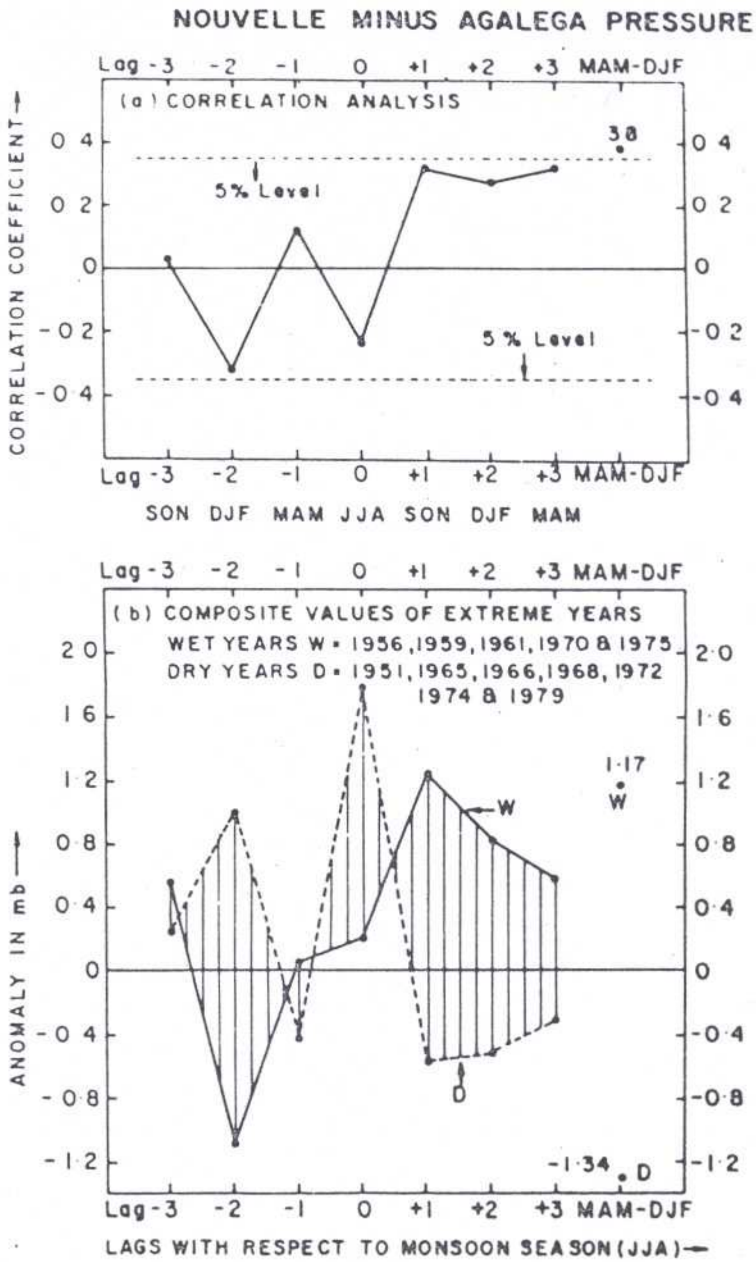

Figure 6. Relationships between HIM rainfall and msl pressure Nouvelle minus Agalega for different seasons during the period 1951–80.

families of predictors: (i) Bombay pressure, (ii) Nouvelle minus Agalega pressure, (iii) Darwin pressure and (iv) Balboa 10 mb zonal wind. The CCs clearly show the marked change in polarity of the relationships as the season changes from winter to spring, in all the pressure parameters. A systematic change in CC values can also be observed as the seasons advance, gradually changing the sign and magnitude before and after monsoon. This systematic variation in the CCs suggests that the large-scale circulation features of the monsoon system may be undergoing a low-frequency transition during anomalous monsoon years. The composite values of the corresponding anomalies for dry/wet years, indicate a good signal of the extreme years of monsoon rainfall

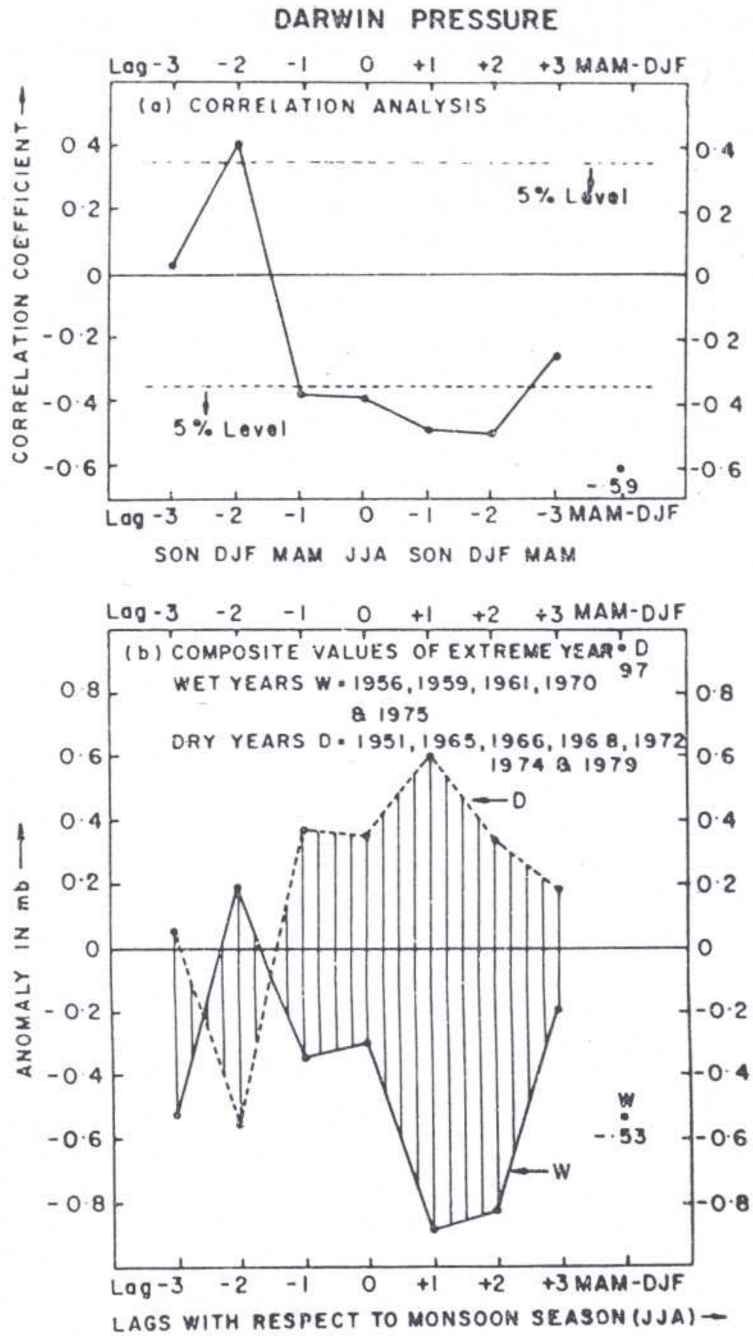

Figure 7. Relationships between HIM rainfall and msl pressure of Darwin for different seasons during the period 1951–80.

during the period. These significant CCs will be helpful for the prediction of HIM rainfall.

Some earlier studies have shown that the relationships between the Indian summer monsoon and its predictors have gone through substantial changes, over a long-period of time (Ananthakrishnan and Parthasarathy 1984; Pant *et al* 1988; Parthasarathy *et al* 1991b). In view of this, we examined the long-term changes in the sliding CCs (Bell 1977) between HIM rainfall and some of its predictors having long records, viz.

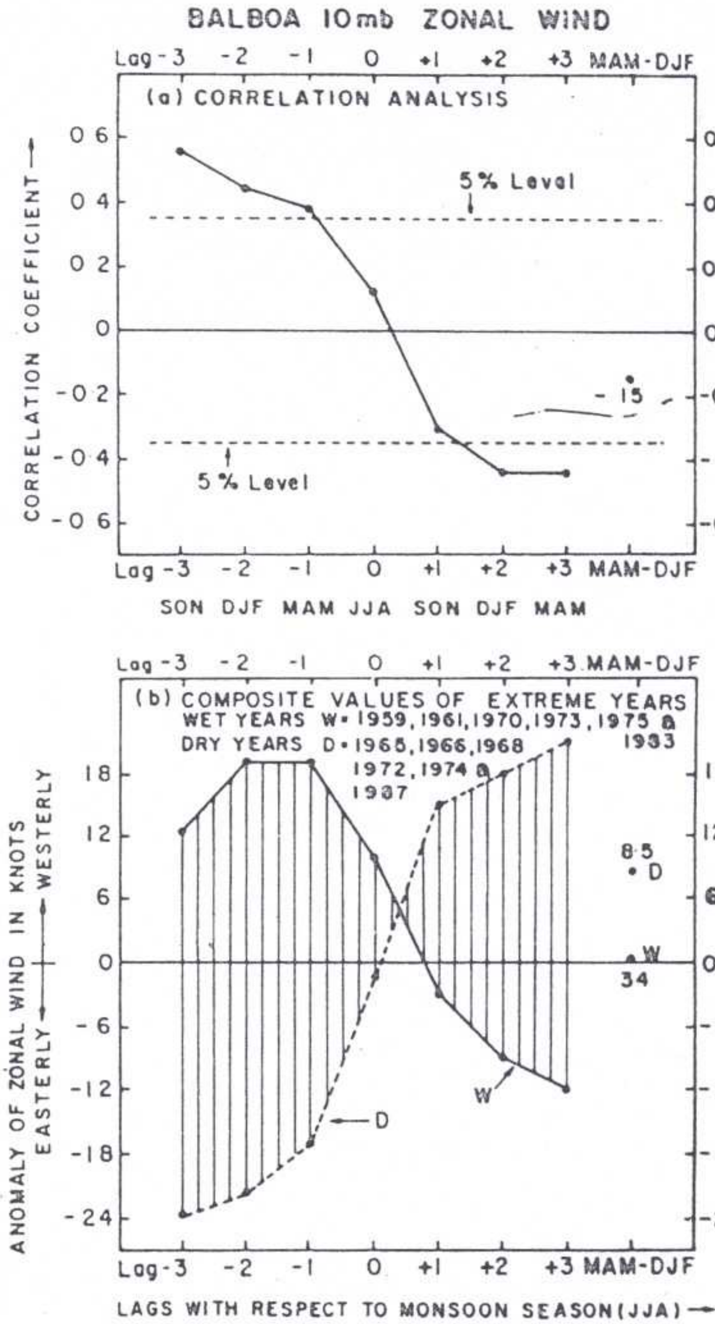

Figure 8. Relationships between HIM rainfall and 10 mb zonal winds of Balboa for different seasons during the period 1958–1987.

(i) Bombay msl pressure, (ii) Darwin msl pressure and (iii) NH temperature using data for the period 1871–1990.

Figure 9 shows the variations of CCs between HIM rainfall and MAM-DJF pressure tendency at Bombay during the period 1871–1990, over sliding windows of widths 11, 21 and 31 years. The CCs are plotted in the central year of the corresponding window. It may be seen that the CCs over windows 11 and 21 years widths are more rapidly fluctuating than those over the windows of 31 years. It is seen that the 31-year sliding width CCs are negative during 1871–1901, positive during 1902–1945 and

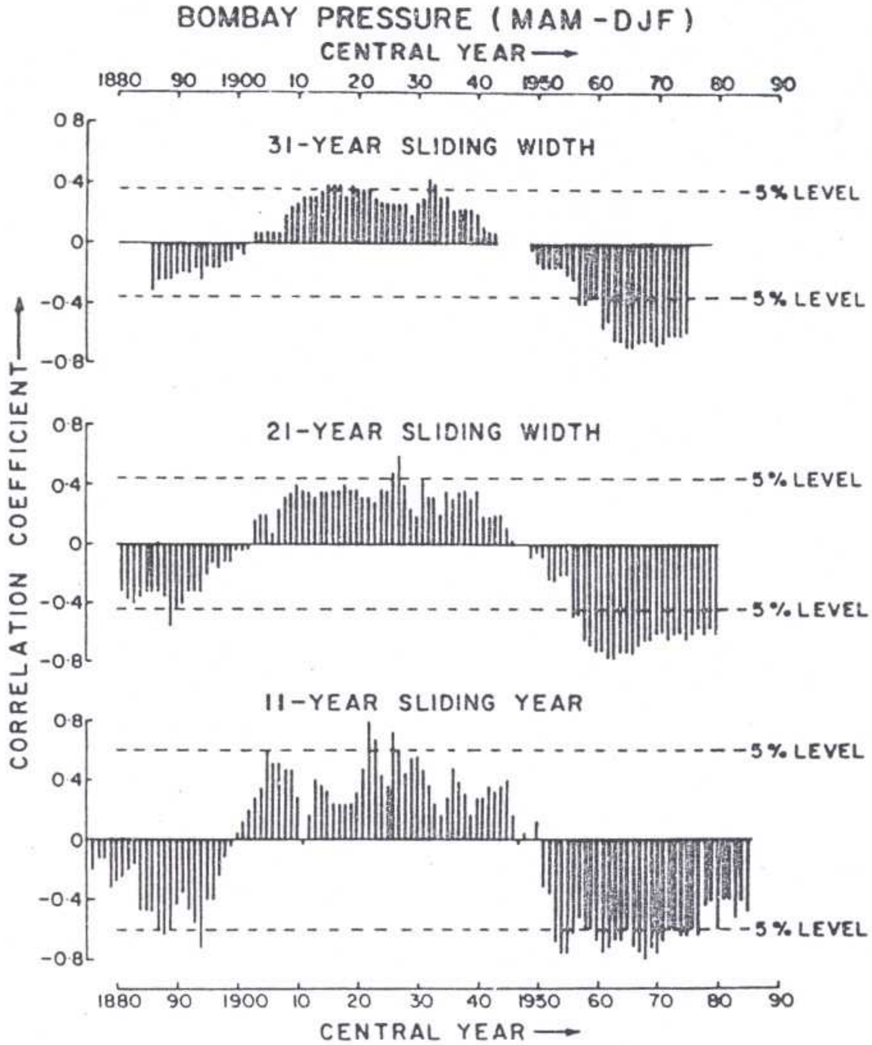

Figure 9. Variation of correlation coefficient over sliding windows of 11, 21 and 31 years between HIM rainfall and msl pressure tendency (MAM–DJF) of Bombay during the period 1871–1990.

again negative during 1946–1990, showing conspicuous turning points of change-over in the signs of CCs around the years 1900 and 1940. These turning points are similar to those observed by Parthasarathy *et al* (1991b) for all-India monsoon rainfall and are temporally coherent with the changes in tropical circulation features noted by Fu and Fletcher (1988) and Eliot and Angell (1987, 1988). It is also argued that these turning points delineate what are called the 'zonal' monsoonal circulation period during 1901–40 and 'meridional' monsoon circulation period during 1940–90. The periods of zonal and meridional monsoons roughly coincide with the low and high epochs of the HIM rainfall series.

The sliding CCs with Darwin MAM-DJF pressure tendency (figure 10) also indicate the above changes, but in a slightly different manner. The 31-year sliding CCs are consistently negative, but they become significant only during 1910–25 and 1960–90. The 11-year sliding CCs have changed sign to positive, around 1900 and 1940 over a few windows.

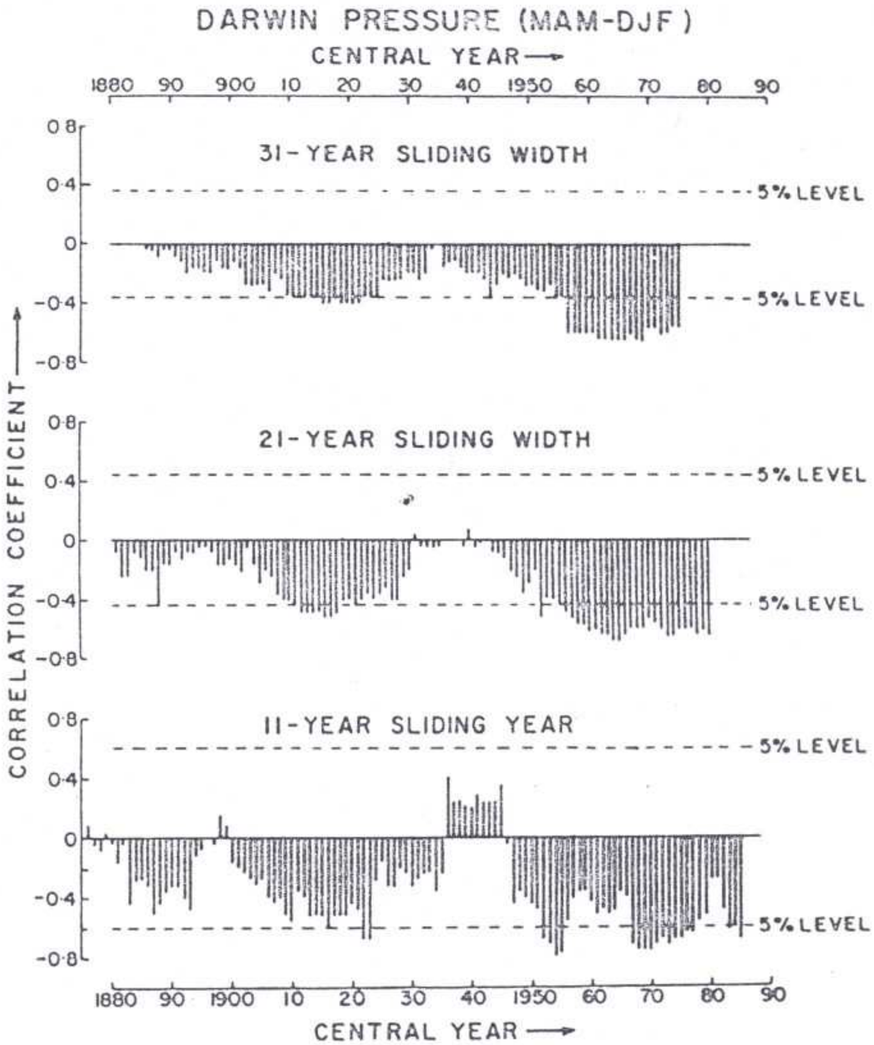

Figure 10. Variation of correlation coefficient over sliding windows of 11, 21 and 31 years between HIM rainfall and msl pressure tendency (MAM–DJF) of Darwin during the period 1871–1990.

The sliding CCs with NH temperatures for J + F (figure 11) for 31-year sliding width were very small and mostly negative upto 1910, became positive with relatively higher magnitudes but still not significant during 1910–1930, again became very small around 1940 and attained statistically significant positive values only after 1956. It is interesting to see that the 11-year sliding CCs change sign to negative around 1900 and 1940.

On the whole, it can be concluded from the above analysis that while the activity of the Indian summer monsoon is strongly linked to several regional and global parameters, the relationships are subject to considerable low frequency variations which may be partly due to the slow changes in the large-scale climatic regimes encompassing the Indian monsoon (Pant *et al* 1988). It is, however, worth mentioning that most of the regional/global circulation parameters show significant relationships during the recent 3 to 4 decades.

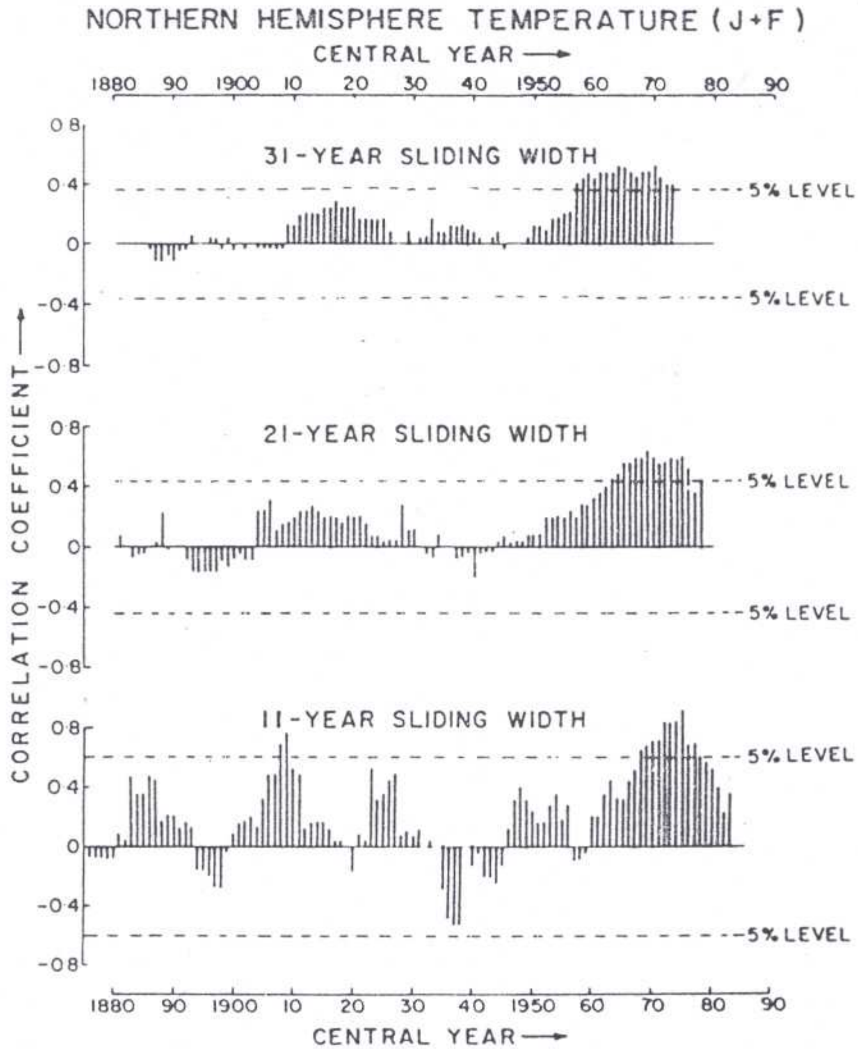

Figure 11. Variation of correlation coefficient over sliding windows of 11, 21 and 31 years between HIM rainfall and Northern Hemispheric surface air temperature for winter (J + F) during the period 1871–1990.

8. Regression models for long-range prediction of HIM rainfall

During the recent years many attempts have been made, notably by Bhalme *et al* (1986); Hastenrath (1987); Shukla and Mooley (1987); Thapliyal (1987); Mooley and Shukla (1987); Gowariker *et al* (1989, 1991); Parthasarathy *et al* (1988, 1990a, 1991a) and Srivastava and Singh (1993), to develop multiple regression equations for long-range prediction of Indian (All-India) monsoon rainfall based on a variety of regional/global parameters. Here we present some regression models for predicting the HIM rainfall, using the 12 parameters discussed earlier, for different periods during 1951–86.

The regression coefficients are calculated by stepwise multiple linear regression procedure, following the algorithm developed by Jennrich (1977). The entry of a variable into the equation is determined by its F-value being significant at 5% level. This screening technique effectively controls the problem of multi-collinearity among

Table 7. Regression models for long-range prediction of HIM rainfall (mm).

No	Period	No. of year	Multi-ple CC	F value	Constant	Regression coefficients with their variance contribution in paranthescs 1	2	3	4
1.	1951–75	25	0·8545	19·0	761·87	Bombay −49·99 (54·9)	Ridge +46·52 (10·7)	S. Amer −43·50 (7·5)	—
2.	1956–80	25	0·8868	18·4	765·40	Bombay −30·24 (42·9)	Ridge +30·62 (16·5)	NH temp +51·63 (11·5)	Nov-Aga +53·28 (7·7)
3.	1961–85	25	0·8147	13·8	768·71	Bombay −47·13 (39·8)	Ridge +50·51 (18·8)	Indian SST +110·90 (7·7)	—
4.	1951–80	30	0·8502	16·3	768·05	Ridge +38·57 (44·8)	Bombay −31·36 (16·5)	NH Temp +34·92 (5·8)	Nov-Aga −37·44 (5·2)
5.	1956–85	30	0·7956	14·9	768·07	Bombay −53·04 (44·3)	Ridge 46·41 (13·4)	S Amer −29·82 (5·6)	—
6.	1951–86	36	0·7925	18·0	763·38	Bombay −45·53 (44·3)	Ridge +41·17 (13·6)	Pacific SST −61·27 (4·9)	—
7.	1951–80	30	0·8441	21·5	768·03	PC1 −42·45 (60·8)	PC5 +36·09 (5·4)	PC4 +27·98 (5·1)	—

Note: All multiple CCs are significant above 0·1% level.
All regression coefficients are significant above 5% level.

the predictors (table 6). Out of the 12 parameters which are highly related with the homogeneous Indian monsoon rainfall for the period 1951–86, only 3 to 4 were ultimately entered into the final equation, depending upon the time interval used. Table 7 gives the details of parameters entering the equation and total variance explained by the parameters with F-ratio. The regression equations explain about 60% to 80% of the variance, involving mainly the parameters (i) Bombay pressure, (ii) April Ridge, (iii) NH temperature (iv) Nouvelle minus Agalega pressure and (v) South American pressure. The performance of the different regression models was tested on independent data points; in general, the estimated and actual HIM rainfall are in good agreement. However, in the years 1961, 1983 and 1986, the prediction errors were relatively more in almost all the models.

In order to further improve the regression model, we subjected 11 circulation parameters (deleting Balboa wind from the predictor set due to shorter data length) to Principal Component Analysis (PCA) and used the components in the regression model. This procedure has also been adopted by Srivastava and Singh (1993) for long-range prediction of Indian monsoon rainfall. Table 8 gives the contribution of the 11 Principal Components (PCs) to the total variance along with their respective factor loadings on the circulation parameters. The first three PCs (PC1, PC2 and PC3) explain 46·4%, 12·5% and 10·2% respectively of the total variance. The first six

Table 8. Factor loadings of the Principal Components (PCs) and variables for the period 1951–80.

Parameters	Principal Components PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11
Variance in percentage accounted by different PCs	46·4	12·5	10·2	9·0	5·7	5·3	4·1	2·7	2·2	1·2	0·8
HIM rainfall (CCs)	−·780	·089	·186	·226	·231	−·007	−·043	−·072	−·117	−·019	−·119
Factors loadings of PCs											
1 Bombay pressure MAM–DJF	·840	−·093	·222	−·061	·061	−·016	·361	·046	·255	−·176	·008
2 500 HPa ridge at 75 E April	−·611	·404	·188	·044	·550	−·289	−·004	·184	·057	·040	−·023
3 WCI temperature MAM	−·700	·132	·456	−·073	−·211	−·324	−·009	−·338	·123	·023	−·010
4 Agalega pressure MAM–DJF	·596	·345	·425	−·447	·104	·127	−·276	−·038	−·137	−·135	·064
5 Nouvelle-Agalega MAM–DJF	−·334	·455	·218	·724	−·006	·298	·060	−·075	−·056	−·090	·016
6 SST of Indian Ocean MAM	−·719	−·146	·358	−·177	−·051	·453	−·125	·133	·227	·088	−·038
7 Darwin pressure MAM–DJF	·889	−·058	·297	·187	·041	−·014	·041	·001	·025	·214	·182
8 Tahiti-Darwin MAM–DJF	−·765	·342	−·427	−·115	−·165	−·038	−·051	·082	·147	−·073	·191
9 SST of Pacific Ocean MAM–DJF	·750	·038	−·353	·200	·227	·037	−·349	−·197	·236	−·003	−·036
10 NH temperature J + F	−·686	−·378	−·130	−·179	·419	·226	·182	−·262	−·060	−·013	·077
11 S. American pressure MAM–DJF	·375	·756	−·240	−·318	−·027	·186	·248	−·103	·013	·129	−·063

PCs put together contribute about 90% of the variance. PC1 shows the highest CC of 0·78 with HIM rainfall and the other components do not show significant CCs. The loading factors of PC1 are almost uniformly distributed over all the eleven parameters, while in PC2 the south American pressure is dominant. In PC3 the WCI temperature, Nouvelle minus Agalega pressure and Tahiti minus Darwin pressure get relatively more weightage and in PC4 the pressure difference of Nouvelle and Agalega dominates. The April ridge shows prominence in PC5 and the Indian ocean SSTs in PC6. The other PCs are less important, their contribution to the total variance being low. These PCs have been used as independent variables in the multiple regression analysis for the period 1951–80. The resultant equation is given in table 7. The first parameter to enter is PC1 which contributes 60·8 of the variance, followed by PC5 and PC4 accounting for about 5% of the variance. The equation has a multiple CC of 0·84 (accounting for 70% of the total variance).

9. Summary

A new Homogeneous Indian Monsoon (HIM) rainfall series has been developed for the period 1871–1990, and its characteristics, and long-term variability studied. Its regional/global teleconnections during 1951–86 have been examined for long-range prediction purposes. The following are the main points of the study:

- Fourteen sub-divisions spread over northwest and central parts of India (about 55% area of the country) showing similar rainfall characteristics and associations with twelve regional/global circulation parameters have been merged to form a Homogeneous Indian Monsoon (HIM) region in order to strengthen the monsoon signal by eliminating the noise component in the All-India monsoon rainfall series.
- The HIM rainfall series for the period 1871–1990 has a mean of 757 mm accounting for 87% of the annual amount, and standard deviation of 119 mm with a CV of 16%.
- There were 21 dry and 19 wet years during this period. Dry years have been found to be more frequent during 1899–1920 and 1965–1987, but, wet years were relatively more well distributed over the period. The present 30-year period (1961–1990) shows very high rainfall variability, with 10 dry and 6 wet years.
- The decadal averages were alternatively positive and negative for three consecutive decades; 1871–1900 (positive); 1901–1930 (negative); 1931–1960 (positive) and 1961–1990 (negative).
- HIM rainfall series shows significant autocorrelation with a lag of 14 years and 2–3 year significant QBO.
- HIM rainfall shows very high and significant CCs with 12 circulation parameters falling into 4 groups of forcings on the monsoon.
- The correlation analysis (for the period 1951–80) between HIM rainfall and circulation parameters upto three lags on either side of the monsoon season indicate a systematic relationship, throwing light on the evolution of the monsoon as a planetary-scale climatic system.
- Sliding correlation analysis between HIM rainfall and some of its predictors over a long period (1871–1990) has indicated systematic turning points delineating the periods 1871–1900 and 1940–1990 having 'meridional' monsoon regime and 1901–1940 having 'zonal' monsoon regime.
- To predict HIM rainfall, multiple regression models have been developed consisting

of 3 to 4 circulation parameters and explaining the 60% to 80% of variance, depending upon the data period used.

- The multiple regression equation based on Principal Components Analysis of the 11 circulation parameters to predict the HIM rainfall consists of three PCs with a multiple CC of 0·84.

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