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VARIABILITY IN SUMMER MONSOON RAINFALL OVER INDIA

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ABSTRACT

Using daily rainfall data for the 30-year period of 1960–1989 and following an objective criterion, the pre-active, active and post-active phases of the summer monsoon (June–September) rainfall are clearly delineated for all-India and homogeneous regions of India. It is seen that on average, the monsoon is active for 103 days over northeast (NE-India) India, for 75–78 days over central-northeast (CNE-India) India and so on for all the regions. Average daily normal rainfall (ADNRF) is at a maximum of 14.7 mm over NE-India and at a minimum of 4.6 mm over NW-India. To investigate possible periodic oscillations in daily rainfall, the daily normal rainfall (DNRF) of all the regions is subjected to power spectrum analysis. This analysis reveals that DNRF exhibits periodicities of 5, 8–12 and 20 days over NE-India, about 5 and 40 days over WC-India, 8–12 and 40 days over NW-India and 8–10 and 40 days over PEN-India. Inter-annual and decadal scale variability of the summer monsoon rainfall over homogeneous regions is studied using the summer monsoon rainfall for the period of 1871–1990. It is discovered that summer monsoon rainfall of WC-India and NW-India is dominated by a quasi-biennial oscillation (QBO), whereas summer monsoon rainfall of NE-India and PEN-India is dominated by ENSO-type periodicities. Epochs of increasing and decreasing rainfall are also observed in the summer monsoon rainfall over homogeneous regions of India.

KEY WORDS: Indian summer monsoon; QBO; ENSO; homogeneous regions; power spectra

1. INTRODUCTION

The Indian summer monsoon rainfall (IMR) is characterized by widespread seasonal rainfall with a high degree of variability, both temporally and spatially. Apart from short-term fluctuations, that is, day to day, or week to month variations, there exists longer time variations that range from a few years even to decades. There are many studies available on the variability of IMR. Some noteworthy studies are Mooley and Parthasarathy (1984), Parthasarathy (1984), Mooley and Shukla (1987), Pant *et al.* (1988) and Parthasarathy *et al.* (1988, 1991, 1995a) etc. Many recent studies in understanding or prediction of seasonal rainfall behaviour over India have focused on the country as one unit, i.e. all-India. For a vast country like India, with inherent spatial variability of monsoon rainfall, it is inevitable that some areas may experience deficient rain, even in the best monsoon years, or some areas of flood, even in the worst monsoon years. However, there are certain regional differences in the monsoon rainfall variability which have important consequences. For example, the rainfall of meteorological subdivisions in the northeastern part of the country is poorly or negatively correlated with the rainfall of the rest of the country. In view of this, the study of the characteristics of monsoon rainfall on a regional scale becomes important. It is well recognized that the rainfall over different subdivisions of India could be grouped together to obtain areal averages for a few homogeneous regions. There are some attempts in this direction; see, for example, Shukla (1987), Gregory (1989), Gadgil *et al.* (1993) and Parthasarathy *et al.* (1995b) etc.

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The economy of India is closely linked with the reliability of the summer monsoon, which gives 70–90% of the annual rainfall in 4 months, from June to September. Timely and well-distributed rain is essential for food production, while the erratic behaviour of the monsoon has an adverse effect on it. Therefore, more concentrated research efforts are required to understand the variability and predictability of monsoon rainfall over India. In view of this, in this paper, an attempt is made to study the intra-seasonal, inter-annual and decadal scale variability of summer monsoon rainfall over all-India, and homogeneous regions of India.

2. DATA

Parthasarathy *et al.* (1995b) grouped 29 meteorological subdivisions of India into five homogeneous regions (Figure 1), and prepared a summer monsoon rainfall (June–September) series for the period of 1871–1990 for all the regions, as well as for all-India. The homogeneous regions are northwest India (NW-India), west-central India (WC-India), central-northeast India (CNE-India), northeast India (NE-India) and peninsular India (PEN-India). These data are used for the study of inter-annual and decadal scale variability of summer monsoon rainfall of all-India and homogeneous regions of India. The homogeneous regions and their areas, expressed as a percentage of the area of India, are given in Table I, column B.

To study the intra-seasonal variability of summer monsoon rainfall of homogeneous regions of India, we have used the daily rainfall data of 52 blocks over India (Figure 2) for the period of 1960–1989, as prepared by Kulkarni and Kripalani (1992). From this data set, daily rainfall data for homogeneous regions of India have been prepared for the period of 1960–1989 by averaging the rainfall of all the blocks in the respective region. To check the applicability of the regional daily rainfall for further study, the seasonal rainfall series for the period of 1960–1989 are prepared for all the regions, as well as for all-India, from this daily rainfall. These rainfall series are correlated with the rainfall series, as prepared by Parthasarathy *et al.* (1995b), using monthly rainfall data. In Figure 3, both the rainfall series, as prepared from daily, as well as from monthly rainfall, are plotted for all the regions. It is found that for all the regions, although the rainfall series prepared using daily rainfall are over-estimated, the correlation coefficients are highly significant. It is to be noted, that while preparing the rainfall series of all-India and homogeneous regions of India, Parthasarathy *et al.* (1995b) have not considered the hilly regions of India and, hence, the high rainfall stations located in the hilly regions are omitted. This may be the reason for seasonal rainfall being higher for the homogeneous regions when it was prepared using daily rainfall. From Figure 3, it is seen that there is good agreement of the variability between the two series. As our aim is to study the intra-seasonal variability, we can use the regional daily rainfall with a high degree of confidence.

3. INTRA-SEASONAL VARIABILITY OF THE SUMMER MONSOON RAINFALL

3.1. Pre-active, active and post-active phase of daily rainfall

Daily rainfall is highly variable in space, as well as in time. There are marked variations in the intra-seasonal variability of the daily rainfall from one year to another year. To obtain the broad picture of the daily rainfall variations over the region, the daily normal rainfall (DNRF) is worked out for all the regions for 122 days of the season, from 1 June to 30 September, which is based on daily rainfall for the period of 1960–1989. DNRF for all the homogeneous regions is plotted in Figure 4, which shows that for all the regions DNRF increases for the first few days (pre-active phase), then it is more or less stable for many days (active phase), and then decreases afterwards (post-active phase). To delineate the duration of the pre-active, active and post-active phases of summer monsoon for all the regions, the following procedure is used.

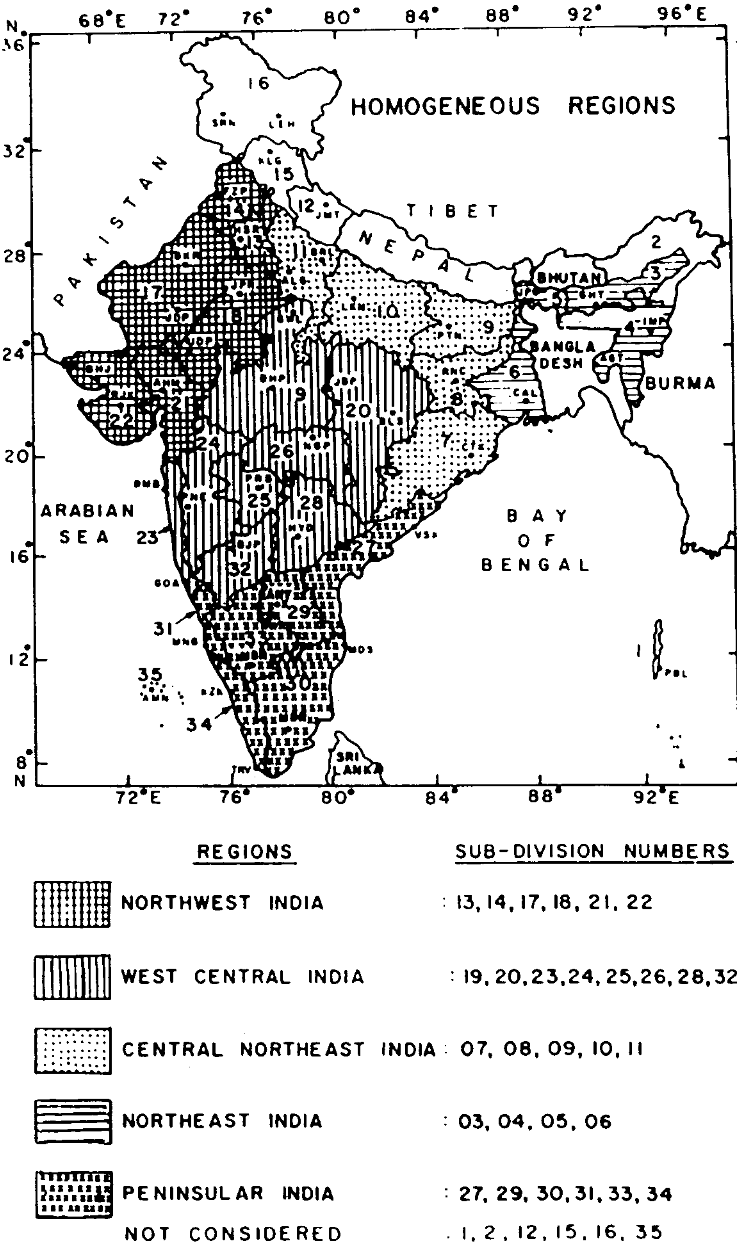


Figure 1. Map showing different homogeneous regions of India

On the basis of the DNRF of 122 days of the summer monsoon season, the average of DNRF is computed (ADNRF), which may be considered as the minimum amount of rainfall/day for the monsoon to be active. The ADNRF is 14.7 mm for NE-India, 8.0 mm for CNE-India, 9.5 mm for WC-India, 4.6 mm for NW-India, 9.2 mm for PEN-India, and 8.6 mm for all-India as one unit. The duration from 1 June up to the day of the first occurrence of DNRF $\geq$ ADNRF is called the pre-active phase, or in a very broad sense, the onset phase of the monsoon. The duration, from the day of the first occurrence of DNRF $\geq$ ADNRF to the day of its last occurrence, is called the active phase of the monsoon, and afterwards, up to the end of the season, it is called the post-active, or in a very broad sense, the withdrawal phase of the monsoon. The duration of the active phase of the summer monsoon for all the

Table I. Area and general statistics of rainfall over homogeneous regions of India

Region	% area of India	Duration of active phase of summer monsoon	Details of summer monsoon rainfall				
			Mean (mm)	% of annual	S.D. (mm)	C.V. (%)	Auto-correlation coefficient lag-1
A	B	C	D	E	F	G	H
NE-India	9.29	5 June–15 September	1419	68.7	121	8.5	0.07
CNE-India	19.90	28 June–13 September	1002	83.3	113	11.2	0.01
WC-India	33.42	22 June–4 September	933	86.3	126	13.5	−0.07
NW-India	22.03	23 June–8 September	490	89.9	132	27.0	−0.08
PEN-India	15.38	6 June–20 August	659	57.0	98	14.9	−0.18
All-India	100	22 June–24 August	852	78.2	85	9.9	−0.12

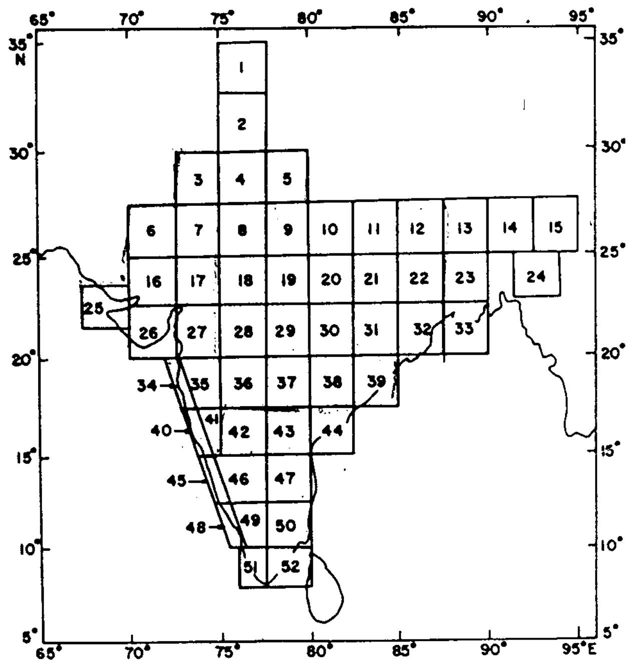


Figure 2. Map showing the locations of 52 blocks of India

regions is tabulated in Table I, column C. It should be noted, however, that for peninsular India during the post-active phase, though rainfall decreases from the first day of the post-active phase, it again shows an increasing tendency after a few days, that is, from about 10 September onwards.

3.2. Periodicities in daily rainfall

Using daily rainfall for the period of 1901–1980 over 52 blocks of India, Singh *et al.* (1992) have found a significant 30–60 day oscillation in the rainfall over west central India.

However, there are lots of year to year variations in the significant spectral peaks. In the present study, to see the overall average feature of periodicities in the daily rainfall over homogeneous regions of India, the DNRF for all the regions is subjected to power spectrum analysis, following the method of Blackman and Tukey (1958) and WMO (1966). The spectrum measures the distribution of variance in a time series over a continuous domain of all possible wavelengths, between infinite wavelength, i.e. trend, and the shortest possible wavelengths, i.e. twice the unit time interval, in this case, 2 days. The data are smoothed

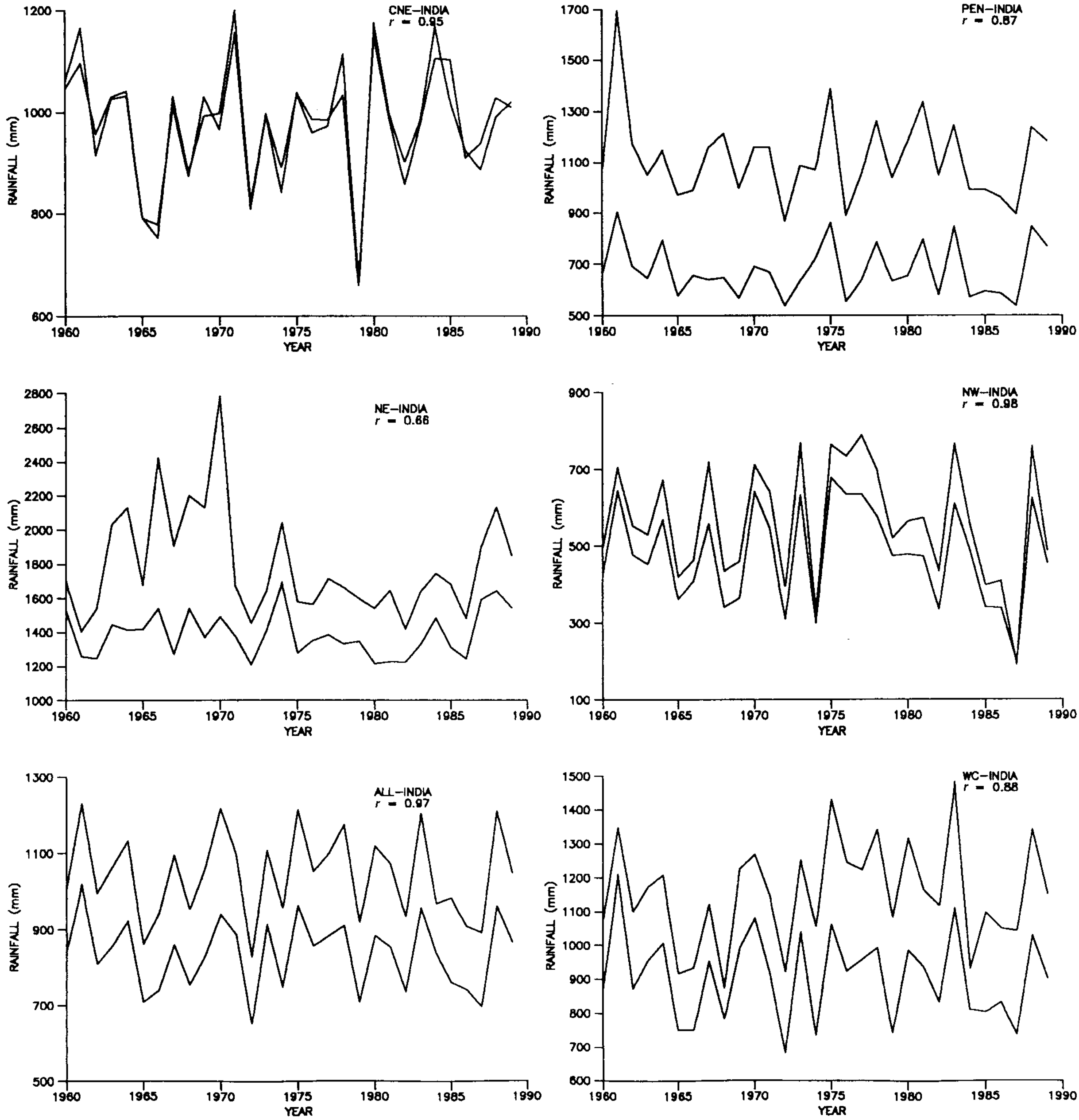


Figure 3. Summer monsoon rainfall series for the period of 1960–1989, prepared from daily rainfall data (upper plot) and from monthly rainfall data (lower plot). *r* denotes the correlation coefficient between them

with a 3-day moving average, which will eliminate high frequency oscillations. The spectra are plotted in Figure 5. The significant periodicities observed in DNRF are tabulated in Table II, column B. It is seen from this table that ADNRF exhibits periodicities of about 5, 8–12 and 20 days for NE-India, about 5 and 40 days for WC-India, as well as for all-India, about 8–12 and 40 days for NW-India, and about 8–10 and 40 days for PEN-India. It should be noted that the above periodicities emerged in the DNRF, which are subject to a lot of variations when we use actual daily rainfall for individual years.

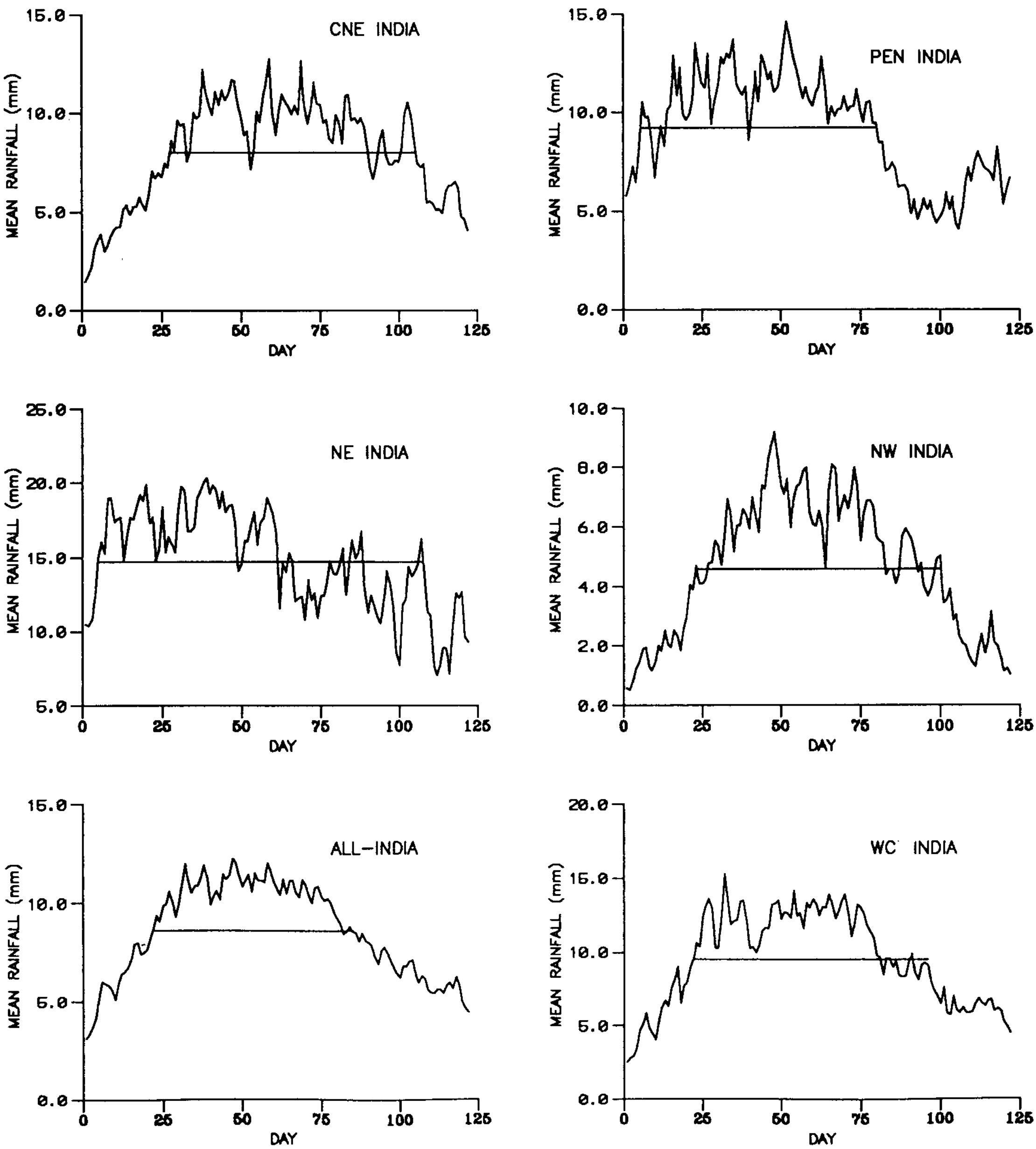


Figure 4. Pre-active, active and post-active phases of summer monsoon rainfall (horizontal line denotes the active phase)

4. INTER-ANNUAL VARIATIONS OF SUMMER MONSOON RAINFALL

So far, we have studied the intra-seasonal variability of DNRF of homogeneous regions of India to obtain the broad picture of intra-seasonal variability of summer monsoon rainfall. In this section, the inter-annual variability of summer monsoon rainfall is studied. For this, the seasonal rainfall series for the homogeneous regions are subjected to statistical analysis and the results are then discussed.

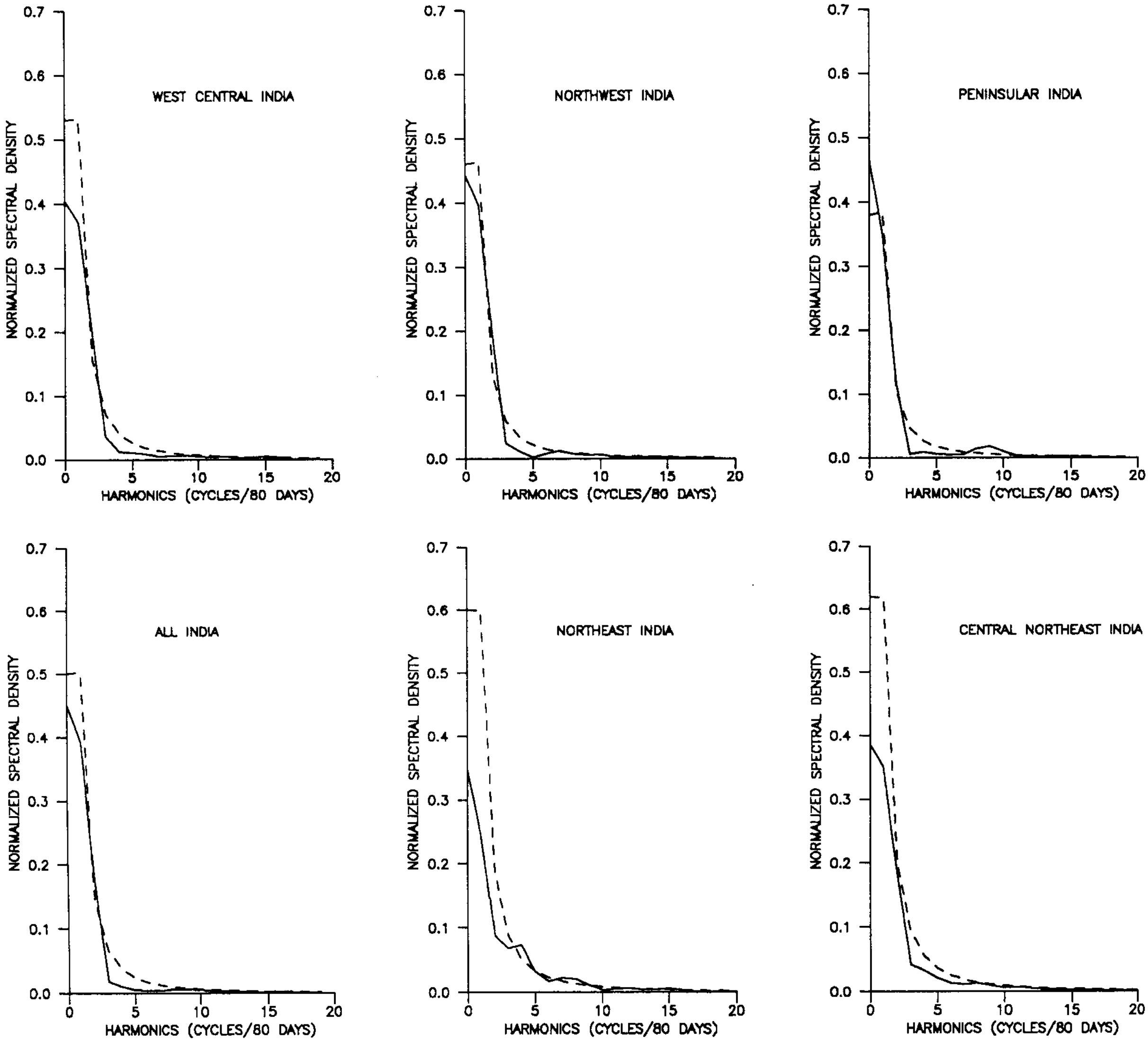


Figure 5. Power spectra of DNRF during summer monsoon season over homogeneous regions of India (--- significant at 5%)

Table II. Spectrum analysis of summer monsoon rainfall over India

Region	Significant periodicities		Auto-correlation coefficient (summer monsoon rainfall)		
	DNRF (days)	Summer monsoon rainfall (years)	Lag-1	Lag-2	Lag-3
A	B	C		D	
NE-India	20, 11.4, 10, 8.9, 5.3	4.71, 4.44, 4	0.07	−0.20	0.05
CNE India	–	–	0.01	−0.04	0.01
WC-India	40, 5.3	2.76, 2.67	−0.07	0.19	0.05
NW-India	40, 11.4, 8	2.76	−0.08	0.02	0.09
PEN-India	40, 10, 8.9, 8	3.64, 3.48, 2.76	−0.18	−0.16	0.02
All-India	40, 5.3	2.76	−0.12	0.04	0.08

4.1. Homogeneity and normality of the rainfall

The homogeneity of the rainfall series is tested by applying the Swed and Eisenhert run test of runs above and below the median. All the series are found to be homogeneous.

The frequency distribution of the series is tested for normality by using the Chi-Square test with equal probability class intervals, as suggested by Cochran (1952). The test shows that the series are Gaussian-distributed.

The auto-correlation coefficients at lag-1 (Table I, column H) are too low to suggest any persistence in the rainfall. Thus, rainfall series for homogeneous regions of India are homogeneous, Gaussian-distributed and free from persistence.

4.2. Statistical details

The statistical parameters, mean, % annual, standard deviation (S.D.), coefficient of variation (C.V.), and auto-correlation coefficient at lag-1 are computed and presented in Table I, columns D–H, which shows that in the summer monsoon season, of all the regions, NE-India receives the maximum amount of rainfall at 1419 mm, with minimum C.V. of 8.5%, whereas NW-India receives a minimum amount of rainfall at 490 mm, with a maximum C.V. of 27%.

4.3. Inter-correlation among the regional rainfall

To discover the relationship between the rainfall series of all the regions, correlation coefficients are computed and tabulated in Table III, which shows that the rainfall of NW-India, WC-India, CNE-India and PEN-India are positively related to each other, whereas rainfall over NE-India is negatively related to rainfall over NW-, WC- and PEN-India. All-India rainfall is positively related to the rainfall of NW-, WC-, CNE- and PEN-India. The correlation coefficients are highly significant. There is no relationship between all-India rainfall and NE-India rainfall, a fact known to Indian meteorologists for quite some time.

4.4. Excess and deficient rainfall years

The rainfall of India exhibits considerable inter-annual variability. There are always years when the rainfall is excessive or deficient on a large scale. The excessive/deficient rainfall puts serious strain on the Indian economy. Therefore, a study of excessive and deficient rainfall becomes extremely important. In view of this, an attempt is made in this study to identify years of excessive and deficient rainfall. The criteria used to identify the excessive and deficient rainfall years are as follows.

Let R_i be the rainfall of ith year, then if

$$R_i \geq \bar{R} + \text{S.D.}$$

the year is called an excess rainfall year, and if

$$R_i \leq \bar{R} - \text{S.D.}$$

Table III. Correlations among summer monsoon rainfall of homogeneous regions of India

Region	NW-India	WC-India	CNE-India	NE-India	PEN-India	All-India
NW-India	1.00					
WC-India	0.699	1.00				
CNE-India	0.243	0.390	1.00			
NE-India	−0.138	−0.202	0.113	1.00		
PEN-India	0.457	0.515	0.095	−0.062	1.00	
All-India	0.822	0.909	0.579	0.002	0.607	1.00

the year is called a deficient rainfall year, where $\bar{R}$ and S.D. are the mean and standard deviation of the rainfall series. Thus, if standardized rainfall [i.e. $(R_i - \bar{R}|\text{S.D.}]$ is ≥ 1.0, the rainfall is excessive, and if it is ≤ -1.0, the rainfall is deficient. Figure 6 shows summer monsoon rainfall series for all the regions for the period of 1871–1990. In this figure, $\bar{R}$ represents the mean rainfall, $\bar{R} + \text{S.D.}$ represents rainfall equal to the mean plus one S.D., and $\bar{R} - \text{S.D.}$ represents the rainfall equal to the mean minus one S.D.; the vertical bar represents the rainfall in units of % departure. The year above the vertical bars represents the excessive/deficient rainfall year. The smoothed line represents the low-pass-filter curve. A five-point Binomial low-pass-filter is used to smooth the rainfall series (WMO, 1966).

The smoothed rainfall S_i is given by

$$S_i = 0.06\ R_{i-2} + 0.25\ R_{i-1} + 0.381\ R_i + 0.25\ R_{i+1} + 0.06\ R_{i+2}$$

Figure 6 is self-explanatory and readers may obtain information regarding the number of excessive and deficient rainfall years, occurrence of a consecutive 2 or more excessive/deficient rainfall years and the behaviour of the low-pass-filter curve etc. from the figure[1].

4.5. Periodicities in the rainfall series

Mooley and Parthasarathy (1984) have shown significant periodicity of 2.8 years in the all-India summer monsoon rainfall series. Krishna Kumar (1997), in his PhD thesis, discovered quasi-biennial oscillation (QBO) and ENSO-type periodicities in the rainfall series over homogeneous regions of India. For the interest of the readers, these periodicities are recalculated and the results are presented here. For this, the rainfall series, all-India and homogeneous regions of India, are subjected to power spectrum analysis, as described in Section 3.2. The spectra are shown in Figure 7. To see the persistence in the series, auto-correlation coefficients are calculated up to lag-3. The results are tabulated in Table II, columns C and D.

Auto-correlation, up to lag-3, does not show any persistence in the rainfall series for any region. The significant cycles emerging out are 2–3 years, which may be attributed to QBO for all-India as one unit, and for NW-, WC- and PEN-India. In NE- and PEN-India rainfall series, 3–5-year cycles are observed, which may be attributed to ENSO. There is no significant periodicity in the CNE rainfall series. It can be concluded that rainfall over NW- and WC-India is dominated by QBO, whereas NE- and PEN-India is dominated by ENSO.

5. DECADAL VARIABILITY IN THE SUMMER MONSOON RAINFALL

To investigate the decadal/multi-decadal variability in the summer monsoon rainfall, 30-year moving mean (expressed as % of departure from whole period mean) and 30-year moving S.D.s (expressed as departure from whole period S.D.) are computed and plotted in Figure 8. For all-, NW- and WC-India the rainfall was below normal from 1895 to about 1930, and above normal from about 1930 to about 1965, with reduced variability. For NE-India, the durations of the above normal and below normal rainfall are approximately 1905–1960 and 1960 onwards, whereas for CNE-India, these durations are approximately 1920–1950 and 1950 onwards, respectively. For PEN-India, the rainfall was below normal during 1920–1945 and above normal from then onwards.

6. SUMMARY AND CONCLUSIONS

In this paper, on the basis of DNRF, the pre-active, active and post-active phases of the summer monsoon are clearly delineated for homogeneous regions of India. It is seen that, on average, the monsoon is active for 103 days over NE-India (5 June–15 September). It is active for 75–78 days for CNE-India (28 June–13 September), WC-India (22 June–4 September), PEN-India (6 June–20 August)

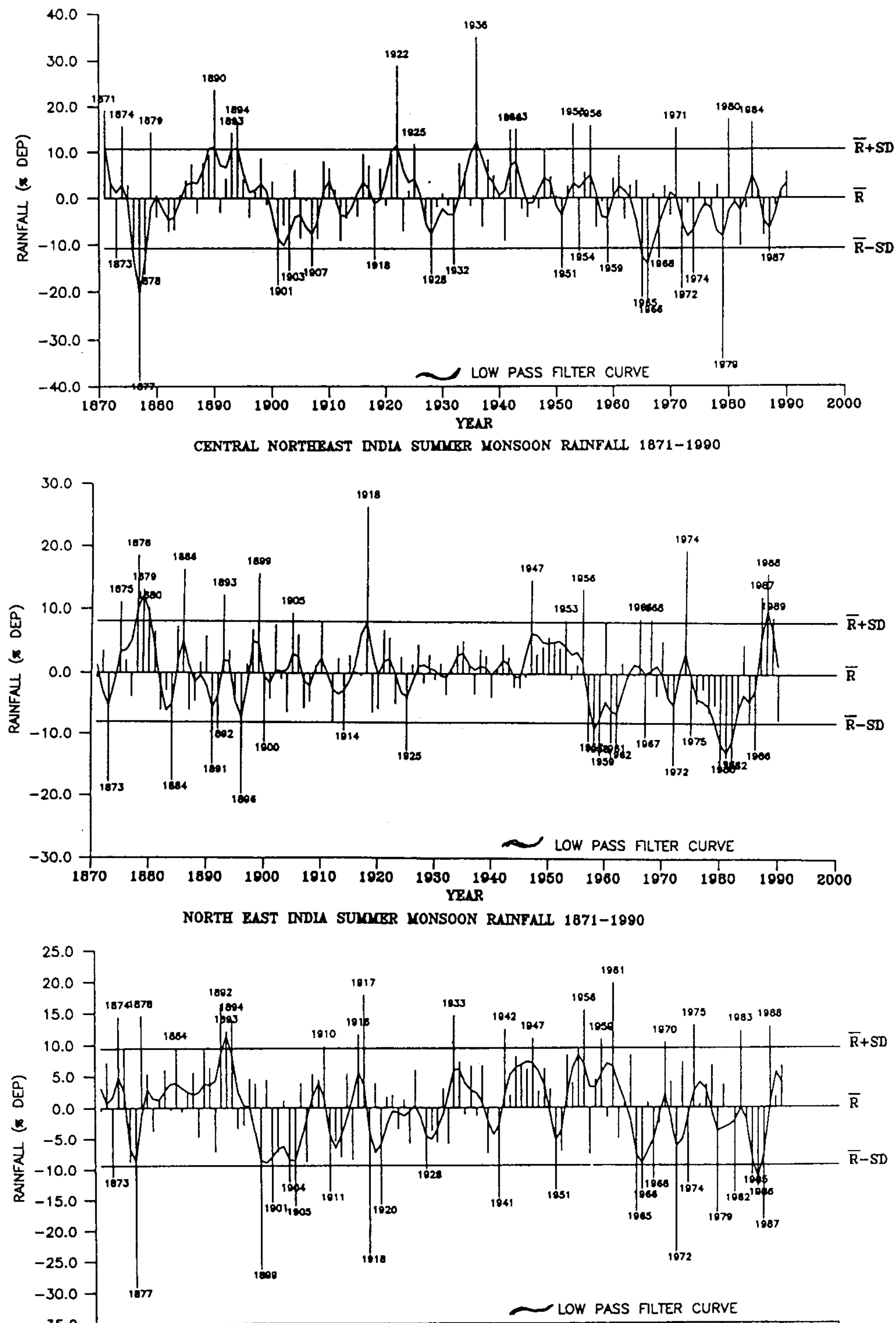
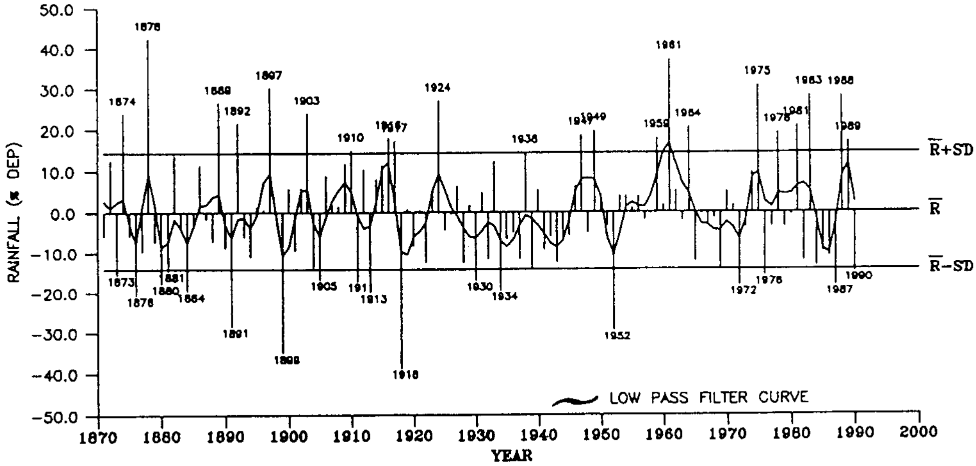
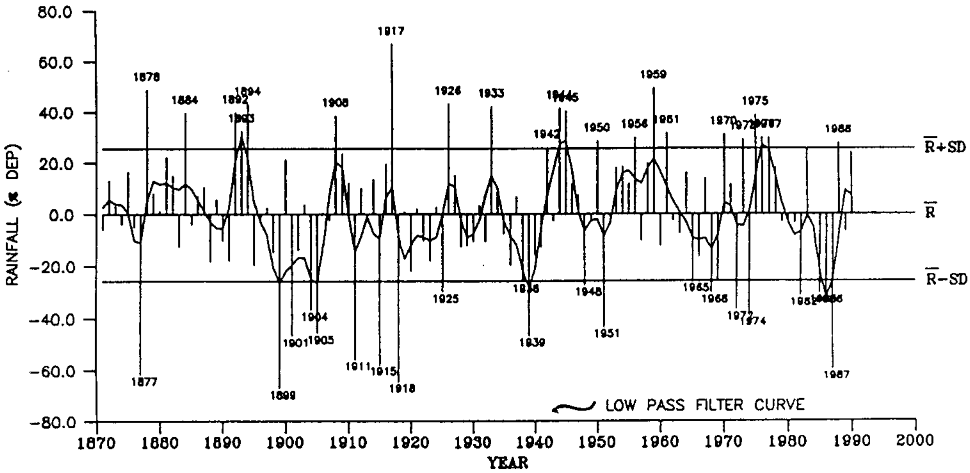


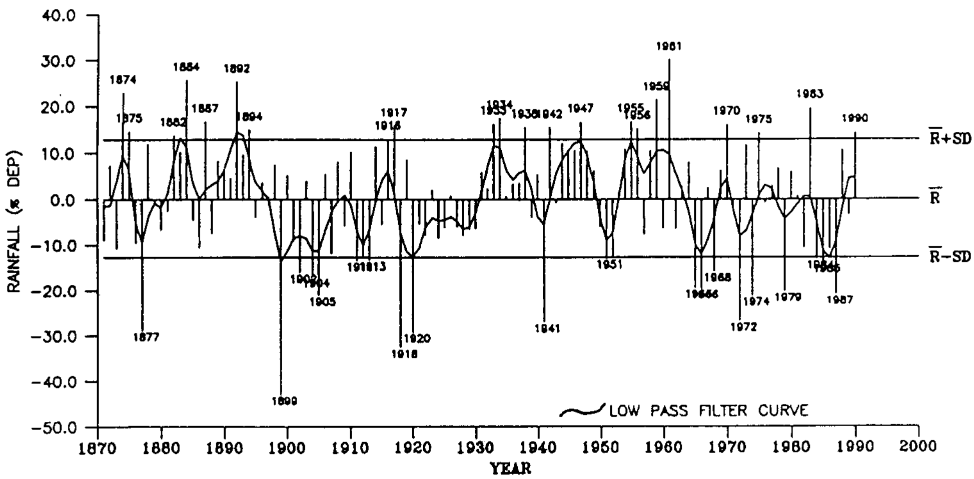
Figure 6. Summer monsoon rainfall series for homogeneous region of India: 1871–1990



PENINSULAR INDIA SUMMER MONSOON RAINFALL 1871–1990



NORTH WEST INDIA SUMMER MONSOON RAINFALL 1871–1990



WEST CENTRAL INDIA SUMMER MONSOON RAINFALL 1871–1990

Figure 6 (*Continued*)

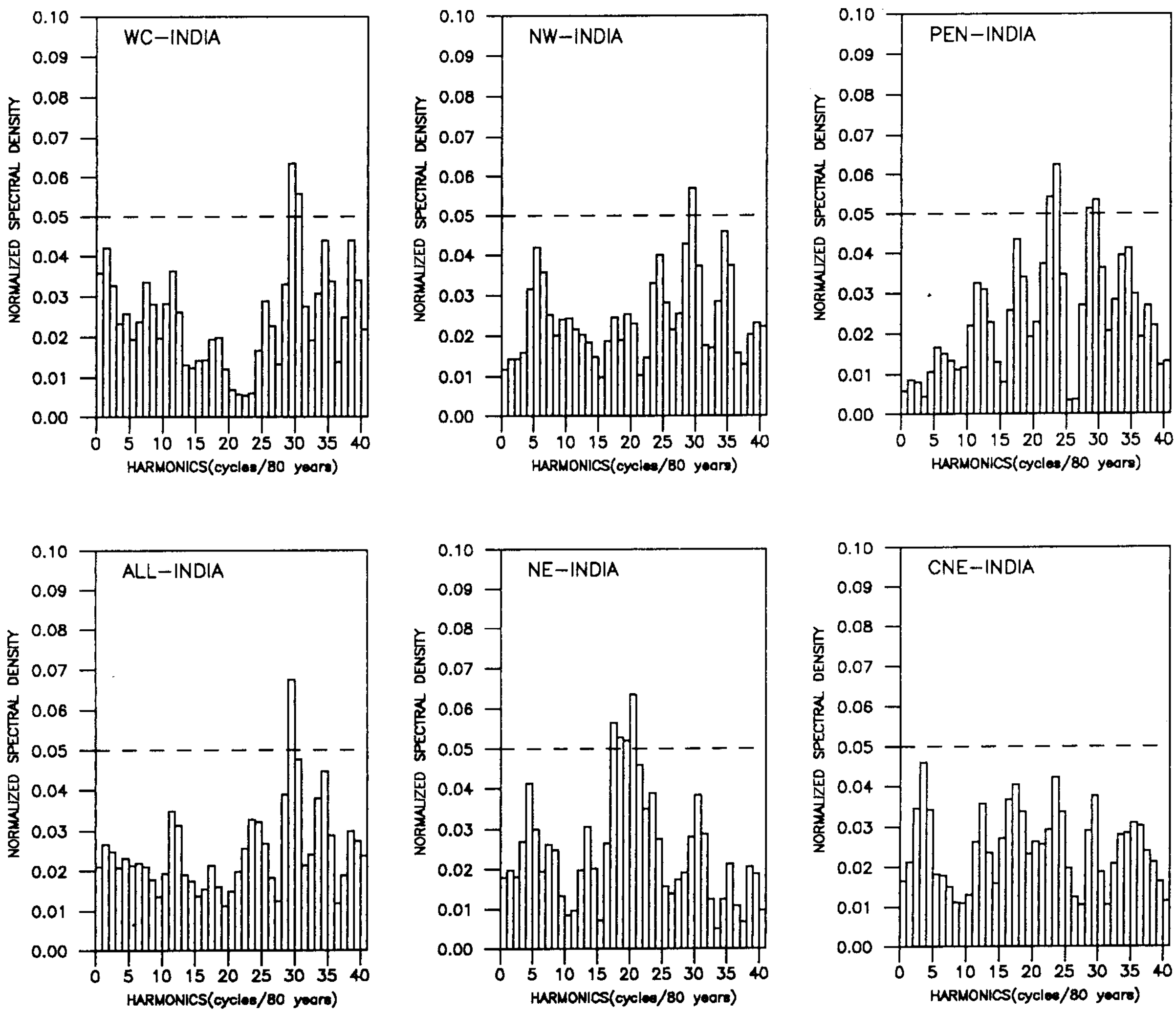


Figure 7. Power spectra of summer monsoon rainfall over homogeneous regions of India. Dashed line shows spectral estimates significant at 5% level

and NW-India (23 June–8 September). For all-India, the monsoon is active for 64 days (22 June–24 August). Although the number of days of the active phase are almost equal for CNE-, WC-, PEN- and NW-India, the magnitude of ADNRF varies from 9.5 mm for WC-India to about 4.6 mm for NW-India.

ADNRF exhibits periodicities of about 5, 8–12 and 20 days for NE-India, about 5 and 40 days for WC-India, as well as for all-India, about 8–12 and 40 days for NW-India, and about 8–10 days and 40 days for PEN-India.

Summer monsoon rainfall over NW- and WC-India is dominated by QBO, whereas rainfall over NE- and PEN-India is dominated by ENSO-type periodicities.

Analysis of decadal scale variability of summer monsoon rainfall brings out the epochs of increasing and decreasing rainfall over homogeneous regions of India.

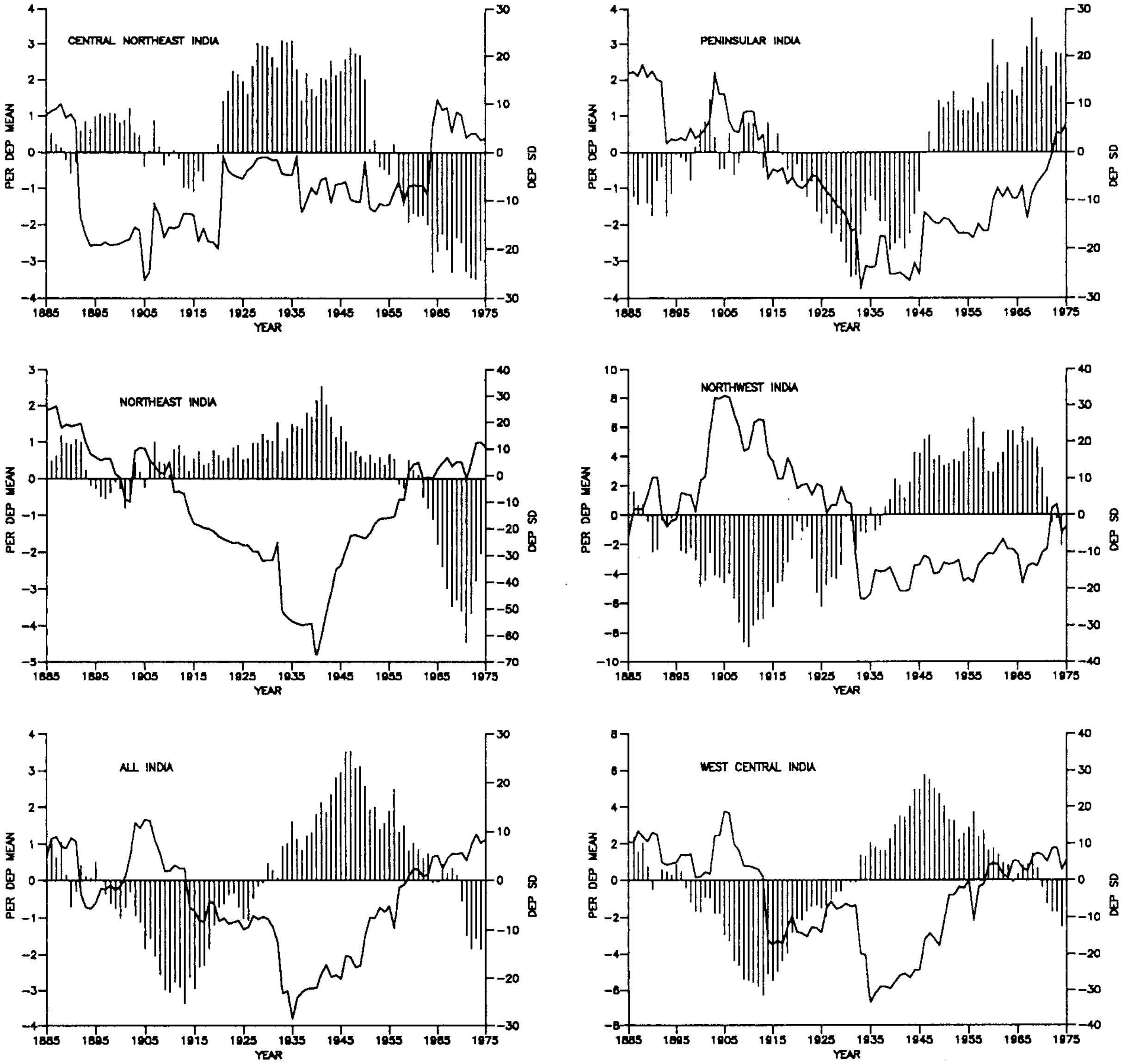


Figure 8. 30-year moving average rainfall (vertical bars), expressed as % departure from whole period mean, and 30-year moving S.D. (continuous line), expressed as departure from whole period S.D., plotted against the central year of the period

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NOTES

1. The rainfall data for homogeneous regions of India are available at http://www.tropmet.ernet.in

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