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# ON THE VARIABILITY AND PREDICTION OF RAINFALL IN THE POST-MONSOON SEASON OVER INDIA

NITYANAND SINGH* and N.A. SONTAKKE
*Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune-411 008, India*

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## ABSTRACT

Considerable rainfall occurs in India during the post-monsoon period from October to December, particularly over north-eastern, eastern and southern regions, and this is of great significance in agricultural and allied sectors. For the first time, we have attempted to provide detailed information on the variability and predictability of the post-monsoon rainfall (PMR) of the country. Details on the summer monsoon rainfall from June to September are extensively documented. This study comprises four sections: (i) examination of large-scale rainfall features; (ii) examination of small-scale (or regional) rainfall features; (iii) diagnostic study in order to identify possible regional forcings and global teleconnections; and (iv) modelling long-period rainfall series and extrapolation of future trends for the next 10 years.

To understand large-scale features from year-to-year, expansion/contraction of the wet area (October–December rainfall $\geq 200$ mm) was examined, involving data from 306 well-separated locations spanning 114 years (1871–1984). The post-monsoon wet area (PMWA) series (1871–1984) is homogeneous, but its interannual variations are quite large. In the low-frequency mode fluctuations however, some distinct wet/dry epochs can be identified that are broadly consistent with the wet/dry epochs of summer monsoon fluctuations, implying that the same forcing factors affect the large-scale rainfall activities of both periods. Variations in the regional rainfall were studied in order to provide some useful information for practical purposes. The longest-possible instrumental period from the October to December rainfall series for each of the six zones of the country was reconstructed by applying the objective optimization technique to the limited observations available. Rainfall series were produced for the following regions of India, the reference period of reconstruction being 1871–1980: northwest India, 1844–1996; North Central India, 1842–1996; northeast India, 1829–1996; West Peninsular India, 1841–1996; East Peninsular India, 1848–1996; and South Peninsular India, 1813–1996. The characteristics of different zonal series are documented; they do not possess a significant long-term trend, and are weakly correlated. The longest-possible all-India October–December rainfall series (1813–1996) has also been reconstructed, since it can be easily updated using the same optimum set of 116 India Meteorological Department (IMD) raingauge stations that are used for the six-zonal series; the PMWA series (1871–1984) would require the data from all 306 raingauges. The correlation between the PMWA and the all-India rainfall series is 0.92.

To identify possible causes of rainfall variation, correlation of zonal, as well as all-India series, with 20 selected regional/global circulation parameters was examined. Correlation, albeit weak, of particularly large-scale features with the Southern Oscillation, El Niño, Quasi-Biennial Oscillation and surface air temperature was found to be of the same sign as that found with the large-scale features of the summer monsoon. This provided support for the previously reported theory that the sources of variation in the occurrence of rainfall during the two periods are the same.

In the fourth section, different zonal and all-India series are subjected to time series analysis. A flexible approach, singular spectrum analysis (SSA), was applied first to smooth out the predictable portion of the low-frequency mode variation in the individual series. Variable harmonics of the smooth series were then estimated at a wavelength resolution of 0.1 year. A subset of a few variable harmonics was objectively identified whose combination was extrapolated to enable prediction of future trends of PMR patterns across India over a 10-year period. There are differences in the future rainfall trend over different parts of the country. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: Indian post-monsoon rainfall variations; optimum rainfall observations; El Niño; Southern Oscillation; Quasi-Biennial Oscillation; time series modelling; singular spectrum analysis; variable harmonic analysis; extrapolation; prediction

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* Correspondence to: Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune-411 008, India. Fax: +91 212 347825; e-mail: nsingh@tropmet.ernet.in

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## 1. INTRODUCTION

According to the India Meteorological Department (IMD) classification of the seasons, the three months October, November and December constitute the ‘post-monsoon season’, otherwise known as the ‘retreating southwest monsoon season’ or the ‘northeast monsoon season’. Considerable rain occurs during this period, particularly over north-eastern, eastern and southern parts of India, and its interannual variability is quite large, which drastically affects agricultural activities and other water-based enterprises. Compared to summer monsoon circulation and rainfall from June to September, only a few broad studies have attempted to understand the post-monsoon rainfall (PMR) of the Indian region *vis à vis* features of atmospheric circulation. Those which have attempted to understand some features of rainfall are Krishna Rao and Jagannathan (1953), Rao and Raghavendra (1971), Dhar and Rakhecha (1983), Krishnan (1984), Raj and Jamadar (1990) and Sontakke (1993). Those dealing with rainfall and regional/global circulation features are Doraiswamy Iyer (1946), Ramaswamy (1972), Srinivasan and Ramamurthy (1973), Cadet and Diehl (1984) and Sridharan and Muthusamy (1990). Some of the limitations of these studies on the PMR of India include the use of short-period rainfall data from casually delineated PMR regimes and too intuitive and tentative inferences or conclusions associating rainfall with circulation from a few case studies. In addition, they are difficult to use for further studies and fail to address the circulation and rainfall of the immediately preceding period from June to September, the main rainy season during which the country receives 78% of its annual rainfall.

During October and November, temperatures are highest and pressures lowest in the Bay of Bengal. The retreating monsoon air circulates around the area of low pressure and blows over Tamil Nadu (a meteorological subdivision in the extreme southeast of the country) from a north-easterly direction. This large low pressure system often extends into the Indian Peninsula via a trough and into the central Arabian Sea as a low pressure area. There is a progressive shift southwards of this extended low pressure area towards the end of November or early December (Das, 1992). According to one description during October and November, the intertropical front is reestablished over the Indian Ocean, extending itself laterally from the Pacific during its southward retreat into this Ocean. Apparently, from November to March the north-easterly winds of the Arabian Sea do not spring directly from the Asiatic anticyclone, but gather strength and persistence some distance from the coast. The north-eastern circulation appears first in the central Arabian Sea in October when winds over the Bay of Bengal are ill-defined. By November, a quite well-marked air flow has become established from the Gulf of Cambay (Gujarat, India) towards Agnate, while a parallel movement is increasingly in evidence off the coast of Myanmar. This is in marked contrast with the winter monsoon of the South China Sea, where the frequency of winds from a northerly quadrant is well in excess of 80%. To describe both air streams as the northeast monsoon is to ignore this important contrast (Anonymous, 1943). The circulation over the Arabian Sea and the Bay of Bengal seems to be much more closely analogous in origin, temperature and strength to the northeast trades, which are normal in this latitude. Indeed, the Indian Ocean must be effectively walled off from the Siberian anticyclone by the massive Tibetan Plateau, which is at least twice as high as the anticyclone; the winter circulation therefore can only be fed, like the trades, by subsiding air probably moving in with the usual north-westerly component.

The post-monsoon season of India, particularly the months of October and November, can also be regarded as a transition period between the southwest summer monsoon from June to September and the northeast winter monsoon from December to February. The northeast winter monsoon circulation occurs over East/Southeast Asia and neighbouring areas. The major monsoon convective zone migrates to the maritime continent of Borneo/Indonesia from its summer position over north-eastern India (Ramage, 1975). The two monsoons of the northern hemisphere are a mirror image of each other, however, the nature and location of their two main components (or poles) are in contrast with each other. The major convection zone of the northeast monsoon system is over the maritime continent (i.e. partly ocean and partly land), whereas the summer monsoon ‘heat low’ is entirely over land. During the summer monsoon period, the major heat source over India, the Tibetan Plateau and subtropical southeast Asia is situated between 15 and 30°N, where the coriolis effect gives rise to highly rotational planetary-scale circulation.

In contrast, the main heat source of the winter monsoon is situated over the equatorial belt, where the divergent component of the motion reveals itself more prominently. The convective zone 5–10°S at the equator near Indonesia, northern Australia and the East Asia landmasses covered by very cold air (owing both to radiative heat loss and large-scale cold air advection) in the north gives rise to a strong north–south heating gradient. This provides the potential energy necessary to support one of the most powerful heat engines driving the general circulation. The horizontal heating contrast of the summer monsoon is considerably less remarkable, and therefore, the kinetic energy of the circulation is less than that during the winter monsoon (Lau and Chang, 1987). Studies on teleconnections of the northeast monsoon of East/Southeast Asia are documented in some of the review articles, e.g. Lau and Li (1984) and Lau and Chang (1987). The Australian summer monsoon is also a component of the northern winter northeast monsoon circulation (Das, 1992). Work carried out on the Australian summer monsoon is summarized by McBride (1987).

The four main objectives of the present study are as follows.

(i) To understand large-scale variations in the PMR over India and to determine their association with the large-scale rainfall variations of the preceding summer monsoon season.
(ii) To provide reliable information on the variability, distribution and fluctuations of the regional-scale PMR based on the longest available instrumental records for practical purposes.
(iii) To examine the correlation with selected regional/global circulation parameters (PCs) in order to identify possible causes of variations in the PMR.
(iv) To develop a suitable method for prediction of regional and all-India PMR.

## 2. LARGE-SCALE INTERANNUAL VARIABILITY OF THE PMR OVER INDIA

In general, the southern peninsula receives maximum rainfall during the post-monsoon season. However, careful examination of the isohyetal pattern reveals that the areas under specified PMR conditions vary considerably from year to year. If the threshold amount of rainfall is properly chosen, an area having rainfall greater than this threshold limit (wet area) would precisely demarcate that portion of the country, more or less contiguously, which could potentially be affected by the rainfall patterns. Expansion and contraction of the wet area in this way perhaps provides a better index than does area-averaged rainfall for studying the large-scale features of rainfall occurrences. Earlier, such indices were used to study large-scale variability of the summer monsoon (Singh, 1995), spatial variability of aridity and occurrence of drought and desertification over the country (Singh *et al.*, 1992a,b). Knowledge of the large-scale characteristics of the summer monsoon rainfall (SMR) and those of the PMR is a prerequisite for planning, implementation and operation of large-scale water-based enterprises in the country. To identify the wet area of the post-monsoon season rainfall, a threshold of 200 mm was used. This was decided by examining the thematic map of India showing isopleths of the probability of non-occurrence of rainfall during the post-monsoon season. The probability is almost zero ($<5\%$) where mean October–December rainfall is $>200$ mm. The area will be referred to as the 'wet area' of the post-monsoon season (PMWA), climatically or in a particular year. As an illustration, for 4 years in each of the three categories extremely small, near-normal and extremely large, the area under wet conditions over the period 1871–1984 is given in Figure 1; the climatically wet area of the country is given in Figure 3(a). These charts were prepared using the October–December total rainfall from 306 raingauges, one from each of the 306 districts (according to the 1971 census) in a relatively plain and contiguous part of the country (excluding the mountainous terrain of Jammu and Kashmir, the hills of Uttar Pradesh, Himachal Pradesh and Arunachal Pradesh, and the islands in the Bay of Bengal and the Arabian Sea), and assuming that the station amount is representative of the rainfall conditions over the entire geographical area of the host district. In India, a district is a small administrative unit, shaped roughly like a polygon. The district headquarters and the raingauge station are located almost in the centre of the district in every case. With the exception of a few cases of isolated districts under wet conditions (due to rigid application of the

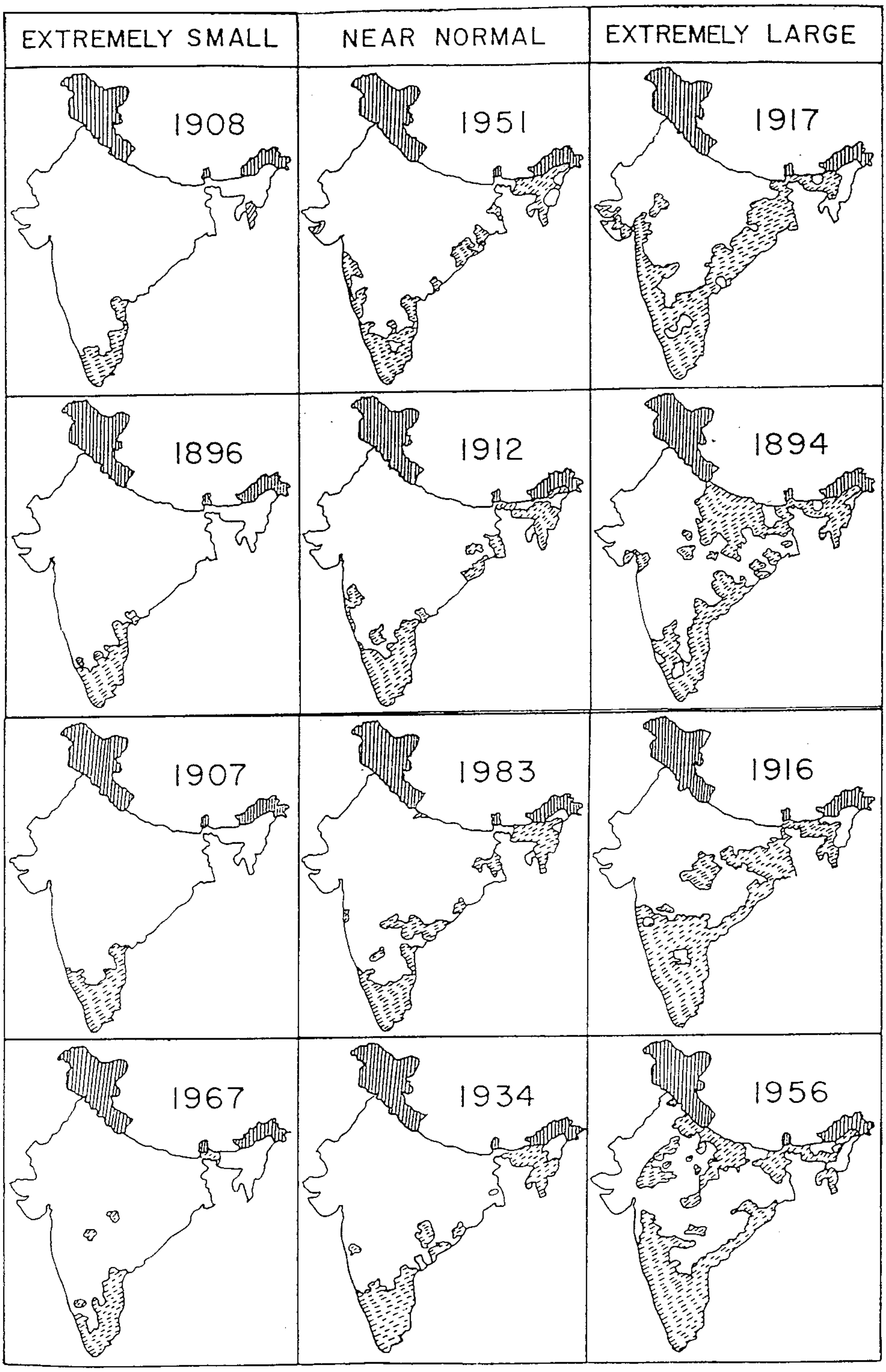


Figure 1. Size of the wet area over the country (October–December rainfall > 200 mm) during 4 years in each of three categories, extremely small, near-normal and extremely large

Table I. Chief statistical properties of the different PMWA series (1871–1984)

| Statistical parameter | Rainfall (mm) | | |
|---|---|---|---|
| | $>200$ | $>100$ | $>150$ |
| Mean (km$^2$) | 566 309 | 1121 507 | 797 419 |
| S.D. (km$^2$) | 214 947 | 384 240 | 293 959 |
| Coefficient of variance (km$^2$) | 37.96 | 34.26 | 36.86 |
| Coefficient of skew ($g_1$) | 0.77 | 0.41 | 0.74 |
| Coefficient of kurtosis ($g_2$) | 0.43 | $-0.41$ | 0.40 |
| $g_1$/S.E. ($g_1$) | 3.40 | 1.81 | 3.25 |
| $g_2$/S.E. ($g_2$) | 0.96 | $-0.91$ | 0.90 |
| Median (km$^2$) | 553 012 | 1090 768 | 765 959 |
| Lower quartile (km$^2$) | 415 301 | 868 438 | 593776 |
| Upper quartile (km$^2$) | 665 242 | 1345 754 | 948 183 |
| Lowest value (km$^2$) | 192 979 | 349 319 | 269 464 |
| % of mean | 34.08 | 31.15 | 33.79 |
| Year of occurrence | 1908 | 1908 | 1908 |
| Highest value (km$^2$) | 1176 902 | 2097 901 | 1639 916 |
| % of mean | 207.82 | 187.06 | 205.65 |
| Year of occurrence | 1956 | 1956 | 1956 |
| $t$-statistic | 1.66 | 1.44 | 1.35 |
| Mann–Kendall $\tau$-statistic | 0.04 | 0.04 | 0.02 |
| No. of runs about the median | 62 | 54 | 54 |

Test statistics for the long-term trends are given in the last three rows.

200-mm criterion), the PMWA displays a sequence in its north-westward expansion and south-eastward contraction from year to year. The size of the wet area is a better indicator of a bad/good year in relation to rainfall than the areally-averaged amount of rainfall. There are, however, practical difficulties in using the PMWA as an index for large-scale rainfall studies and these are addressed later in the paper.

In addition to the previously mentioned 306-raingauge network and the 1871–1984 period, limited available rainfall data prior to 1871 obtained from Blanford (1886), and for the 116 selected stations for the period 1985–1996 (collected from the relevant records of the IMD), are also utilized in the present study.

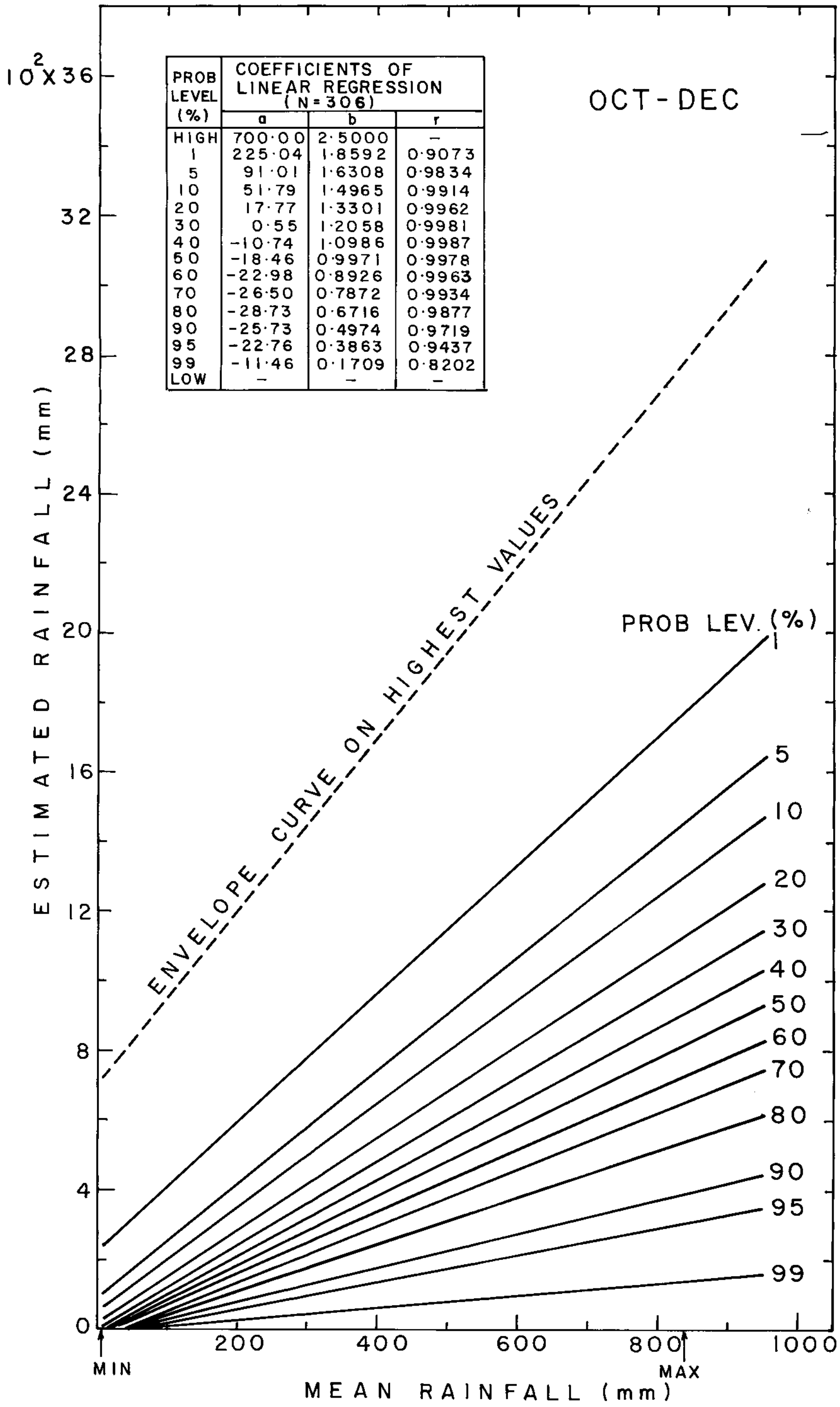
## 3. SOME IMPORTANT STATISTICAL CHARACTERISTICS OF THE PMWA

The mean, standard deviation and coefficient of variation of the PMWA series (1871–1984) are 566309 km$^2$, 214947 km$^2$ and 37.96%, respectively (Table I); its frequency distribution is positively skewed, as indicated by Fisher's $g$-statistic test (Rao, 1952). The coefficients of skew ($g_1$) and kurtosis ($g_2$), and error statistics $g_1$/S.E.($g_1$) and $g_2$/S.E.($g_2$), where S.E. denotes standard error, are also given in Table I. The square-root transformation of the PMWA is however found to be near-normal, according to Fisher's $g$-statistic test. The actual PMWA series is free from Markovian-type persistence, as suggested by its first three autocorrelation coefficients. Table I also lists some other important features of the PMWA variations.

## 4. PROBABILITY DISTRIBUTION OF THE SPATIAL VARIATIONS OF THE PMWA

Distribution analysis was carried out to describe the probabilistic characteristics of expansion and contraction of the wet area. The average probability diagram (APD) or average probability relationships (APRs) of the October–December rainfall, prepared utilizing data collected over a period of 114 years

(1871–1984) from the 306 stations, is used in the analysis. Under Indian conditions, the spatial variation of the October–December rainfall expected with any specified exceedance/non-exceedance probability is an excellent linear function of spatial variation of the mean October–December rainfall. The APD in



| PROB LEVEL (%) | COEFFICIENTS OF LINEAR REGRESSION (N=306) | | |
|---|---|---|---|
| | a | b | r |
| HIGH | 700·00 | 2·5000 | – |
| 1 | 225·04 | 1·8592 | 0·9073 |
| 5 | 91·01 | 1·6308 | 0·9834 |
| 10 | 51·79 | 1·4965 | 0·9914 |
| 20 | 17·77 | 1·3301 | 0·9962 |
| 30 | 0·55 | 1·2058 | 0·9981 |
| 40 | -10·74 | 1·0986 | 0·9987 |
| 50 | -18·46 | 0·9971 | 0·9978 |
| 60 | -22·98 | 0·8926 | 0·9963 |
| 70 | -26·50 | 0·7872 | 0·9934 |
| 80 | -28·73 | 0·6716 | 0·9877 |
| 90 | -25·73 | 0·4974 | 0·9719 |
| 95 | -22·76 | 0·3863 | 0·9437 |
| 99 | -11·46 | 0·1709 | 0·8202 |
| LOW | – | – | – |

Figure 2. The APD of the October–December rainfall over India, prepared using 114 years (1871–1984) of data from 306 well-separated stations (after Singh and Mulye, 1991)

Figure 2 presents such a relationship for 13 selected exceedance probabilities between 1 and 99%, as well as the product–moment correlation coefficient (CC) and the coefficients of the least-squares estimated linear regression for the individual relationship. The linear regressions will be referred to as the APRs. The high value of the CC suggests that the probability distribution of October–December rainfall at stations throughout India is highly dependent on the mean October–December rainfall of the respective stations. Further details of the APD are given in Singh and Mulye (1991). Some of its applications include: (i) use as a risk diagram in evaluating the success of an enterprise with a known water requirement (Landsberg, 1951); (ii) use as a nomogram to interpolate the rainfall distribution of a station having incomplete, or no, historical records; the result would be in accordance with a large area rather than a few surrounding points; and (iii) use as a valuable tool to study the distribution of the spatial variations of the isohyets and the climatic regions (Singh, 1984).

Using the APD, the mean rainfall whose isohyet delimits the region of India likely to be under wet conditions at that exceedance probability is estimated. At a point 200 mm along the ordinate of the APD, a line is drawn parallel to the abscissa. From the intersection of this line with the linear curve, which shows the relationship between the probabilistic estimated rainfall and the mean rainfall, a vertical projection is drawn on the abscissa. Mean rainfall at the drop on the abscissa is thus calculated. The APRs can be used to directly estimate the mean rainfall. The mean isohyet for selected exceedance probabilities is shown in Figure 3(b). The probability of a spreading wet area in north-western India, where mean October–December rainfall is $<70$ mm, is $<5\%$. In the region where the mean rainfall is between 170 and 220 mm, the probability of spreading is between 30 and 50%. The occurrence of 200 mm of rainfall with 50% probability at stations with a mean rainfall of 220 mm suggests that the distribution of station PMR series has a slightly positive skew. The occurrence probability of wet conditions during the post-monsoon season is $>90\%$ over the extreme southeast peninsula, where the mean rainfall is $>450$ mm.

## 5. FLUCTUATION CHARACTERISTICS OF THE PMWA

### *5.1. Low-pass filter*

The PMWA series 1871–1984 is presented in Figure 4(a) on a standardized scale (actual minus mean divided by standard deviation (S.D.)) to facilitate visual examination of the wet area fluctuations. Large, abrupt changes from one year to the next, persistently larger or smaller values for a few years (epochs) and short-term increasing and decreasing trends are some of the easily discernible features. Overall, the series appears stationary; in order to determine whether the series possesses any regular component in the low-frequency mode fluctuations, it was smoothed by a 9-point Gaussian low-pass filter, which effectively suppresses the high frequency variations with period shorter than 10 years (WMO, 1966). The choice of the filter is subjective. Some distinct wet/dry epochs embedded in the profuse interannual variations can be seen: the wet epochs are 1882–1894, 1915–1917, 1928–1934, 1952–1963 and 1973–1977; and the dry epochs are 1870–1881, 1895–1914, 1918–1927, 1964–1972 and 1978–1984. Broadly speaking, the period of these epochs is synchronous with similar epochs of the large-scale SMR fluctuations over India (Mooley and Parthasarathy, 1984; Singh, 1995). Following an approach similar to the present one, Singh (1995) studied the large-scale fluctuations of the summer monsoon by examining the expansion and contraction of the summer monsoon dry area (SMDA; the area with an SMR $<800$ mm). On the mean SMR chart, the 800-mm isohyet divides the country into two equal halves. The correlation between variations of the actual SMDA and that of the PMWA based on data from 1871–1984 is $-0.34$ (significant at the 0.1% level). Therefore, large-scale patterns of the summer monsoon can provide useful supplemental information for prediction of the large-scale pattern of the PMR.

From examination of the large-scale fluctuations of the Indian SMR and the tracks of the Bay cyclones, Joseph (1976) divided the period 1891–1974 into three epochs, i.e. 1891–1920, 1931–1960 and 1965–1974. During 1891–1920 and 1965–1974, the SMR and cyclone tracks exhibited large interannual

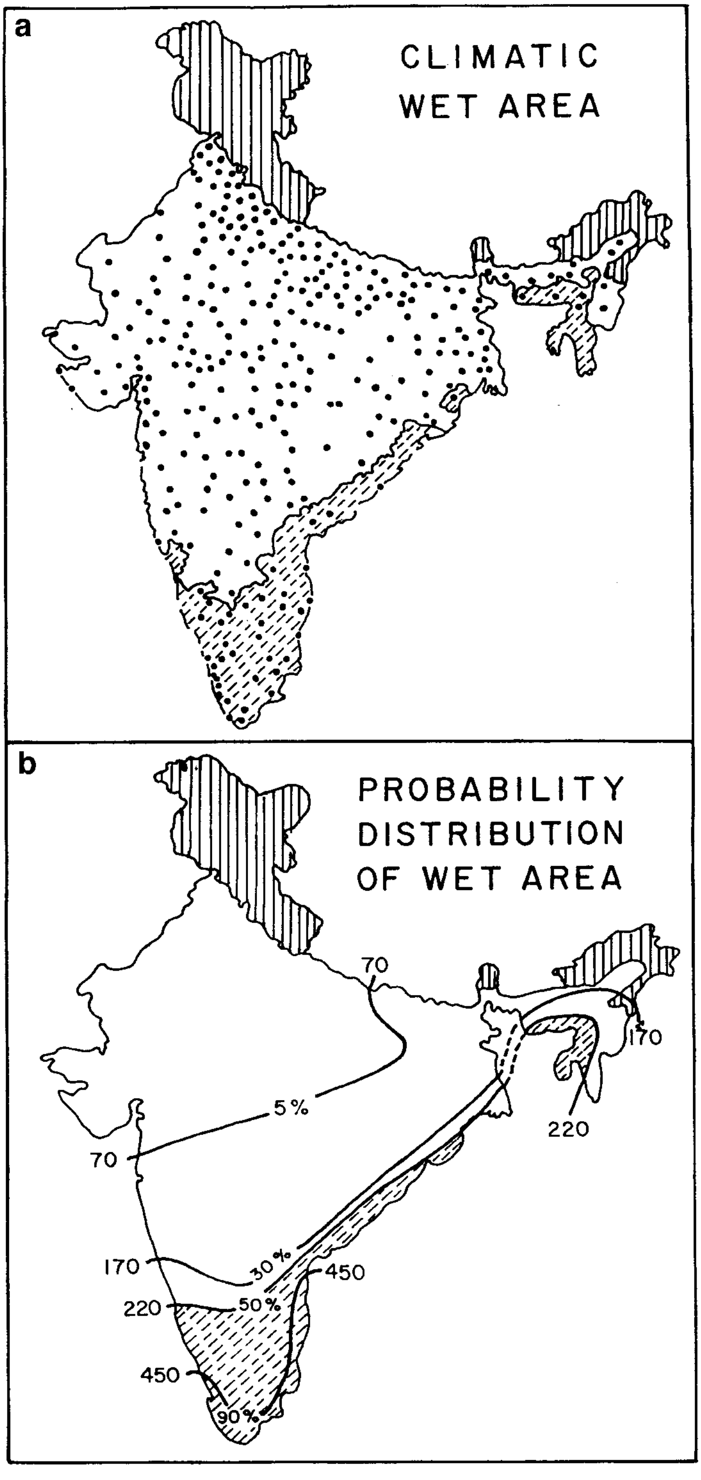


Figure 3. Showing: (a) the climatically wet area of the post-monsoon season (hatching), and the locations of the 306 raingauge stations (dots); (b) normal October–December isohyets demarcate the size of the wet area at selected exceedance probabilities, and hatching shows the area likely to be under wet conditions with a probability of ≥ 50%

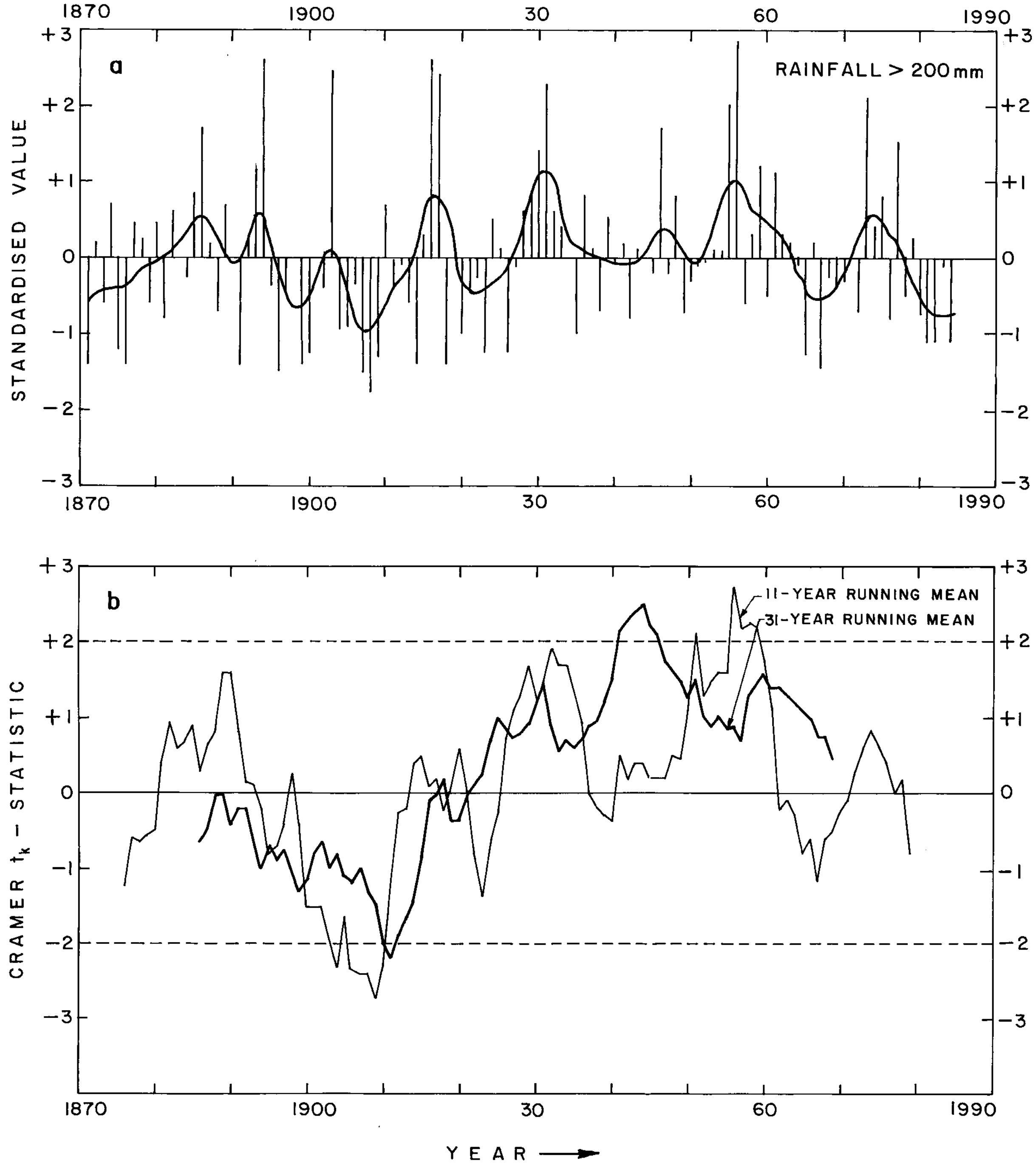


Figure 4. Showing: (a) a plot of the standardized (actual minus mean divided by S.D.) wet area series of the period 1871–1984. The filtered values obtained after applying a 9-point Gaussian low-pass filter are shown by the thick, curved line; (b) a plot of the Cramer's $t_k$-statistic applied on the departure of the 11- and 31-year running means of the PMWA from its overall mean

variations, and summer monsoon failures were frequent, while during 1931–1960, the interannual variability was small and summer monsoon failures were rare. In the fluctuation frequency of precipitation surges over the Line Islands in the equatorial East Pacific during 1910–1977, Reiter (1978) identified three epochs 1911–1928, 1929–1962 and 1963–1977. He observed that during the epochs of 1911–1928 and 1963–1977 the El Niño phenomenon occurred frequently and interannual rainfall fluctuations in the equatorial East Pacific large, while the epoch 1929–1962 was characterized by infrequent El Niño episodes and lesser rainfall fluctuations. It can be seen that during persistent warmer/cooler northern hemisphere conditions, convection and circulation over the tropical Indian and West Pacific Oceans are activated/suppressed and infrequent/frequent El Niños occur over the equatorial East Pacific. A note of caution is necessary here, since these inferences are made from low-frequency mode fluctuations and their usefulness to the outcome of interannual studies is limited.

### *5.2. Long-term features*

The nature of long-term change in contemporary climatic fluctuations is desirable information to obtain from any study of the present type. In order to confirm the previously stated visual observation that the PMWA series does not seem to possess a significant long-term trend, three statistical tests were applied, namely: Student's $t$-test on the difference between means of the two subperiods of equal lengths; the Mann–Kendall rank test of randomness against trend; and the Swed–Eisenhart runs test (WMO, 1966). The resultant statistics are given in Table I, and confirm an insignificant long-term trend or cycle in the series.

### *5.3. Short-term features*

The occurrence of epochs in the fluctuations of the shorter period mean rainfall, characterized by a persistently larger/smaller amount of rainfall compared to the long-term mean, is of considerable significance both in scientific investigations and for practical purposes. The evidence suggests that extreme events often occur in groups of consecutive years. High/low values of associated climatic parameters generally occur during such periods, and they often show spatial correlations of similar or opposite sign (teleconnections) with other climatic events in far-distant areas of the globe (Flohn, 1981). However, the expected tendency of wetter/dryer climatic conditions to persist provides information of the greatest value for the planning and execution of large-scale, long-term, water-dependent programmes.

Epochs and short-term trends in the fluctuations of the PMWA are studied using variations in its 11- and 31-year running means. Cramer's $t_k$-statistic test was applied on the departure of the running means in order to determine whether the means were significantly different at times, or whether they fluctuated within normal limits. The $t_k$-statistic is defined as (WMO, 1966)

$$t_k = \left[\frac{n(N-2)}{N-n(1+A_k^2)}\right]^{1/2} A_k, \tag{1}$$

in which

$$A_k = \frac{\bar{x}_k - \bar{x}}{s},$$

where $\bar{x}$ and $s$ are the mean and standard deviation respectively, of the entire series (1871–1984), $\bar{x}_k$ is the $n$-term running mean (i.e. $n = 11$ or 31) and $N$ is the number of observations (114). The departure is treated as being statistically significant (at the 5% level) if $t_k \geq |2.0|$. For both the 11- and 31-year running means, the $t_k$-statistic is presented in Figure 4(b). The 11-year means first showed an increasing trend up to the 11-year period centered around 1890, followed by a decreasing trend up to 1909 (significant at the 5% level), a generally increasing trend up to 1956 (significant at the 5% level) and finally a decreasing trend, albeit within normal limits. The 31-year means first showed a decreasing trend with significantly fewer values around 1911, but this was generally followed by an increasing trend. The highest positive (and significant at the 5% level) departure was seen during the 1940s. Fluctuations of the PMWA are almost exactly opposite to that of the SMDA (Singh, 1995).

We repeated the above analysis for the PMWA series prepared by changing the rainfall threshold for a 'wet area' to $> 150$ mm, followed by 100 mm, and obtained similar results as with the 200-mm PMWA. Characteristics of the 150- and 100-mm PMWA are given in Table I. The CC between the 200- and the

150-mm PMWA is 0.97, and between the 200- and the 100-mm PMWA and the 150- and the 100-mm PMWA it is 0.91 and 0.96, respectively. Thus, with some differences in the threshold, the inferences in relation to large-scale interannual variability of the PMR do not differ greatly. The CC between the 800-mm SMDA (Singh, 1995) and the 150-mm PMWA is $-0.34$ (significant at the 0.1% level), and between the SMDA and the 100-mm PMWA it is $-0.29$ (significant at the 1% level). Statistically speaking, large-scale rainfall features of the summer monsoon and those of the post-monsoon period are significantly positively correlated.

## 6. PMR STUDIES FOR THE SIX ZONES OF THE COUNTRY

Bearing in mind the limitations of large-scale studies owing to large spatial variability, as well as the pressing needs for more precise information about rainfall characteristics in order to solve practical problems, regional studies of the PMR were carried out. Rather than making new classifications, the six-zone classification of the country undertaken earlier by the authors (Singh and Sontakke, 1996a; Sontakke and Singh, 1996) for an effective study (forecasting, monitoring and other practical problems related to agriculture, hydrology, etc.) of the SMR variations was adopted for the regional studies of the PMR. The division of the country into six zones is based on between-station similarity in the SMR fluctuations. SMR from the same 306-raingauge network of the period 1871–1984 used in the present study were analyzed using four methods to define the spatially coherent stations. The methods are: (i) obtaining a CC between the all-India SMR and the individual gauges (1871–1980); (ii) determining the change in mean SMR from the periods 1901–1940 to 1941–1980 at the individual sites; (iii) the $S$-mode empirical orthogonal function analysis of the SMR series; and (iv) a cluster analysis based on the CC, as well as the distance coefficient between the gauges. Subjective judgmental approaches were used on the results of the analyses to carefully choose the geographic meridians and parallels to divide the country into the following six zones (Figure 5).

| | |
|---|---|
| Northwest India (NWI): | north of 21°N latitude and west of 80°E longitude. |
| North Central India (NCI): | north of 21°N latitude and between the longitudes of 80 and 88°E. |
| Northeast India (NEI): | north of 21°N latitude and east of 88°E longitude. |
| West Peninsular India (WPI): | between the latitudes of 15 and 21°N and west of 79°E longitude. |
| East Peninsular India (EPI): | between the latitudes of 15 and 21°N and east of 79°E longitude. |
| South Peninsular India (SPI): | south of 15°N latitude. |

Since the summer monsoon is the most dominant component of the climate, this six-zone classification can be used to monitor general climatic conditions across the country. The adaptation of this classification for the PMR studies would facilitate integration of the system as an important component into a comprehensive climate monitoring programme for the country.

From Figures 1 and 5, it can be seen that a diagonally elongated area of the main PMR activity is spread over SPI, EPI and NEI. In SPI, the mean PMR is 395 mm, contributing 26% to its annual total, in EPI it is 203 mm, giving an 18% contribution to the annual total and in NEI, it is 170 mm, giving an 8% annual contribution. Over the two peripheral zones, WPI and NCI, the mean PMR is 107 and 79 mm respectively, contributing, respectively, 10 and 6% to the annual total. Rainfall over the peripheral zones during October to December can be either owing to delayed summer monsoon (particularly during October), or to tropical cyclones forming over the Bay of Bengal and moving over the land areas. In the farthest zone, NWI, the mean PMR is 35 mm, giving 5% of the annual rainfall. A deep trough in the extra-tropical westerlies generally provides good rainfall over NWI during this period. In addition, there is evidence that tropical cyclones in the October–December period produce good rainfall over this area. Leaving the critical issues aside to be tackled in future studies, we will treat the rainfall of the period from October to December as PMR. The mean PMR for the entire country is 125 mm, and its contribution to the annual total is 11%.

Further using an objective selection technique (Singh, 1994), the authors (Singh and Sontakke, 1996a; Sontakke and Singh, 1996) also identified an optimum set of 116 IMD raingauge stations (19 in NWI, 27 in NCI, 15 in NEI, 18 in WPI, 14 in EPI and 23 in SPI) for the reconstruction, in addition to real-time update of the different zonal and all-India SMR series. The same set of 116 IMD raingauges was adopted for the zonal and all-India PMR series. The correlation between the PMWA and the all-India PMR series (1871–1984) is 0.92, which implies that in general, the wet area expands and contracts parallel to the isohyets with the maximum and minimum amounts of the all-India rainfall. To update the all-India PMR series 116 observations are adequate, while all 306 observations will be required to update the PMWA series.

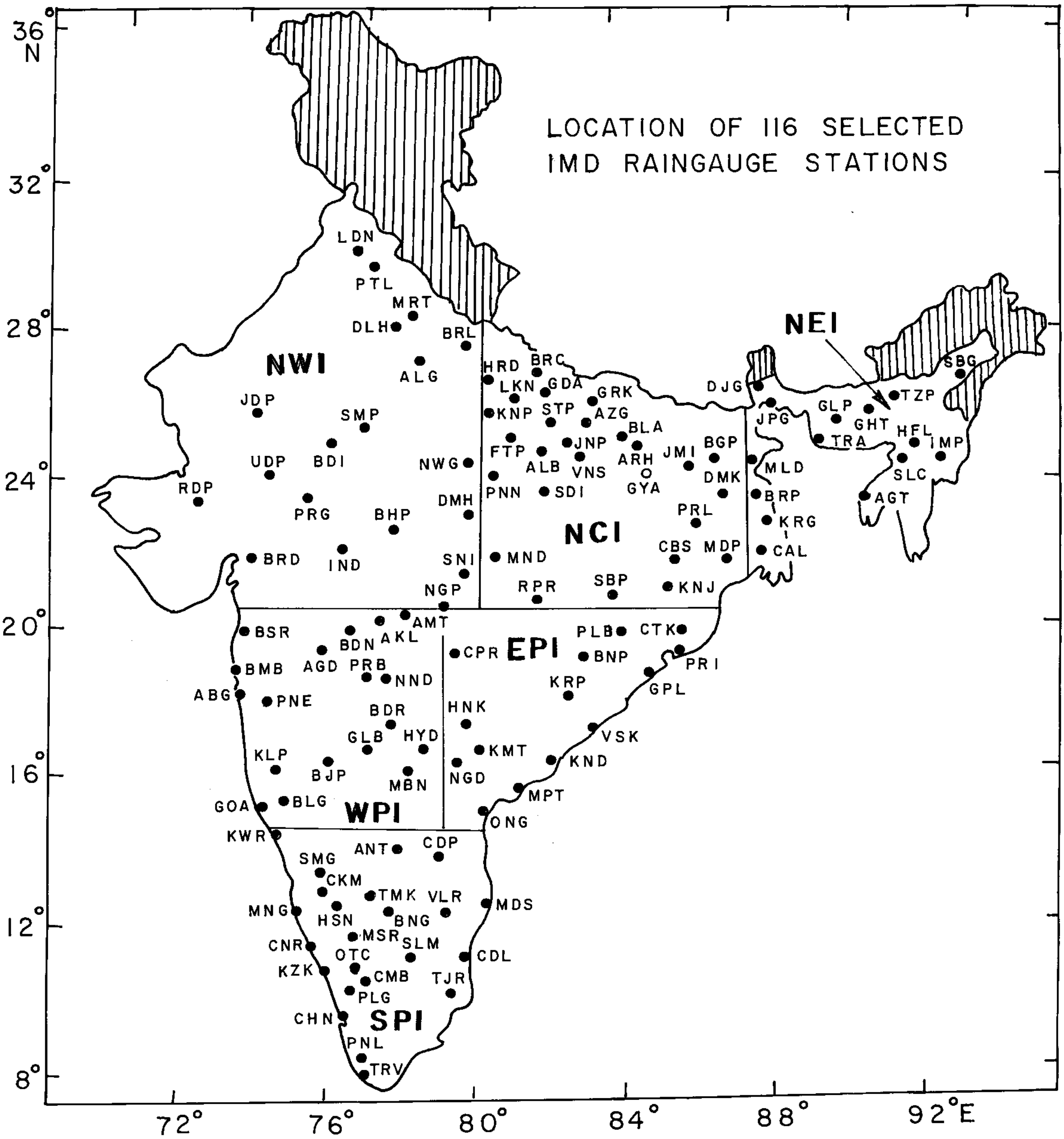


Figure 5. The six-zone classification of India for regional rainfall studies (after Sontakke and Singh, 1996). Dots show the location of the 116 IMD raingauge stations selected for the real-time update of the different zonal and all-India rainfall series

Table II. Parameters giving details of the representative zonal and all-India PMR series (1871–1984)

| | NWI | NCI | NEI | WPI | EPI | SPI | AI |
|---|---|---|---|---|---|---|---|
| Geographical area (km$^2$) | 997 525 | 586 187 | 229 002 | 414 202 | 319 184 | 334 224 | 2880 324 |
| Interseries CC ($\bar{r}$) | 0.3690 | 0.4169 | 0.3994 | 0.3854 | 0.3871 | 0.3740 | 0.2036 |
| Mean CC ($R$) | 0.6078 | 0.6516 | 0.6493 | 0.6329 | 0.6344 | 0.6180 | 0.4343 |
| IAR (%) | 33.5 | 40.2 | 39.0 | 38.9 | 36.1 | 34.8 | 12.5 |
| Intercept ($a$) | 0.8373 | 6.6483 | 11.4001 | 5.5872 | −4.5891 | 12.9519 | 0.5366 |
| Slope ($b$) | 0.9408 | 0.9654 | 0.9551 | 0.9721 | 0.9066 | 1.0266 | 0.9874 |
| RMSE 1981–1984 (mm) | 5.9 | 5.3 | 9.2 | 3.7 | 10.9 | 21.08 | 3.7 |

$\bar{r}$, mean interseries CC; $R$, mean CC between the representative series and the individual gauges; IAR, index of aerial representativeness The ratio of variance of the representative series and mean variance of the individual gauges are expressed as a percentage (Singh *et al.*, 1991). The intercept ($a$), the slope ($b$) and the biased RMSE on the independent sample of 4 years (1981–1984) of the linear regression of the representative series on the mean series of a few selected gauges are given in the last three rows.

Table III. The correlation matrix for the representative PMR series (1871–1984) of the different zones and the all-India (AI), as well as the 200 mm PMWA series

| | NWI | NCI | NEI | WPI | EPI | SPI | AI | PMWA |
|---|---|---|---|---|---|---|---|---|
| NWI | 1.00 | | | | | | | |
| NCI | 0.60 | 1.00 | | | | | | |
| NEI | 0.22 | 0.54 | 1.00 | | | | | |
| WPI | 0.50 | 0.39 | 0.23 | 1.00 | | | | |
| EPI | 0.33 | 0.44 | 0.29 | 0.49 | 1.00 | | | |
| SPI | 0.13 | 0.03 | 0.44 | 0.33 | 0.16 | 1.00 | | |
| AI | 0.74 | 0.75 | 0.51 | 0.74 | 0.67 | 0.50 | 1.00 | |
| PMWA | 0.59 | 0.74 | 0.60 | 0.72 | 0.70 | 0.33 | 0.92 | 1.00 |

## 7. RECONSTRUCTION OF THE LONGEST INSTRUMENTAL ZONAL AND ALL-INDIA PMR SERIES

Experience has shown that any area-averaged climatic series prepared involving large a number of observations can be reconstructed using a few selected observations from the network. Singh (1994) developed an objective technique to select the optimum number of observations for any area-averaged climatic series. Using selected observations for the application of this technique, Sontakke and Singh (1996) reconstructed the longest instrumental SMR series for each of the six zones and the whole country. Following the same procedural details, the longest PMR series was reconstructed for the Indian region. Three steps were involved in accomplishing the task: (i) preparation of the representative area-averaged rainfall series for a long period using all available observations; (ii) reconstruction of the series using the same optimum subset that is used for reconstruction of the SMR series; and (iii) backward extension using optimally selected observations from the less-available observations. A brief description of the different reconstructions is given below.

### *7.1. Preparation of the representative area-averaged PMR series*

The simple arithmetic mean of all the available gauges in the respective areas was calculated to prepare the representative areal PMR series for the period 1871–1984. Within the 306-raingauge network, the gauges considered number 116 in NWI, 65 in NCI, 25 in NEI, 37 in WPI, 22 in EPI and 41 in SPI. The representative all-India series is the mean of all 306 raingauges. In addition to computational simplicity, easy interpretation and a wide area of application, the reason for adopting the simple mean series is that the highest CC achieved in the optimum selection can be compared with its theoretical value for exact equality (Wigley *et al.* 1984; Singh, 1994). In an experiment, Singh *et al.* (1991) prepared the all-India SMR series (1871–1984) using nine different methods, finding the series derived from the simple arithmetic mean as the second most-representative, as indicated by the index of areal representativeness (IAR); the most representative was found to be that prepared by averaging the non-exceedance probability derived from the two-parameter gamma distribution fitted by the maximum likelihood method. Taking advantage of the inference from that study, the simple mean zonal and all-India PMR series were assumed as the most representative. Table II gives the details of the different representative series.

The correlation matrix given in Table III shows that among themselves, zonal series are weakly correlated. It is ironic to see that both the PMWA and the all-India rainfall show the weakest correlation with SPI, the most important area of PMR. The correlation is highest with the peripheral zones, NCI and WPI, in which expansion and contraction of the wet area occurs to a maximum, i.e. the maximum effect of large-scale variability of the PMR can be seen in the marginal areas. Zonal rainfall studies are therefore deemed necessary for practical purposes.

### *7.2. Reconstruction and real-time update of the representative series using optimum observations*

In order to update the six-zonal representative summer monsoon rainfall series of the country, Sontakke and Singh (1996) identified a set of 116 IMD raingauge stations by applying the objective optimum selection technique (Singh, 1994). Of the 306 raingauges, 231 are maintained by the IMD and the remaining 75 by state agencies. The IMD gauges are known for timely availability of quality-controlled data. The all-India SMR series is updated from the area-weighted mean of the six-zonal series. New selection for the rainfall series of a different period would negate the purpose of optimization and reconstruction. In this study, the same set of 116 IMD stations as was used for the PMR series was adopted, keeping in view the general problem of updating the rainfall series of different seasons, as well as the comprehensive programme to monitor detailed climatic conditions across the country. It may be noted that the summer monsoon and post-monsoon contribute nearly 90% to the total annual rainfall. The CC between the mean series of the optimum gauges and the representative PMR series based on data of the 1871–1980 period is given in Table IV against the year 1871. The last column of Table IV gives the CC between the area-weighted mean of the reconstructed six-zonal series and the representative all-India series—the simple mean of the 306 gauges. Coefficients of the linear regression are given in Table II, which also lists other important details of the different series. It is interesting to note that the CC exceeded 0.98 in every case, and for all-India the CC exceeded 0.99. Therefore, the reconstruction is quite reliable. (It should be noted that equally satisfactory results were obtained when the same optimum gauges were adopted for the summer monsoon monthly rainfall series (June, July, August and September) of the six zones and the entire country (Singh and Sontakke, 1996a).) The different reconstructed and updated (1996) PMR series are presented in Figure 6. Perhaps the most significant aspect of this reconstruction is the use of a fixed, albeit limited, number of observations from 1871 onwards. This provides a genuine basis for using the reconstructed series for detailed scientific investigations.

### *7.3. Backward extension prior to 1871*

Prior to 1871, the individual PMR series is extended as far backward as possible following the same procedural details used earlier by Sontakke and Singh (1996) for the SMR series. For each time, the series is extended by 1 year and the following calculations are carried out in the given order.

(i) Find the gauges prior to 1871 whose data is already available for the period 1871–1984.
(ii) Apply the objective technique to select a few gauges from the available set whose mean showed the highest correlation with the reconstructed representative series of the period 1871–1984.
(iii) Estimate the least-squares linear regression of the reconstructed representative series (dependent) of the mean series of the selected gauges (independent) using the data from the 1871–1980 period.
(iv) Substitute the mean of the year 1870 of the selected gauges into the regression and obtain an estimate of a 1-year backward extension of the representative series.
(v) Inflate the variance of the estimated rainfall amount by a factor of '$p$' (ratio of the S.D. of the reconstructed representative series to that of the estimated series obtained from the fitted regression; Klein *et al.*, 1959) and obtain the final reconstructed rainfall amount for the year 1870.
(vi) Shift to the year 1869 and repeat the above calculations sequentially.
(vii) Continue the process to shift backward by 1 year as long as the means of the few selected observations from the available set of gauges shows significant correlation (at least at the 5% level) with the reconstructed representative series.

For each year of the pre-1871 observation period, the number of available gauges, the number that entered the selection, the highest CC achieved and the S.D. of the estimated series are given in Table IV for the six zones and the whole country. The NWI series was extended back to 1844, NCI to 1842, NEI to 1829, WPI to 1841, EPI to 1848 and SPI and the whole of India to 1813. The different reconstructed PMR series are displayed in Figure 6 for the entire period; the estimation is most reliable for SPI, since the CC always exceeded 0.70.

Table IV. Some important statistics related to the reconstruction of the longest-possible instrumental PMR series for the six zones and the whole country

| Region | NWI | | | | NCI | | | | NEI | | | | WPI | | | | EPI | | | | SPI | | | | AI | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 1813–25 | – | – | – | – | – | – | – | – | | | | | | | | | – | – | – | – | 1 | 1 | 7329 | 79 | 1 | 1 | 2140 | 8 |
| 1826–28 | – | – | – | – | – | – | – | – | | | | | | | | | – | – | – | – | 1 | 1 | 7329 | 79 | 3 | 2 | 61341 | 21 |
| 1829 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 2 | 2 | 8284 | 88 | 5 | 4 | 7457 | 26 |
| 1830 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 2 | 2 | 8284 | 88 | 5 | 4 | 7457 | 26 |
| 1831 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 2 | 2 | 8284 | 88 | 5 | 4 | 7119 | 25 |
| 1832 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 2 | 2 | 8284 | 88 | 4 | 3 | 6143 | 21 |
| 1833 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 1 | 1 | 7329 | 79 | 2 | 1 | 4376 | 15 |
| 1834 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 1 | 1 | 7329 | 79 | 2 | 1 | 4376 | 15 |
| 1835 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 2 | 2 | 8166 | 87 | 3 | 2 | 5970 | 21 |
| 1836 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 2 | 2 | 8166 | 87 | 4 | 3 | 6324 | 22 |
| 1837 | – | – | – | – | – | – | – | – | 2 | 2 | 7339 | 52 | – | – | – | – | – | – | – | – | 5 | 4 | 8617 | 92 | 7 | 5 | 6558 | 23 |
| 1838 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 6 | 5 | 9225 | 99 | 7 | 3 | 6336 | 22 |
| 1839 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 6 | 5 | 9225 | 99 | 7 | 3 | 6336 | 22 |
| 1840 | – | – | – | – | – | – | – | – | 1 | 1 | 7263 | 52 | – | – | – | – | – | – | – | – | 6 | 5 | 9225 | 99 | 7 | 3 | 6336 | 22 |
| 1841 | – | – | – | – | - | – | – | – | 1 | 1 | 7263 | 52 | 1 | 1 | 5743 | 31 | – | – | – | – | 6 | 5 | 9225 | 99 | 8 | 3 | 6336 | 22 |
| 1842 | – | – | – | – | 1 | 1 | 7528 | 39 | 1 | 1 | 7263 | 52 | 2 | 2 | 7602 | 40 | – | – | – | – | 8 | 7 | 9565 | 102 | 12 | 5 | 7886 | 28 |
| 1843 | – | – | – | – | 1 | 1 | 7528 | 39 | 1 | 1 | 7263 | 52 | 2 | 2 | 7393 | 39 | – | – | – | – | 8 | 7 | 9565 | 102 | 12 | 5 | 8030 | 28 |
| 1844 | 29 | 4 | 9255 | 27 | 13 | 6 | 9257 | 47 | 1 | 1 | 7263 | 52 | 5 | 3 | 8976 | 47 | – | – | – | – | 8 | 7 | 9565 | 102 | 56 | 15 | 9460 | 33 |
| 1845 | 29 | 4 | 9255 | 21 | 12 | 6 | 9257 | 47 | 1 | 1 | 7263 | 52 | 5 | 3 | 8976 | 47 | – | – | – | – | 8 | 7 | 9565 | 102 | 55 | 15 | 9460 | 33 |
| 1846 | 29 | 4 | 9255 | 27 | 12 | 6 | 9257 | 47 | 1 | 1 | 7263 | 52 | 5 | 3 | 8976 | 47 | 1 | 1 | 7218 | 59 | 9 | 7 | 9565 | 102 | 56 | 15 | 9460 | 33 |
| 1847 | 29 | 4 | 9255 | 27 | 13 | 6 | 9257 | 47 | 1 | 1 | 7263 | 52 | 10 | 5 | 939S | 50 | 1 | 1 | 7218 | 59 | 8 | 6 | 9437 | 101 | 61 | 14 | 9526 | 33 |
| 1848 | 29 | 4 | 9255 | 27 | 18 | 7 | 9678 | 50 | 7 | 5 | 9156 | 65 | 5 | 4 | 9120 | 48 | 1 | 1 | 7218 | 59 | 8 | 6 | 9437 | 101 | 68 | 18 | 9597 | 34 |
| 1849 | 29 | 4 | 9255 | 27 | 22 | 12 | 9742 | 50 | 10 | 8 | 9561 | 67 | 3 | 3 | 9033 | 48 | 1 | 1 | 7218 | 59 | 7 | 6 | 9290 | 99 | 72 | 29 | 9614 | 34 |
| 1850 | 22 | 6 | 9115 | 26 | 21 | 13 | 9712 | 50 | 9 | 8 | 9609 | 68 | 2 | 2 | 8134 | 43 | 1 | 1 | 7218 | 59 | 7 | 6 | 9290 | 99 | 62 | 20 | 9435 | 33 |
| 1851 | 23 | 9 | 9241 | 27 | 22 | 5 | 9546 | 49 | 11 | 8 | 9636 | 68 | 2 | 2 | 8134 | 43 | 1 | 1 | 7218 | 59 | 7 | 6 | 9290 | 99 | 66 | 15 | 9296 | 33 |
| 1852 | 25 | 9 | 9279 | 27 | 15 | 5 | 9209 | 47 | 10 | 8 | 9636 | 68 | 4 | 3 | 8464 | 45 | 2 | 2 | 8759 | 71 | 9 | 6 | 9290 | 99 | 65 | 20 | 9546 | 33 |
| 1853 | 25 | 8 | 9288 | 27 | 15 | 5 | 9416 | 48 | 9 | 7 | 9551 | 67 | 5 | 4 | 8747 | 46 | 2 | 2 | 8759 | 71 | 13 | 12 | 9698 | 104 | 69 | 20 | 9600 | 34 |
| 1854 | 23 | 4 | 8929 | 26 | 15 | 6 | 9538 | 49 | 7 | 5 | 9249 | 65 | 5 | 4 | 8747 | 46 | 2 | 2 | 8759 | 71 | 14 | 14 | 9701 | 104 | 66 | 22 | 9616 | 34 |
| 1855 | 8 | 7 | 8896 | 26 | 3 | 3 | 8920 | 46 | 4 | 3 | 8770 | 62 | 3 | 3 | 8525 | 45 | 2 | 2 | 8759 | 71 | 9 | 7 | 9402 | 100 | 29 | 20 | 9509 | 33 |
| 1856 | 9 | 6 | 9145 | 27 | 3 | 3 | 8920 | 46 | 3 | 3 | 8770 | 62 | 6 | 4 | 9092 | 48 | 2 | 2 | 8759 | 71 | 9 | 7 | 9402 | 100 | 32 | 21 | 9527 | 33 |
| 1857 | 12 | 7 | 9281 | 27 | 3 | 3 | 8920 | 46 | 2 | 2 | 8515 | 60 | 6 | 4 | 9092 | 48 | 2 | 2 | 8759 | 71 | 9 | 7 | 9402 | 100 | 34 | 20 | 9518 | 33 |
| 1858 | 13 | 7 | 9281 | 27 | 3 | 3 | 8920 | 46 | 2 | 2 | 8515 | 60 | 6 | 4 | 9092 | 48 | 2 | 2 | 8759 | 71 | 9 | 7 | 9402 | 100 | 35 | 20 | 9518 | 33 |
| 1859 | 13 | 7 | 9281 | 27 | 7 | 4 | 9461 | 48 | 3 | 3 | 8555 | 60 | 8 | 7 | 9570 | 51 | 2 | 2 | 8759 | 71 | 9 | 7 | 9402 | 100 | 42 | 23 | 9646 | 34 |
| 1860 | 31 | 8 | 9646 | 28 | 21 | 14 | 9831 | 50 | 6 | 4 | 9072 | 64 | 9 | 8 | 9591 | 51 | 2 | 2 | 8759 | 71 | 9 | 7 | 9402 | 100 | 78 | 25 | 9731 | 34 |
| 1861 | 39 | 12 | 9744 | 28 | 22 | 15 | 9857 | 50 | 6 | 5 | 9128 | 64 | 19 | 15 | 9751 | 52 | 2 | 2 | 8759 | 71 | 10 | 8 | 9507 | 102 | 98 | 35 | 9817 | 34 |
| 1862 | 44 | 18 | 9835 | 29 | 23 | 15 | 9857 | 50 | 9 | 8 | 9316 | 66 | 20 | 12 | 9823 | 52 | 2 | 2 | 8759 | 71 | 10 | 8 | 9507 | 102 | 108 | 38 | 9833 | 34 |
| 1863 | 51 | 15 | 9867 | 29 | 25 | 16 | 9854 | 50 | 9 | 9 | 9447 | 67 | 21 | 15 | 9876 | 52 | 6 | 5 | 9368 | 76 | 24 | 20 | 9868 | 105 | 136 | 33 | 9853 | 35 |
| 1864 | 54 | 17 | 9912 | 29 | 25 | 16 | 9854 | 50 | 9 | 9 | 9447 | 67 | 21 | 15 | 9876 | 52 | 6 | 5 | 9368 | 76 | 24 | 20 | 9868 | 105 | 139 | 23 | 9774 | 34 |
| 1865 | 54 | 17 | 9912 | 29 | 25 | 16 | 9854 | 50 | 10 | 10 | 9468 | 67 | 22 | 18 | 9891 | 52 | 6 | 5 | 9368 | 76 | 25 | 19 | 9879 | 106 | 142 | 23 | 9774 | 34 |
| 1866 | 55 | 17 | 9912 | 29 | 26 | 16 | 9874 | 51 | 11 | 10 | 9553 | 67 | 22 | 18 | 9891 | 52 | 7 | 6 | 9535 | 78 | 25 | 19 | 9879 | 106 | 146 | 38 | 9870 | 35 |
| 1867 | 57 | 17 | 9912 | 29 | 43 | 16 | 9898 | 51 | 13 | 11 | 9707 | 68 | 22 | 18 | 9891 | 52 | 8 | 7 | 9743 | 79 | 25 | 19 | 9879 | 106 | 168 | 27 | 9808 | 34 |
| 1868 | 63 | 15 | 9904 | 29 | 44 | 18 | 9905 | 51 | 16 | 14 | 9788 | 69 | 22 | 18 | 9891 | 52 | 8 | 7 | 9743 | 79 | 25 | 19 | 9879 | 106 | 178 | 33 | 9862 | 35 |
| 1869 | 64 | 15 | 9904 | 29 | 45 | 17 | 9909 | 51 | 16 | 12 | 9767 | 69 | 22 | 18 | 9891 | 52 | 8 | 7 | 9743 | 79 | 24 | 18 | 9875 | 106 | 179 | 32 | 9886 | 35 |
| 1870 | 64 | 15 | 9904 | 29 | 49 | 14 | 9903 | 51 | 18 | 15 | 9837 | 69 | 22 | 18 | 9891 | 52 | 9 | 7 | 9743 | 79 | 28 | 17 | 9873 | 106 | 190 | 29 | 9894 | 35 |
| 1871 | 84 | 19 | 9867 | 29 | 50 | 27 | 9883 | 51 | 20 | 15 | 9855 | 69 | 32 | 18 | 9849 | 52 | 15 | 14 | 9921 | 81 | 31 | 23 | 9852 | 105 | 232 | 116 | 9915 | 35 |

The first column gives the available number of gauges, the second gives the number that entered the selection, the third gives the highest CC ($\times 10^{-4}$) achieved and the fourth gives the S.D. of the estimated series (1871–1980) from the fitted regression. These details against the year 1871 are based on the IMD raingauge stations.

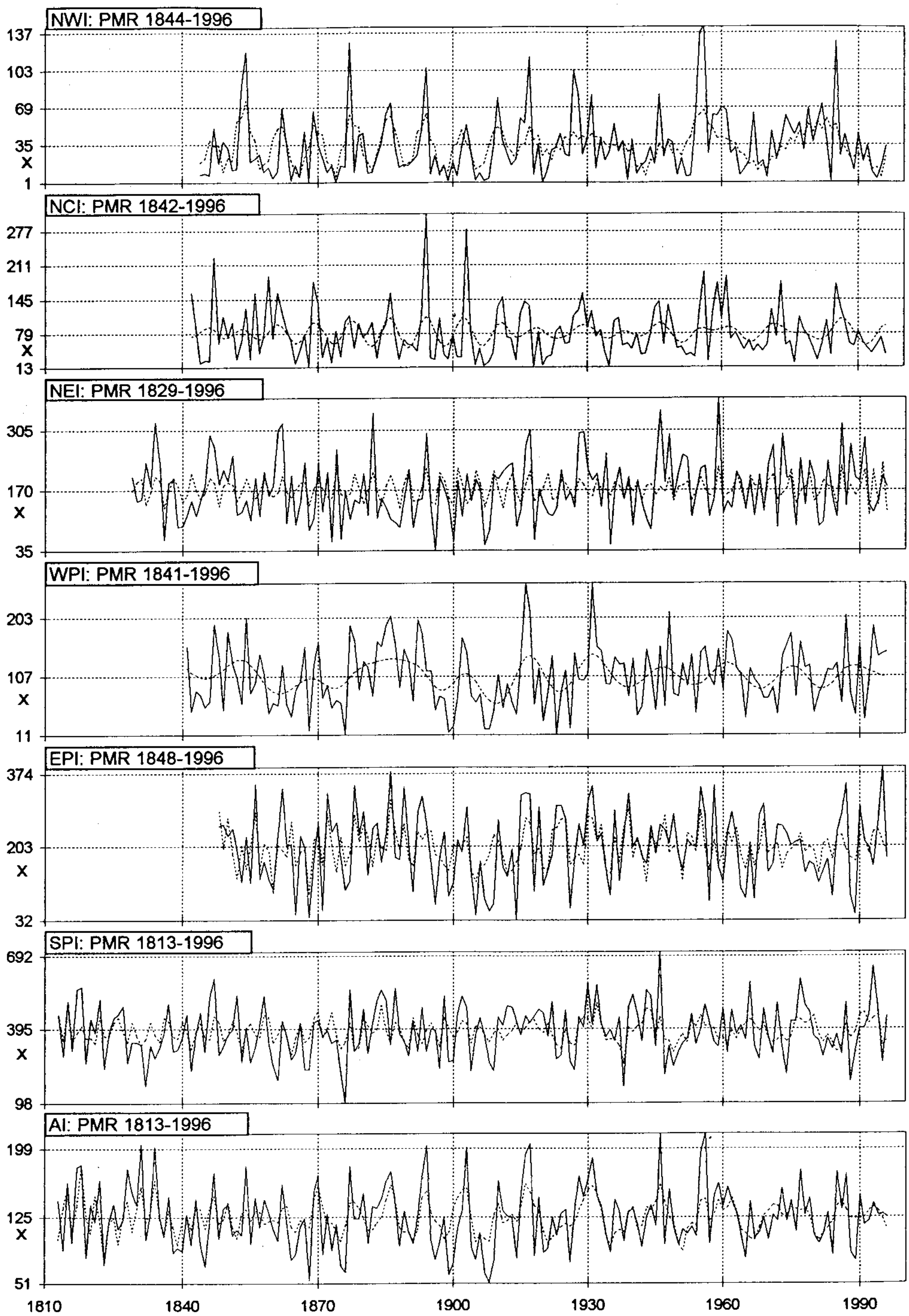


Figure 6. Reconstructed longest instrumental interannual PMR (in mm) of the six zones and the whole country (thin curve), and the smoothed version of the corresponding series (explained in the text; dotted curve)

Table V. Chief statistical properties of the regional and whole country PMR series (1848–1996)

| Statistical parameter | NWI | NCI | NEI | WPI | EPI | SPI | AI |
|---|---|---|---|---|---|---|---|
| Mean (mm) | 34.7 | 79.3 | 170.1 | 107.3 | 202.7 | 395.1 | 124.7 |
| S.D. (mm) | 29.3 | 50.0 | 69.0 | 51.5 | 82.3 | 105.2 | 33.8 |
| Coefficient of variance (mm) | 84.6 | 62.7 | 40.2 | 48.0 | 40.8 | 27.3 | 27.3 |
| Coefficient of skew ($g_1$) | 1.58 | 1.49 | 0.50 | 0.36 | 0.01 | 0.14 | 0.40 |
| Coefficient of kurtosis ($g_2$) | 2.56 | 3.47 | −0.09 | −0.27 | −0.67 | −0.09 | −0.03 |
| $g_1$/S.E. ($g_1$) | 7.95 | 7.51 | 2.51 | 1.83 | 0.03 | 0.73 | 2.01 |
| $g_2$/S.E. ($g_2$) | 6.49 | 8.78 | −0.24 | −0.69 | −1.70 | −0.23 | −0.08 |
| Median (mm) | 26.7 | 69.6 | 165.5 | 101.5 | 203.9 | 373.9 | 124.1 |
| Lower quartile (mm) | 14.0 | 41.9 | 117.1 | 67.0 | 143.9 | 305.0 | 98.7 |
| Upper quartile (mm) | 45.4 | 108.4 | 213.5 | 144.7 | 258.0 | 458.9 | 144.4 |
| Lowest value (mm) | 1.1 | 13.1 | 35.6 | 11.6 | 32.7 | 98.0 | 51.8 |
| % of mean | 3.2 | 16.4 | 20.7 | 10.8 | 16.2 | 25.4 | 41.9 |
| Year of occurrence | 1878 | 1872 | 1900 | 1880 | 1918 | 1880 | 1912 |
| Highest value (mm) | 142.7 | 311.7 | 378.1 | 258.2 | 388.2 | 709.7 | 215.5 |
| % of mean | 411.4 | 391.1 | 220.1 | 240.7 | 192.5 | 184.0 | 174.2 |
| Year of occurrence | 1960 | 1898 | 1963 | 1920 | 1995 | 1950 | 1960 |
| Autocorrelation ($r_1$) | $0.18^{5}$ | 0.06 | −0.11 | 0.12 | 0.02 | −0.00 | 0.11 |
| $t$-statistic | $1.81^{10}$ | 0.13 | $2.14^{5}$ | 0.93 | 1.06 | 0.89 | 1.62 |
| Mann–Kendall $\tau$-statistic | $0.11^{10}$ | −0.02 | 0.08 | 0.05 | 0.00 | 0.07 | 0.06 |
| No. of runs about the median | 61 | 68 | 82 | 72 | 67 | 77 | 69 |

Test statistics for detecting persistence and long-term trends are given in the last four rows.

## 8. CHARACTERISTICS OF THE RECONSTRUCTED REGIONAL AND ALL-INDIA PMR SERIES

### *8.1. Chief statistical characteristics*

To facilitate comparison between zones, the chief statistical characteristics of the different PMR series were determined based on data of the longest common period 1848–1996, given in Table V. The mean PMR over the zones increases in the order NWI (35 mm), NCI (79 mm), WPI (107 mm), NEI (170 mm), EPI (203 mm) and SPI (395 mm), and the coefficient of variation decreases in the same order from 85 to 27%. This is consistent with the well-known relationship between rainfall and variability. According to Fisher's $g$-statistic test, the distribution of WPI, EPI and SPI series is Gaussian, but all-India and NEI series suffer from significant positive skew and NWI and NCI from both significant skew and kurtosis. Table V gives some other important statistical parameters that are self-explanatory.

### *8.2. Fluctuation characteristics*

From the application of three statistical tests, the Mann–Kendall rank test against randomness, the Swed–Eisenhart run test and Student's $t$-test for the difference between mean rainfall of the two equal subperiods, it was ascertained that the long-term trend in the PMR fluctuations during the common period 1848–1996 is not significant for any one zone or the country as a whole; the test statistics are given in Table V. To examine short-term features, the Cramer's $t_k$-statistic test was applied on 11- and 31-year running means of the full reconstructed series, and the results are shown in Figure 7. Over NWI, the PMR has become more variable in the present century, showing a downward trend in recent years. The NCI displayed the most stationary behaviour among all the series analyzed. The 11-year mean of NEI attained its lowest value centered around 1888, after which fluctuations became larger, with a slight upward trend. WPI showed large fluctuations prior to 1910, but these moderated somewhat after this time. The EPI short-term features are similar to those of WPI. SPI showed a declining trend from the beginning of the data period and attained its lowest (significant at the 5% level) value around 1864; thereafter, an increasing tendency continued up to 1940, followed by a stationary trend. The all-India 11-year mean was lowest (significant at the 1% level) around 1904, its fluctuation being generally below the long-term mean prior to 1904 and above it after this time. The long-term features as revealed by the 31-year running means are: an upward trend in NWI and NEI, stationary features in NCI, WPI, SPI and all-India, and a downward trend in EPI.

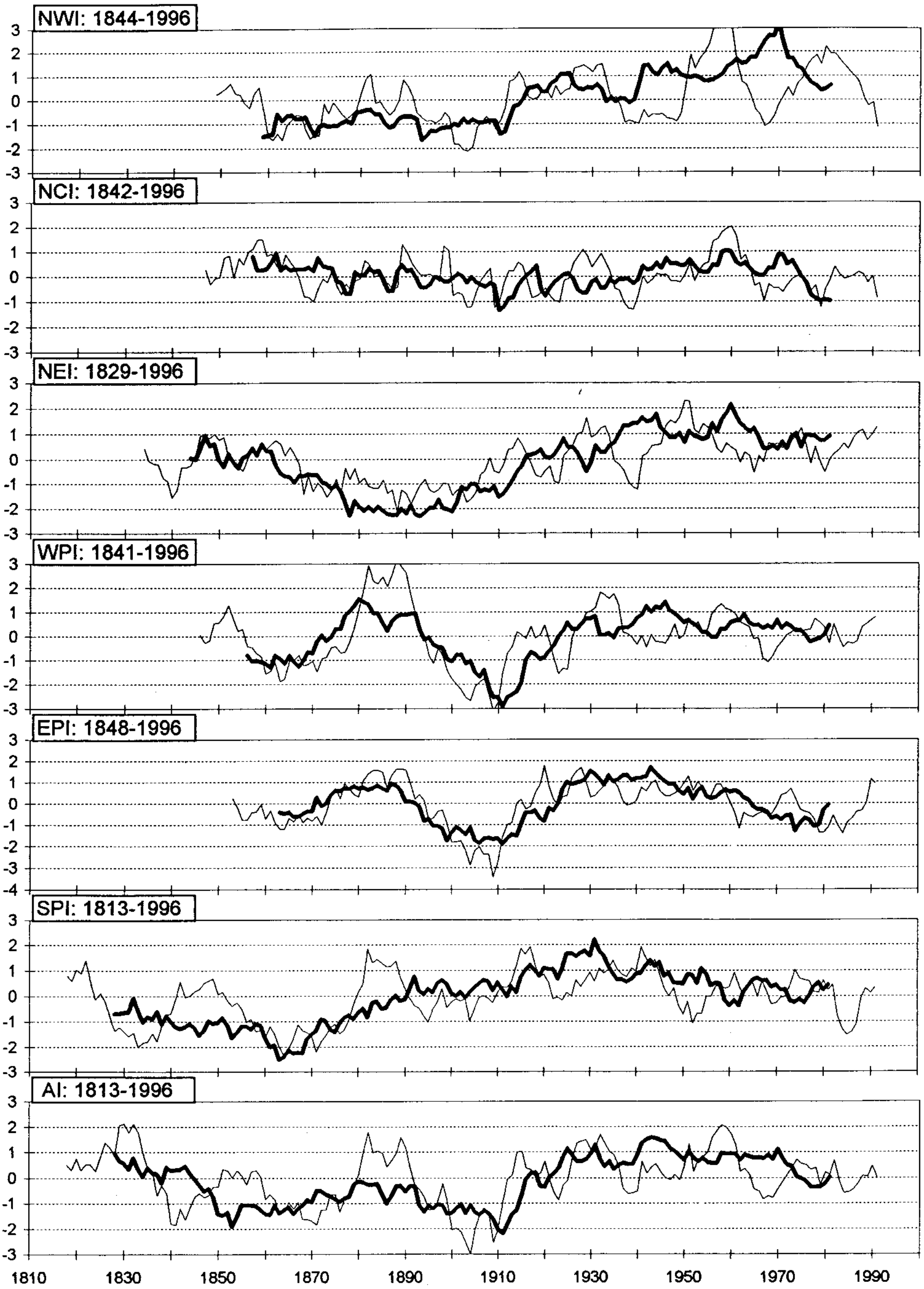


Figure 7. Plot of Cramer's $t_k$-statistic applied to the departure of 11- and 31-year running means of the different series from the respective overall mean. Thin, curved line is for the 11-year means and thick, curved line is for the 31-year means

## 9. INFLUENCE OF REGIONAL/GLOBAL CIRCULATION ON THE PMR

Studies in the past have identified regional and global circulation features that considerably influence the SMR variations over India. Investigation into whether their influence on the post-period rainfall patterns of the summer monsoon season persists is expected to be useful in two ways; first, to determine whether the potential predictor of the summer monsoon can be useful in predicting the PMR, and second, to add to the present knowledge regarding climate variability in the Indian subcontinent during the transit period between the southwest summer monsoon and the northeast winter monsoon. Thus, the genesis of the monsoonal wind/circulation and associated rainfall over this part of the globe will be better understood, and possible causes of their variations may be identified. Among others, Tomita and Yasunari (1996) hypothesized that northern hemisphere temperature, Indian summer monsoon, northeast winter monsoon, Walker Circulation, sea surface temperatures (SSTs) over tropical Indian and Pacific Oceans, trade winds, Pacific/North American (PNA) pattern, North Pacific Oscillation (NPO) and Eurasian Pattern are dynamically/thermodynamically linked in a quasi-biennial oscillation (QBO) mode. The 20 parameters that were selected for the study are shown below, with the period of data collection given in parentheses. With the exception of those indicated against the parameter, the association between these parameters and the Indian summer monsoon is reported by Mooley *et al.* (1985), Parthasarathy *et al.* (1988, 1990b) and others.

(i) Sea level pressure (SLP) at Mumbai: 18°54′N, 72°49′E (1941–1990).
(ii) SLP at Darwin: 12°28′S, 130°51′E (1941–1990).
(iii) SLP at Tahiti: 17°32′S, 149°35′W (1941–1990).
(iv) SLP at Cape Town: 33°56′S, 18°29′E (1951–1986).
(v) SLP at Agalega: 10°26′S, 56°45′E (1941–1990).
(vi) SLP at Nouvelle: 37°50′S, 77°34′E (1941–1990).
(vii) SLP at six selected stations over West Central India: mean of Jodhpur, Ahmedabad, Mumbai, Indore, Sagar and Akola (1941–1990).
(viii) SLP difference between South America: mean of Buenos Aires 34°35′S, 58°29′W; Cardoba 31°19′S, 64°13′W; Santiago 33°26′S, 70°41′W; and Mumbai (1951–1986).
(ix) SLP difference between Tahiti and Darwin (1941–1990).
(x) SLP difference between Tahiti and Mumbai (1941–1990).
(xi) Surface air temperature (SAT) over the northern hemisphere (Verma *et al.*, 1985; 1941–1987).
(xii) SAT over India (Parthasarathy *et al.*, 1990a; 1941–1988).
(xiii) SAT over Pakistan (Singh and Sontakke, 1996b; 1941–1993).
(xiv) SST at Niño West: 160°E–150°W, 5°N–5°S (1940–1986).
(xv) SST over the Indonesian region: 120°E–160°E, 5°S–15°S (Nicholls, 1995; 1949–1991).
(xvi) SST at Puerto Chicama: 08° S, 79°W (Parthasarathy and Sontakke, 1988; 1941–1989).
(xvii) Frequency of westerly wind days over Britain (Singh, 1995; 1941–1989).
(xviii) 50-mb QBO at Balboa: 9°N, 80°W (Singh, 1995; 1951–1987).
(xix) 30-mb QBO at Balboa (Mukherjee *et al.*, 1985; 1951–1987).
(xx) 10-mb QBO at Balboa (Bhalme *et al.*, 1987; 1958–1986).

The correlation is calculated using the 3-month running mean of the parameter from the preceding through the concurrent to the following 1-year period, with respect to the post-monsoon season over India. For brevity, the results are presented in Figure 8 for all-India only; however, a brief description is also provided for other zones.

*All-India*: significant correlation was shown by only seven parameters, i.e. the SLP at Mumbai, Tahiti, Nouvelle and the west coast of India; the SLP difference between South America and Mumbai, and between Tahiti and Mumbai; and the SST over the Niño West area; and by the Balboa 10-mb zonal wind. With the exception of the Tahiti SLP and the Niño West SST, the different parameters showed correlation of the same sign as with the SMR.

*Northwest India*: significant correlation was shown by the SLP at Mumbai, Darwin, Capetown, Nouvelle and West Central India; the SLP difference between South America and Mumbai; the Pakistan temperatures; the SST over the Niño West area and that over Puerto Chicama; and by the Balboa 10-mb zonal wind. A good number of parameters that showed a significant correlation with the summer

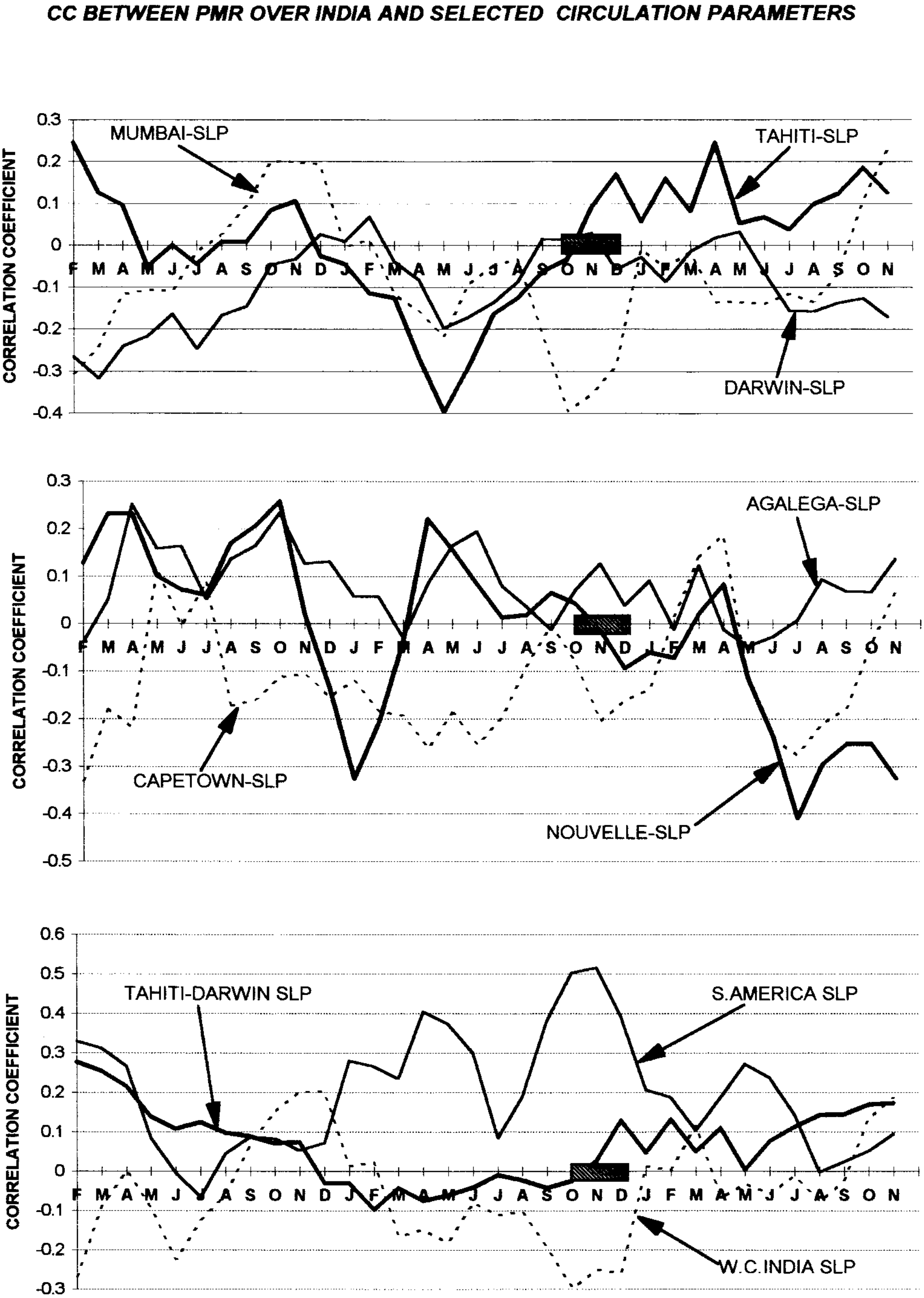
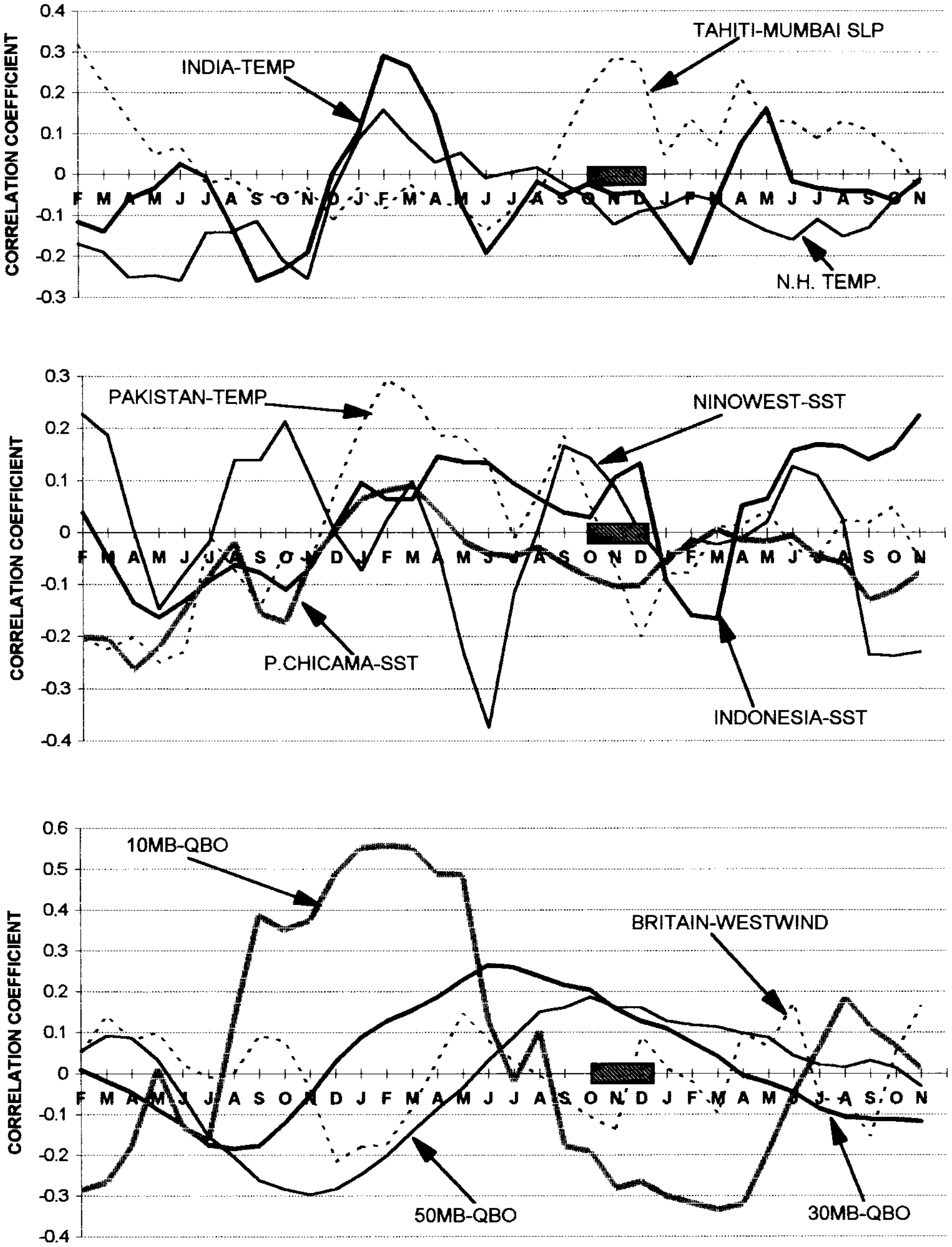


Figure 8. The CC between the 3-month running mean from the preceeding year through the present to the following year of the indicated CP and the all-India PMR (data used in the calculation is given in the text)



CC BETWEEN PMR OVER INDIA AND SELECTED CIRCULATION PARAMETERS

Figure 8 (*Continued*)

monsoon also showed a significant correlation with the PMR of the area. However, in the case of the post-monsoon, the period(s) of significant correlation occur well before the start of the season.

*North Central India*: only seven parameters, i.e. the SLP at Mumbai, Darwin, Capetown, Nouvelle, the west coast of India; and the SLP difference between South America and Mumbai; and the Balboa 10-mb zonal wind showed significant correlation. It is interesting to note that with the exception of the SLP at Nouvelle, the period of occurrence of different parameters is well ahead of the season.

*Northeast India*: contrary to popular belief, a much greater number of parameters showed significant correlation with the PMR over this area. The parameters are: the SLP at Mumbai, Capetown, Agalega and the west coast of India; the SLP difference between South America and Mumbai, Tahiti and Darwin, and Tahiti and Mumbai; the SAT over India and over Pakistan; the SST of the Indonesian region and the Balboa 50-mb zonal wind. With respect to the lead-time occurrence period of the significantly correlated CPs, it is much earlier compared to the summer monsoon rainfall over the area.

*West Peninsular India*: the parameters that showed significant correlation in the concurrent and the preceding periods are: the SLP at Mumbai, Capetown and the west coast of India; the SLP difference between South America and Mumbai; and the 50-mb zonal wind over Balboa.

*East Peninsular India*: the parameters of the preceding and the concurrent period that showed significant correlation are: the SLP at Mumbai and that at Tahiti; the SLP difference between South America and Mumbai; the SAT of India; and the SST of the Niño West area. The development of a predictive model does not seem to be an easy task.

*South Peninsular India*: the SLP at Mumbai, Darwin, Tahiti, Agalega and Nouvelle; the SLP difference between Tahiti and Darwin and between Tahiti and Mumbai; and the SAT over India, Pakistan and that over the northern hemisphere showed significant correlation. Some of the parameters, such as the SLP at Tahiti, the SLP difference between Tahiti and Darwin and between Tahiti and Mumbai and the SAT, showed correlation of an opposite sign to that shown with the SMR of the area. To a large extent this is consistent with normal expectations, since there is a reversal in the mean flow of the lower tropospheric wind from southwest to northeast. However, pressure, wind and thermal conditions must be conducive for low level moisture convergence, convective activities, enhanced vertical velocities and rainfall over the Indian region during the October–December period. In what manner, then, does the reversal in direction of certain processes continue to help the rainfall activities of the post-monsoon period despite other parameters which show correlation of the same sign as with the SMR? Any attempt to obtain a physical picture of this situation will raise doubt as to whether the correlation is realistic or mere a chance. For a moderate correlation value of around 0.4, a change in the sign of correlation between two parameters with the change in the data period is not unexpected.

## 10. PREDICTION BY MODELLING AND EXTRAPOLATING THE LONGEST PMR SERIES

Extrapolation through modelling climatic time series is one of the empirical approaches to climate prediction (Schickedanz and Bowen, 1977; Kane and Teixeiro, 1990 and others). The different methods in use have their own merits and limitations. The method developed and used in this study consists of three components: singular spectrum analysis (SSA), variable (or non-integer) harmonic analysis (VHA) and selection of an optimum number of harmonics whose combination shows the highest correlation with the series subjected to the VHA. The combination of selected variable harmonics is extrapolated to make the prediction.

### *10.1. Singular spectrum analysis*

Experience suggests that it is generally difficult to model the interannual climatic time series; even if some complicated function is fitted, the prediction is not reliable. The purpose of the SSA is to smooth out the slowly varying low-frequency mode fluctuations in the series, which will be subjected to modelling and extrapolation. The SSA provides flexibility to retain a near-desired portion of variance in the smooth series. A detailed account of SSA is given in Vautard *et al.* (1992).

SSA is based on principal component analysis (PCA) in the vector space of delay coordinates for a time series $\{\text{e.g. } x_j,\ j = 1, 2, 3 \ldots N\}$. It extracts as much reliable information as possible on the dominant modes of fluctuation without using prior knowledge about the underlying physics or biology of the system and thus provides valuable information for the development of predictive models. Its superiority over classical spectral methods lies in the data-adoptive character of the eigenelements it is based on. To obtain smoother series retaining a near-specified portion of the actual series variance, the different calculations, carried out in order, are:

(i) Preparation of the Toeplitz matrix using serial covariance up to a maximum of 31 lags.
(ii) Computation of the eigenvalues of the Toeplitz matrix and their eigenvectors.
(iii) Computation of the principal components using the actual data and the eigenvectors.
(iv) Reconstruction of the series using a few principal components and their corresponding eigenvectors.

In a unified manner, a fixed number of lags (31) is used for the different series. This is decided after a few experiments. It is seen that more than 99% variance can be restored in the reconstructed series if all 31 principal components derived from the Toeplitz matrix of size 31 × 31 are combined; more are neither necessary nor desirable. A singular spectrum is shown in Figure 9 for the different zones and for all-India, which also gives the cumulative variance explained by the eigenvalues. The smoothed series of the desired length $N$ can be reconstructed ($\boldsymbol{R}_\alpha x$), and can also be called reconstructed components (RCs), by projection of any specified subset of principal components ($\boldsymbol{a}$) of length $N-M$, on their eigenvectors (empirical orthogonal functions (EOFs), $\boldsymbol{E}$) using the following three expressions obtained from the least-squares solution (Vautard *et al.*, 1992):

$$(\boldsymbol{R}_\alpha x)_i = \frac{1}{M}\sum_{j=1}^{M}\sum_{k\in\alpha} \boldsymbol{a}_{i-j}^{k}\boldsymbol{E}_j^k \quad \text{for } M \le i \le N-M+1 \tag{2}$$

$$(\boldsymbol{R}_\alpha x) = \frac{1}{i}\sum_{j=1}^{i}\sum_{k\in\alpha} \boldsymbol{a}_{i-j}^{k}\boldsymbol{E}_j^k \quad \text{for } 1 \le i \le M-1 \tag{3}$$

$$(\boldsymbol{R}_\alpha x) = \frac{1}{N-i+1}\sum_{j=i-N+M}^{i}\sum_{k\in\alpha} \boldsymbol{a}_{i-j}^{k}\boldsymbol{E}_j^k \quad \text{for } N-M+2 \le i \le N \tag{4}$$

The subscript '$\alpha$' denotes the set of all principal components calculated. It should be noted that the index number $i-j$ is valid when the elements of the principal components are also stored in the 0th row; if stored from the first row, the starting index number will be $i-j+1$.

### 10.2. Variable harmonic analysis

VHA was developed from classical harmonic analysis (Schickedanz and Bowen, 1977). The method is adopted mainly for two reasons: (i) it is computationally simple and easy to visualize the results; and (ii) its application has not been explored much in long-range weather or short-term climate predictions. In essence, the method is a generalization of classical harmonic analysis, in which the sine and cosine waveforms are computed for periods which are integer as well as multiples of the fundamental period. In contrast with classical harmonic analysis where the number of harmonics are limited to half the number of data points and all of them close at the end points, in VHA, depending upon wavelength resolution within a fundamental period, any number of harmonics can be estimated in which all non-integer harmonics will be open-ended. Other notable differences are sine and cosine functions of two different harmonics, as well as sine and cosine functions of the same harmonic, which are orthogonal in classical analysis, but are correlated, albeit weakly, in the VHA. Continuity of waveforms beyond the fundamental length makes the VHA a potential tool for extrapolation. The sine coefficient (a) and cosine coefficient (b) are defined by the expressions:

$$a_p^i = \left(\frac{2}{N}\right)\sum_{j=1}^{N} x_j \sin(p) \tag{5}$$

$$b_p^i = \left(\frac{2}{N}\right)\sum_{j=1}^{N} x_j \cos(p) \tag{6}$$

$$b_2 = \left(\frac{1}{N}\right)\sum_{j=1}^{N} x_j \cos(2\pi j/p) \tag{7}$$

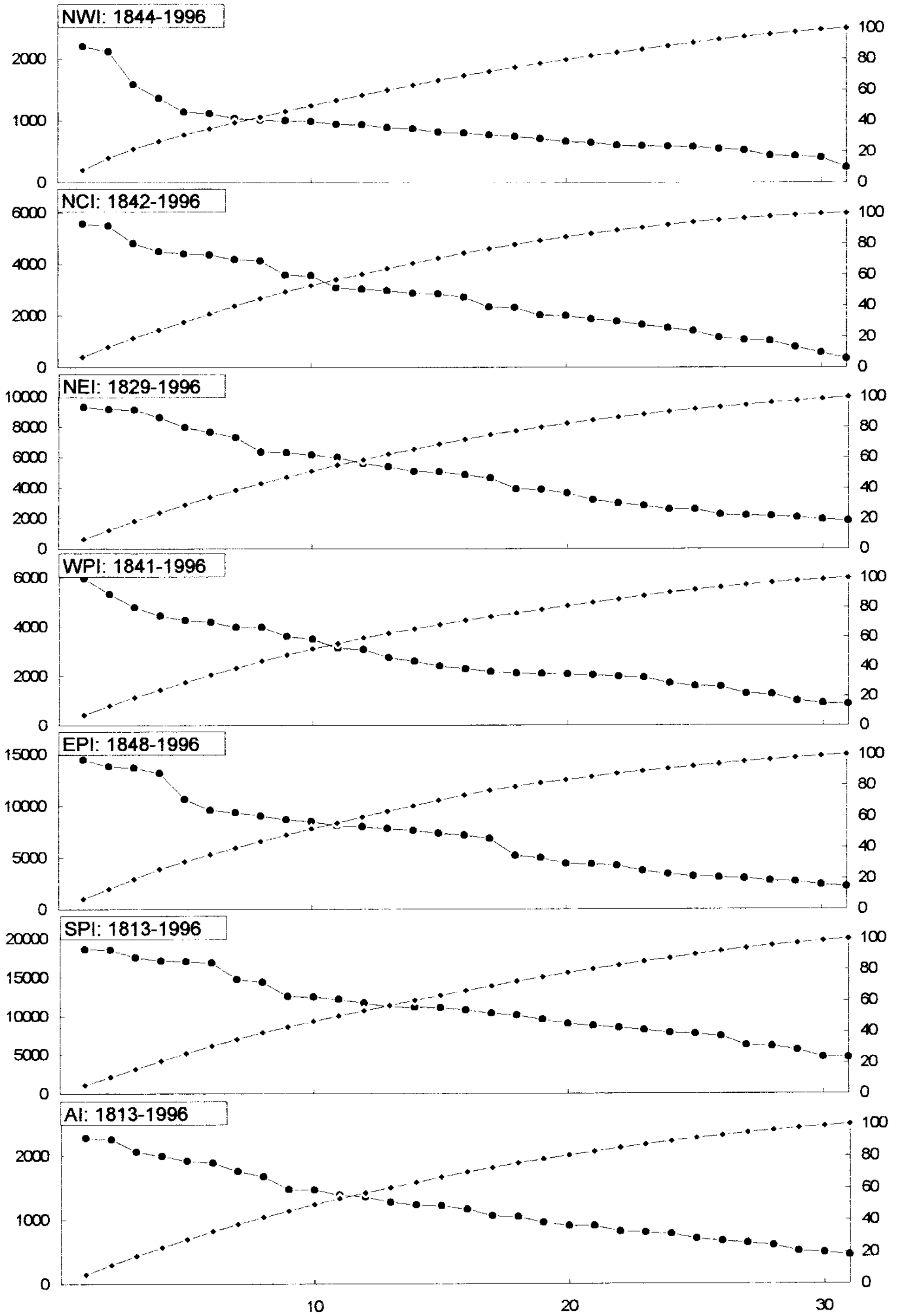


Figure 9. SSA of the different PMR series derived from the autocovariance Toeplitz matrix of size 31 × 31 (dotted line with closed big circles). The cumulative percent variance contribution is shown by the dotted line with small closed squares

where $p$ is the wavelength of the variable harmonic denoted as $i$ and $i$ is a counter for the number of waveforms that are calculated. The wavelength $p$ of the particular harmonic and fundamental period $P$ are related as follows.

$$p = P - \beta(i - 1) \tag{8}$$

where $\beta$ is the chosen wavelength resolution (0.1 year) for the spectral estimation. The ratio of $P$ to $p$ will give the frequency of the variable harmonic with period $p$, and it can be an integer or a non-integer number.

Figure 10 gives the normalized spectrum of the different PMR series, which suggests large concentration of variance in the wavelength region of $< 10$ years. However, there are significant peaks in the wavelength region $> 10$ years, while at times there are also peaks in the region $> 80$ years. Reliable prediction can be expected from the extrapolation of long waves beyond the data period, although they possess limited variance. Prediction by extrapolating short wavelengths is generally not reliable.

### *10.3. Prediction of the future trend for a 10-year period*

The procedural details are such that will suitably graduate the actual/smooth PMR series using a linearly combined optimum number of selected variable harmonics to test the extrapolation on a 10-year independent period and to predict the fluctuation over a 10-year future period.

(i) Reconstruct the series using the first principal component and its eigenvectors.
(ii) Subject the reconstructed series to VHA, excluding the data of the latest 10-year period (independent sample for verification).
(iii) Select objectively an optimum subset of about five to six wavelengths whose combination shows a high correlation of $\sim 0.85$ with the reconstructed series (Singh, 1994). In this process, the selection preference should be given to longer wavelengths (longer than 10 years). If the desired correlation ($\sim 0.85$) is not achieved, then 8-, 7- etc. year wavelengths can also be considered successively.
(iv) Estimate the least-squares linear regression of the reconstructed series on the mean of the selected wavelengths.
(v) Compare the result of the fitted regression on the independent sample of 10 years; if it is satisfactory, make a prediction for 10 years from the fitted model.
(vi) If less than six wavelengths showed a correlation of 0.85, reconstruct the series using the first two principal components and repeat the above calculations.
(vii) Continue the process of reconstructing the series by involving one additional principal component each time.
(viii) Discontinue the process if the CC limit of $\sim 0.85$ is not attained.

If the prescribed specification is not achieved in any of the series, the best-possible result obtained after various experiments by:

(i) changing the number of PCs in reconstructing the series;
(ii) allowing only the wavelengths of specified periods;
(iii) changing the limit of the attainment of highest correlation in the optimum selection of wavelengths; and
(iv) testing that the performance of the model on the independent sample of the 10-year period is satisfactory.

### *10.4. Results of the predicted future trend*

The number of PCs finally considered in the reconstruction of the series and the percentage variance explained (PVE) by it are given in Table VI; the reconstructed series is presented in Figure 6 along with the original version. The PVE shows the portion of the actual series variance that can be explained by extrapolating the dominant subset of selected wavelengths. The optimum number of wavelengths were selected one by one in a manner similar to the forward selection of the independent parameters in the multiple linear regression model. The number of wavelengths that entered the selection and the CC achieved are also given in Table V for the different series. The results of the fitted model along with the reconstructed series are shown in Figure 11. For the independent sample of the 10-year period from 1987 to 1996, the performance of the model is found to be satisfactory in the case of NWI, NCI, WPI and all-India. It is partially satisfactory in the cases of EPI and SPI, but worse in the case of NEI. Over NWI, the PMR is likely to decrease up to 2000 AD and then increase; over NCI, it is likely to decrease up to 1999 AD, increase up to 2004 AD and then decrease; over WPI, it is likely to be above normal in the forthcoming 10-year period; over EPI, it is likely to increase up to 1998 AD, decrease up to 2004 AD and then increase; and over SPI, it is likely to decrease up to 1998 and then increase. It is clear from these

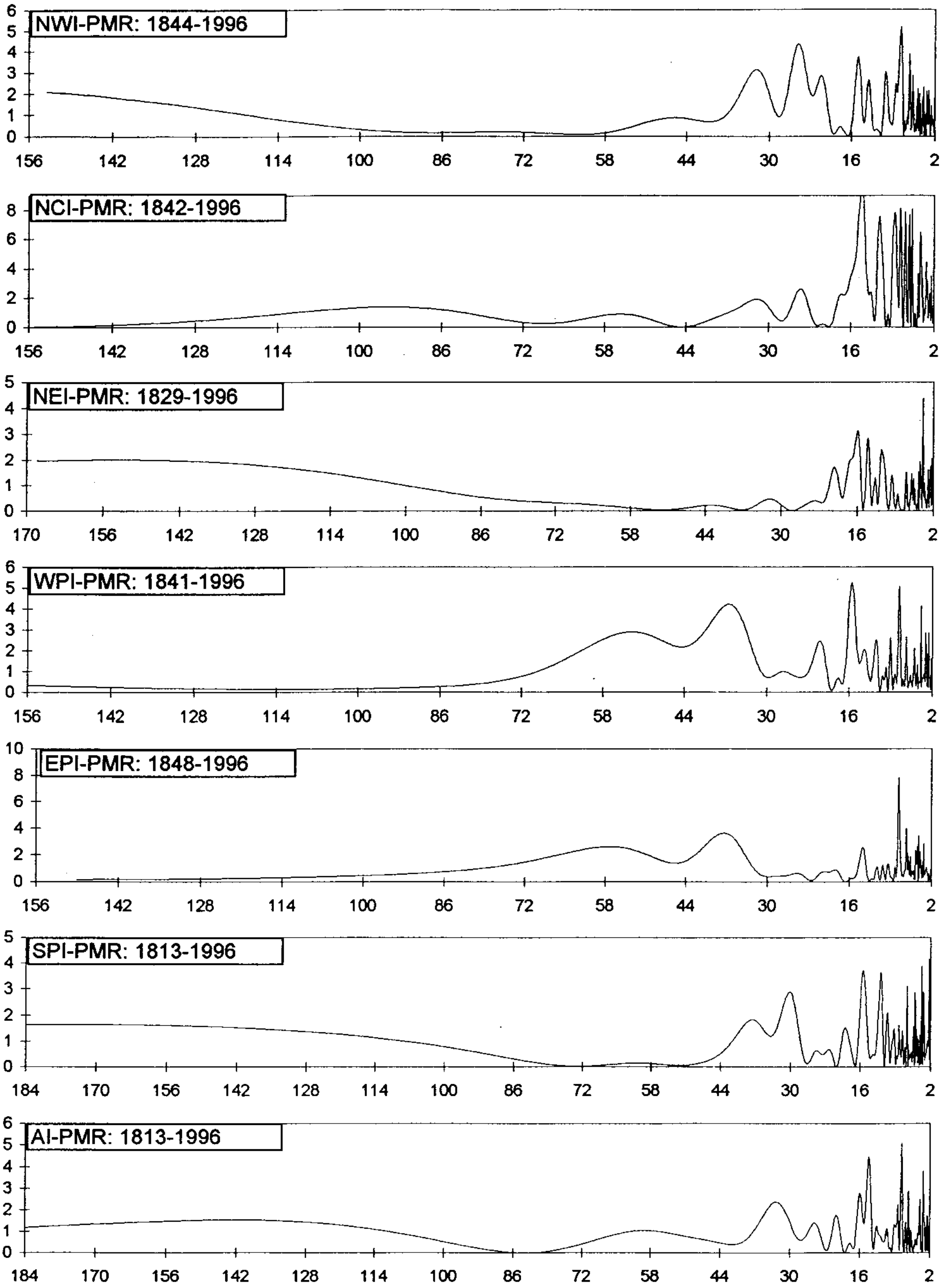


Figure 10. Normalised power spectrum of the longest reconstructed zonal and all-India PMR series obtained using the VHA technique. The scale is in years

Table VI. Details of the modeling of the reconstructed PMR series

| | PCs | PVC | Wavelengths considered (years) | Wavelengths selected (years) | CC achieved |
|---|---|---|---|---|---|
| NWI | 5 | 30.9 | >8 | 8.0, 25.0, 8.4, 21.4, 31.0, 9.0 | 0.86 |
| NCI | 2 | 13.1 | >5 | 8.4, 7.9, 9.0 | 0.87 |
| NEI | 3 | 18.1 | All | 3.9, 4.0, 3.8 | 0.88 |
| WPI | 3 | 18.9 | >7 | 15.3, 38.2, 13.6 | 0.87 |
| EPI | 6 | 35.3 | >5 | 7.5, 40.4, 57.1, 6.8, 8.4 | 0.68 |
| SPI | 5 | 25.9 | >4 | 11.9, 14.7, 12.7, 16.1, 10.6, 13.6 | 0.61 |
| AI | 6 | 32.6 | All | 14.2, 7.6, 3.3, 15.7, 8.4, 3.2 | 0.85 |

Shown are: the number of principal components (PCs) combined; the percentage variance contained (PVC); the wavelengths of the variable harmonics that were considered in the selection; the wavelengths that entered the selection (in order); and the CC achieved between the reconstructed series and the selected wavelengths.

projections that there is not going to be any consistent pattern in PMR variations over different parts of the country. There does not seem to be any influence on the PMR over the Indian region from large-scale changes in climatic conditions, such as global warming. Overall, the PMR over the Indian region is likely to have a tendency to increase over the next 10 years, as shown by the all-India rainfall tendency.

## 11. SUMMARY AND CONCLUDING REMARKS

i) Large-scale variability of the PMR over India was studied by examining the expansion and contraction of the wet area (October–December rainfall > 200-mm PMWA) over a long period (1871–1984). The interannual variation of the PMWA is large, free from Markovian-type persistence, and does not show any significant long-term trend. Short-term fluctuations of the PMWA showed epochal behaviour, consistent with the large-scale features of the summer monsoon rainfall over the country.

ii) Small-scale features were studied, bearing in mind the requirements of practical problems and regional differences in the post-monsoon circulation and associated rainfall. The longest-possible instrumental area-averaged PMR was reconstructed for the six zones and the whole country by applying established objective approaches. A reliable representative series for NWI was reconstructed for 1844–1996; for NCI, 1842–1996; for NEI, 1829–1996; for WPI, 1841–1996; for EPI, 1848–1996; and for SPI and all-India, 1813–1996. The WPI, EPI and SPI series of the main PMR belt are Gaussian, while the others significantly different from normal distribution. The long-term trend is not significant in any of the series. Short-term features evaluated from 11- and 31-year means characterized by short-term upward/downward trends, distinct wet/dry epochs and oscillatory behaviour showed regional differences. The different PMR series are weakly correlated among themselves.

iii) From a large number of CCs worked out using 20 selected regional/global CPs and the zonal and all-India PMR series, as well as from the widely varied results obtained, our inference is that different CPs showed correlation of the same sign, albeit weaker in strength, with the post-monsoon as with the SMR, implying that the same forcing factors operate on the rainfall patterns of both periods.

iv) An attempt to predict the interannual variation of the PMR by extrapolating a combination of a few wavelengths was not found to be satisfactory, either for any of the six zones or for all-India. Some interesting results were obtained when the technique was applied after smoothing the series to predict the future trend of rainfall fluctuations over the 10-year period. By smoothing, only limited variance—generally from the low-frequency side—was retained. Over NWI, the PMR is likely to decrease up to 2000 AD and then increase; over NCI it is likely to decrease up to 1999 AD, increase up to 2004 AD and then decrease; over WPI it is likely to be above-normal in the forthcoming 10-year period; and over EPI it is likely to increase up to 1998 AD. A reliable prediction could not be made for NEI. For the country as a whole, the PMR is likely to have a tendency to increase over the next 10-year period.

The detailed information about the variability of PMR over India is expected to make a valuable contribution to studies intended to increase the understanding of the genesis and causes of variability of the two planetary-scale atmospheric circulation systems that are the northern summer southwest monsoon and the northern winter northeast monsoon occurring over the tropical Indian Ocean.

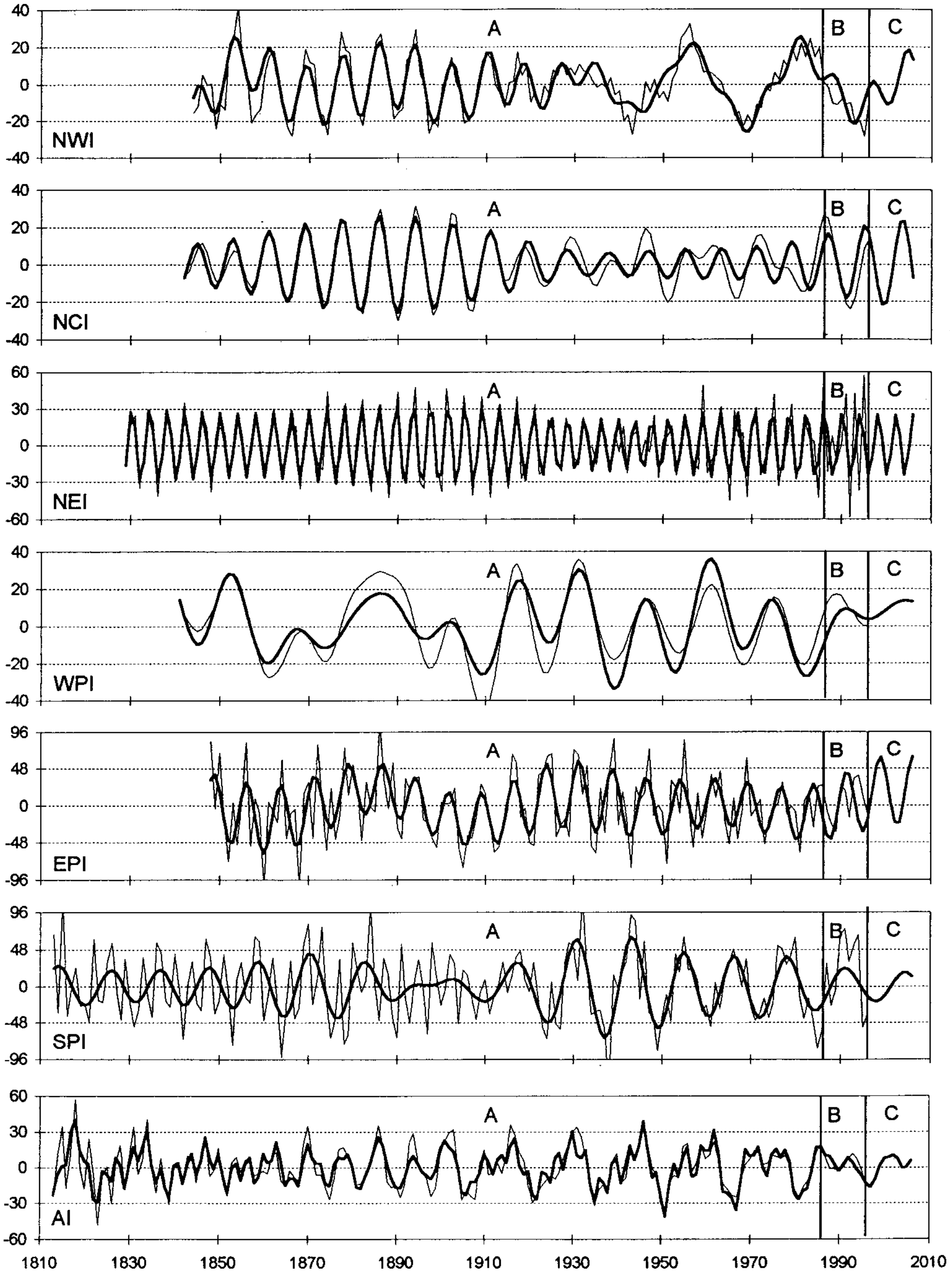


Figure 11. Filtered (thin curve) and estimated (thick curve) PMR series of the six zones and the country as a whole. A indicates the dependent sample period (from the start of the series up to 1986); B indicates the independent sample period (1987–1996); and C indicates the prediction for a 10-year future period (1997–2006)

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