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Patterns of India monsoon rainfall anomalies

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ABSTRACT

Pattern characteristics of annual rainfall anomalies over India during 1900–72 are studied from precipitation records of 31 regional subdivisions and series of annual cyclone frequency and number of break monsoon days. Methods include spatial correlation, pattern stratification, and principal component and spectral analyses.

Pattern stratification with respect to an all-India rainfall index yields largest concordant departures in the Central and Western portions of the country. Pattern stratification with respect to the largest annual frequency of cyclonic storms in the Bay of Bengal and Arabian Sea show large positive rainfall departures over Eastern, Southeastern and Western India, and negative departures in the North and a limited area of the Southwest; for the collective of years with smallest storm frequency a partly inverse rainfall anomaly pattern is obtained. Pattern stratification with respect to the years of most numerous break monsoon days yields deficient rainfall in a large, broadly zonally oriented band across Central India, and positive departures in most other parts of ther country. Stratification with respect to the least numerous break monsoon days yields a broadly inverse pattern.

The first eight principal component patterns account for 74% of the total variance. The first component resembles the pattern obtained by stratification with respect to the all-India rainfall index, the two time series being highly positively correlated. The third component is approximately inverse to the pattern constructed from stratification with respect to the most numerous break monsoon days, the two time series being negatively correlated. The seventh component is similar to the pattern derived from stratification with respect to the largest frequency of cyclonic storms; this is consistent with the positive correlation between the two time series. No physical significance is apparent for the other principal components. The combination of the various analysis techniques thus serves to identify spatial and temporal pattern characteristics of possible physical significance.

1. Introduction

Year-to-year variations of the summer Southwest monsoon and seasonal rainfall forecasting have been of central concern to Indian meteorologists for more than a century (Normand, 1953; Jagannathan, 1960; Rao, 1965; Rao, 1976). Their work is an important precursor to the current international endeavors directed at the mechanisms of interannual climate and circulation variability in the global tropics (World Meteorological Organization, 1980; World Meteorological Organization-ICSU, 1975). Thanks to the long meteorological tradition, the Indian sub-continent possesses the densest surface and upper air network in monsoon Asia. While precipitation varies greatly from year to year, rainfall anomalies are not uniform over the subcontinent (Subbaramayya, 1968). Such spatial diversity must be accounted for in diagnosing the circulation mechanisms of anomalies in monsoon rainfall. The purpose of the present study is to identify organized spatial patterns in seasonal rainfall departures, as a basis for subsequent investigations into the general circulation mechanism of interannual climate variability in the Indian Ocean sector.

2. Observations

Annual rainfall amounts for 31 subdivisions of India (Fig. 1) for the period 1900–72 were obtained from the India Meterological Department. Parthasarthy and Dhar (1974) evaluated the 1901–60

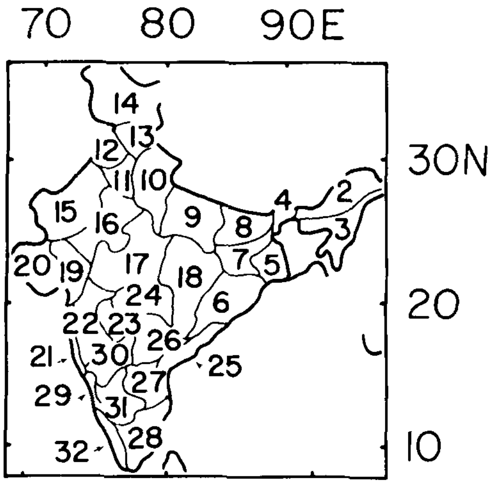

Fig. 1. Map showing rainfall subdivisions. Identification numbers are as used by the India Meteorological Department.

portion of this data set and consider the subdivisions as homogeneous regarding rainfall. For each area, departures of annual values from the long-term average were divided by the standard deviation, so as to obtain index series of normalized departures. In addition, an index series for India as a whole was constructed by calculating for each year the arithmetic mean of normalized departure of 31 subdivisions.

The annual number of break monsoon days during 1888–1967 was extracted from Ramamurthy (1969). Similarly, the annual number of cyclonic storms with winds exceeding 8 beaufort in the Arabian Sea and Bay of Bengal during 1891–1960 were copied from India Meteorological Department (1964). These series are considered as useful indices of synoptic climatology.

3. Methods

The techniques applied in Sections 4 to 8 include correlation, stratification, and principal component and spectral analyses. Correlation coefficients (Panofsky and Brier, 1958) are in part displayed in the form of isocorrelate maps. Stratification (Hastenrath, 1976, 1978; Hastenrath and Heller, 1977) is based on identifying extreme years in the rainfall, break monsoon, and cyclone frequency series; rainfall departure maps are the constructed for composites of such extreme years. Principal components are a set of orthogonal functions each depicting a prominent pattern from the data with disproportionately more variance explained by the first few components. The principal components can often be related to other fields of data, casting light on possible relationships of physical significance. For a description of the techniques, reference is made to Kutzbach (1967), Kidson (1975), and Davis (1976). Power spectra were calculated by means of an Illinois State Water Survey program (Schickedanz and Bowen, 1977; Hastenrath and Wendland, 1979; Hastenrath and Kaczmarczyk, 1981).

4. Spatial correlation

Fig. 2 portrays the spatial correlation between the rainfall in the 31 subdivisions of India. Rainfall departures in the Northwestern (subdivisions 14, 12, 13, 15, 11, 16, 20, 19, 22, 21, 29, 30, 31) and the Central portions (subdivisions 10, 17, 23, 9, 18, 24, 26) are strongly positively correlated. By contrast, the Northwestern and Central regions exhibit little coupling with the Northeast (subdivisions 2, 3, 4) and Southeast (subdivisions 27, 28). Fig. 2 broadly confirms a similar study by Subbaramayya (1968) limited to 1941–60.

5. Stratification

The all-India index series of normalized rainfall departure described in Section 2 was plotted in time series form, and the most extreme wet and dry years were identified as follows: 1917, 33, 46, 55, 56, 59, 61 as wet; and 1904, 05, 18, 20, 51, 65, 66, 68, 72 as dry. The all-India average normalized departure is $+1.3\sigma$ or larger for the 7 wet years. For the 9 dry years it is 1.5σ or beyond. Composite maps of normalized rainfall departure of these two collectives of opposing extremes are presented in Figs. 3a and b. Not surprisingly, map (a) shows mostly positive, and map (b) mostly negative departures. Values are largest in the Central and Western portions of the country, and patterns show some similarity with the isocorrelate maps, Fig. 2.

From similar time series plots of the frequency of cyclonic storms in the Bay of Bengal and Arabian Sea (Section 2), the following most extreme years

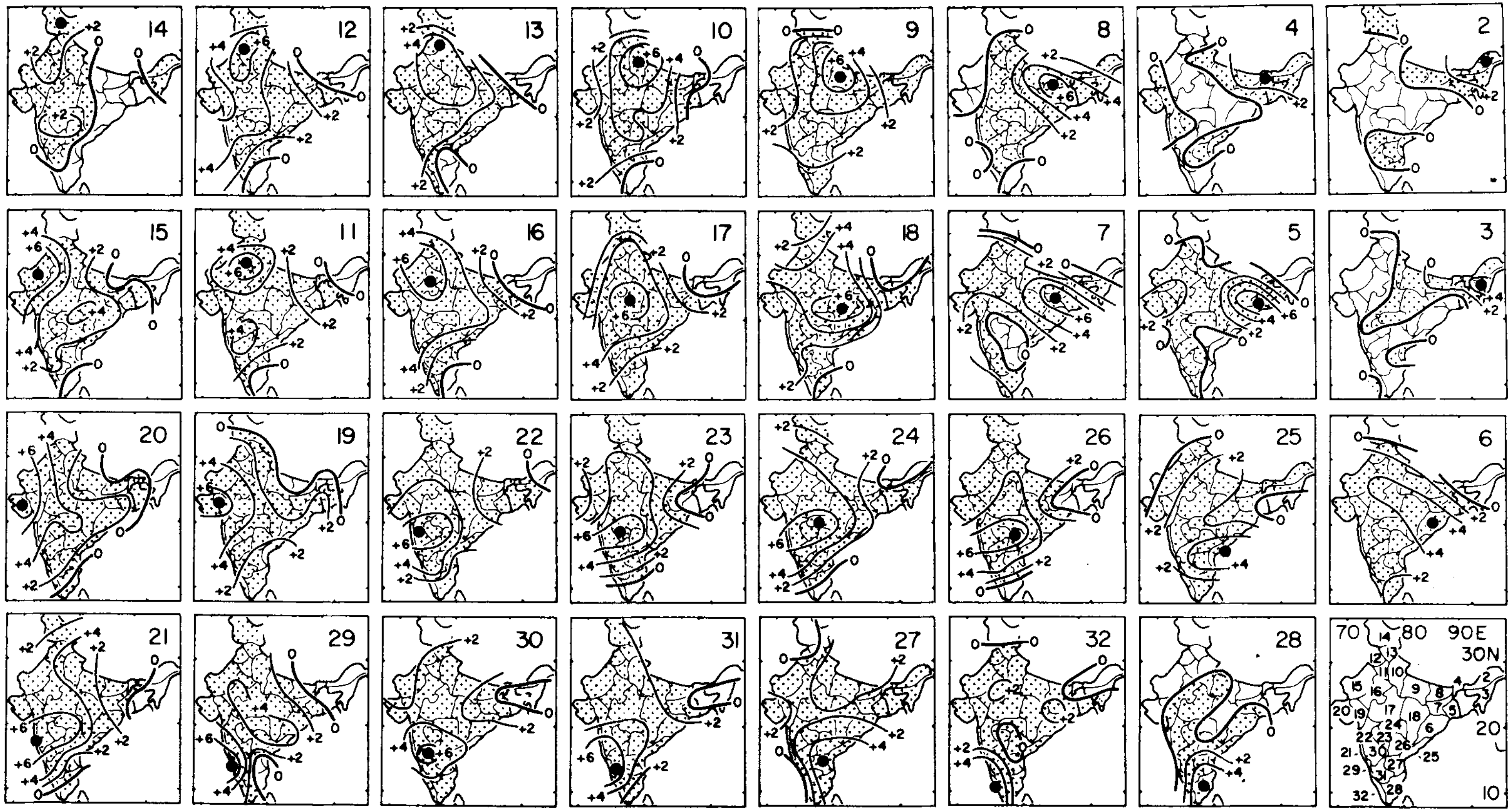

Fig. 2. Maps of correlation between annual rainfall in subdivisions. Isocorrelates are in tenths, zero line is heavy, and dot raster indicates positive areas. Subdivision orientation map is in lower right-hand corner.

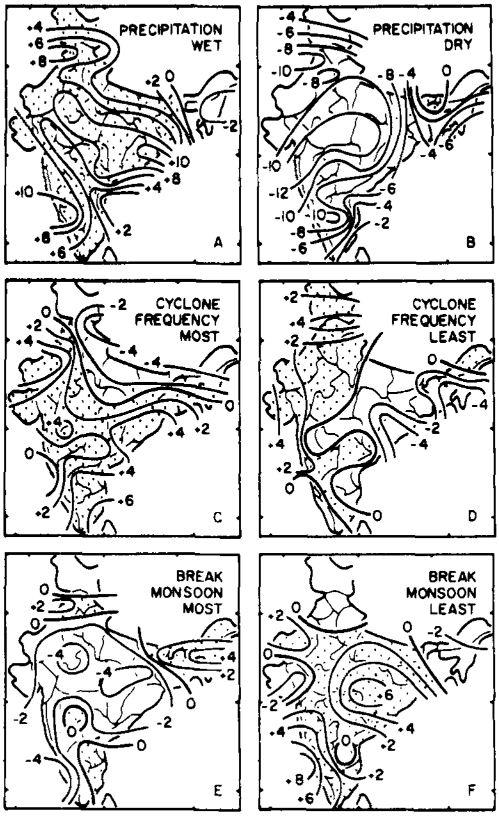

Fig. 3. Normalized departures of rainfall in hundredths for composites of extreme years: (a) all-India wet; (b) all-India dry; (c) storms most frequent; (d) storms least frequent; (e) break monsoon days most numerous; (f) break monsoon days least numerous.

were found: 1903, 07, 16, 26, 30, 40, 41, 44 as most frequent; 1901, 17, 20, 45, 49, 53, 54, 57 as least frequent. Composite maps of normalized departure for these two collectives of opposing extremes are displayed in Fig. 3c and d. The map (c) for the collective of largest storm frequency shows large positive rainfall departures over Eastern, Southeastern and Western India, and negative departures in the North and in a limited area of the Southwest. The map (d) for the collective of smallest storm frequency shows positive departures over most of the Western part of the country except the extreme Southwest, and deficient rainfall in the East and Northeast.

From the time series of the number of break monsoon days (Section 2), extreme years were selected as follows: 1906, 09, 10, 13, 15, 18, 32, 54 as having the most break monsoon days; and 1907, 23, 29, 31, 36, 40, 43, 44, 61 as having the least break monsoon days. Composite maps of normalized rainfall departure for these two collectives are presented in Figs. 3e and f. The map (e) for the collective of most break monsoon days shows deficient rainfall in a large broadly zonally oriented band across Central India, and positive departures in the Southeastern, Northern and Northeastern extremities of the country. The map (f) for the collective of least break monsoon days exhibits a pattern broadly inverse to the map (e). Moreover, map (e) is approximately opposite to the all-India wet composite map (a).

6. Principal components

Fig. 4 shows the patterns of the first eight (non-normalized) principal components of rainfall departure. Some of these resemble stratification maps presented in Fig. 3. In order to complement the visual impression, correlation coefficients are calculated (Table 1) between the time series of synoptic-climatological events used for stratification (Fig. 3) and the time series of the principal components (Fig. 4).

The first component (P1) explaining 28.8% of the variance exhibits factor loadings of one sign throughout most of the subcontinent with values decreasing towards the Northeast and Southeast. This component resembles the rainfall departure maps for composites of extremely wet and dry years in India as a whole (Fig. 3a, b), as well as the isocorrelate maps for subdivisions in West Central India (Fig. 2, subdivisions 19, 20, 22). The time series of P1 and of the all-India rainfall index are highly positively correlated (Table 1).

The second component (P2), explaining 10.5% of the variance, is dominated by factor loadings of one sign in the Northeast and loadings of opposite sign in the West, except the extreme Southwest of the subcontinent. This component resembles the isocorrelate maps for subdivisions in the Northeast (Fig. 2, subdivisions 5, 7, 8), and is similar to the rainfall departure pattern for the composite of extremely small storms frequency (Fig. 3d), with which it weakly negatively correlated (Table 1).

The third principal component P3, explaining 8.8% of the variance, shows factor loadings of one sign in a broad Northwest–Southeast oriented band across North-Central India.

The fourth principal component P4, explaining

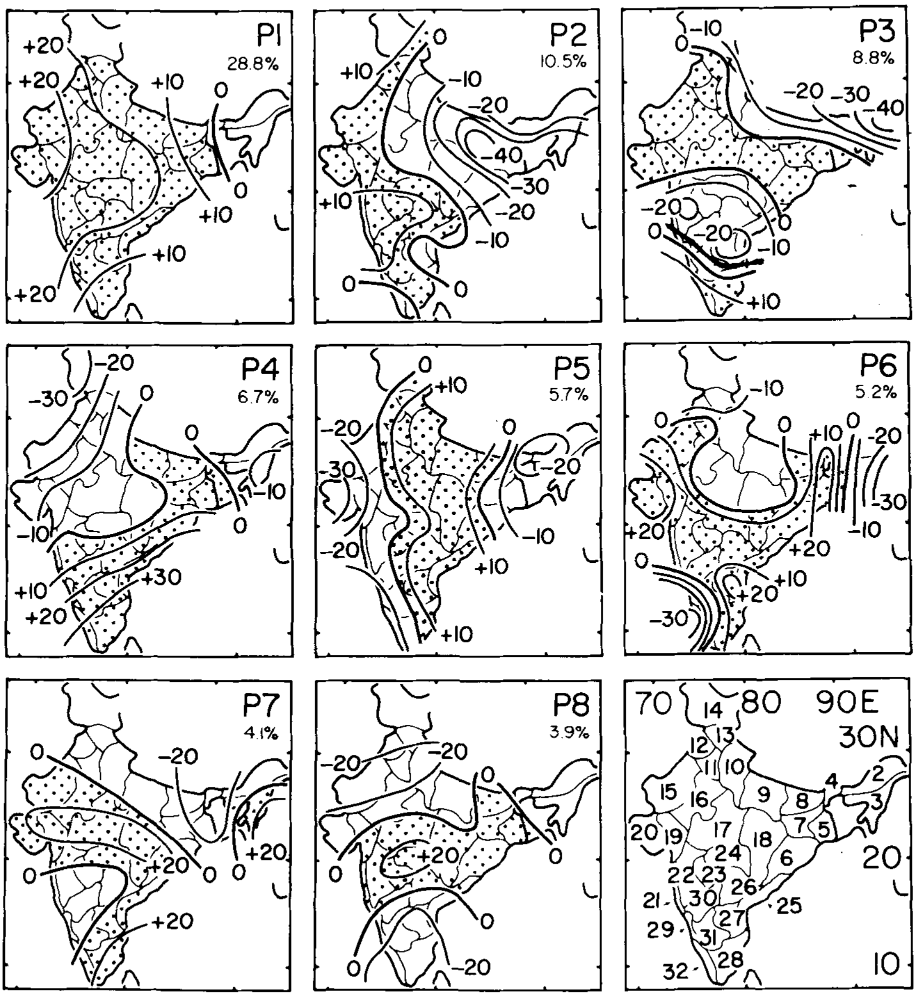

Fig. 4. Patterns of first eight principal components (non-normalized) of normalized rainfall departure, with percentage of explained variance.

6.7% of the variance, is characterized by factor loadings of one sign in the Northwest and extreme Northeast, and loadings of the opposite sign in the rest of the country, with largest values in the extreme Southeast. The fifth component P5, explaining 5.7% of the variance, has factor loadings of one sign in a North–South oriented band across Central India, and opposite loadings in the West and Northeast. The sixth component P6, explaining 5.7% of the variance, exhibits loadings of one sign in the extreme Southwest and North-Central part of the country, and opposite loadings throughout the rest of the subcontinent.

The seventh component P7, explaining 4.1% of the variance, shows factor loadings of one sign in a broad Northwest–Southeast oriented band across Central India, as well as in the Southeast and extreme Northeast, while opposite loadings cover much of the North and a limited area in the Southwest. The component P7 resembles the pattern for the collective of years with largest storm frequency (Fig. 3c). These two time series are in fact positively correlated (Table 1).

The eighth principal component P8, explaining 3.9% of the variance, shows loadings of one sign in a broad zonally oriented band across Central India, and opposite loadings in the Northwest, South, and extreme Northeast.

Table 1. *Correlation coefficients (in hundredths) between principal components of annual rainfall P1–P8, all-India annual rainfall index RA, annual frequency of cyclonic storms in the Bay of Bengal and Arabian Sea CF, and annual number of break monsoon days BM*

	RA	CF	BM
P1	+97	–00	–30
P2	–18	–10	+04
P3	–13	+18	–18
P4	–03	+23	–20
P5	–06	+2	+03
P6	–01	+23	+26
P7	–00	+41	–14
P8	–08	–09	–15
RA	+100	+00	–30
CF	+00	+100	–18
BM	–30	–18	+100

As will be discussed in Sections 8 and 9, the principal component patterns P1, P2, P3, and P7 are of particular interest, while no physical significance is suggested for patterns P4, P5, P6, and P8.

7. Power spectrum

The normalized rainfall departure series of 31 subdivisions shown in Fig. 1 were subjected to the spectral analysis technique of Schickedanz and Bowen (1977). The most prominent concentration of power was found for the quasi-biennial frequency band. This is broadly consistent with the results of Parthasarathy and Dhar (1974), Koteswaram and Alvi (1969), Bhargava and Bansal (1969), Jagannathan and Bhalme (1973), Jagannathan and Parthasarathy (1973), and Parthasarathy and Mooley (1978), all based on the Blackman and Tukey (1958) procedure.

8. Correlation between rainfall and synoptic events

With the purpose of further elucidating pattern characteristics, the normalized rainfall departure series of the 31 subdivisions were correlated with the time series of storm frequency and break monsoon days (Section 2). The resulting isocorrelate maps are shown in Fig. 5.

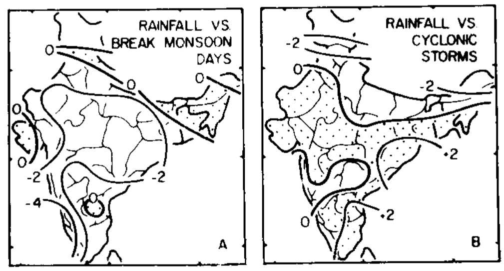

Fig. 5. Map of correlation between annual subdivision rainfall and (a) annual number of break monsoon days, and (b) annual number of cyclones. Isocorrelates are in tenths, zero line is broken, and dot raster indicates positive areas.

The isocorrelate pattern for the rainfall versus break monsoon time series (Fig. 5a), not surprisingly, resembles the rainfall departure map obtained by stratification with respect to the years with largest number of break monsoon days (Fig. 3e). Moreover, the isocorrelate map Fig. 6a is approximately inverse to the principal component pattern P1 (Fig. 4).

The isocorrelate pattern for the rainfall versus cyclone frequency time series (Fig. 5b) resembles the rainfall departure map for stratification with respect to the largest storm frequency (Fig. 3c), as expected.

9. Summary and conclusions

Spatial and temporal pattern characteristics were studied here by a combination of various analysis techniques, as a basis for possible physical interpretation.

In confirmation of Subbaramayya's (1968) earlier work, there is a strong spatial coupling between annual rainfall in Northwestern and Central India, while these regions have little affinity with the Northeast and Southeast.

Pattern stratification was carried out with respect to three index series. Stratification according to the largest values of an all-India rainfall index yields largest positive departures in Central and Western India. Stratification with respect to the years of smallest all-India rainfall index shows mostly negative departures. Pattern stratification with respect to the largest annual frequency of cyclonic storms in the Bay of Bengal and Arabian Sea shows large positive rainfall departures over

Eastern, Southeastern, and Western India, and negative departures in the North and a limited area of the Southwest. For the collective of years with smallest storm frequency, a partly inverse rainfall anomaly pattern is obtained. Pattern stratification with respect to the years of most numerous break monsoon days yields deficient rainfall in a large, broadly zonally oriented band across Central India, and positive departures in most other parts of the country. Stratification with respect to the least numerous break monsoon days yields a broadly inverse pattern.

Principal component analysis describes 74% of the total variance by the first eight components. The first component resembles the pattern obtained by stratification with respect to the all-India rainfall index, the two time series being highly positively correlated (Table 1). The second component resembles the pattern obtained by stratification with respect to the least frequent cyclonic storms, consistent with the weak negative correlation between the two time series (Table 1). The third component is approximately inverse to the pattern constructed from stratification with respect to the most numerous break monsoon days, the two time series being negatively correlated (Table 1). The seventh component is similar to the pattern derived from stratification with respect to the largest frequency of cyclonic storms; this is consistent with the positive correlation between the two time series.

Stratification and principal component analyses are complementary rather than redundant. Stratification highlights the patterns characteristic of certain synoptic-climatological events such as cyclonic storms and break monsoon. By contrast, principal component analysis identifies the most prominent or common spatial patterns. Pattern characteristic of extreme climatic events may, but need not be, common. Thus the prominent component P1 corresponds to the spatial anomaly pattern characteristic of extreme annual rainfall depatures in India as a whole. Similarly, the rainfall anomaly patterns identified as characteristic of extreme years in cyclonic storm frequency and number of break monsoon days are found to be approximately the commonly occurring patterns P2 and P3. Such correspondence between results from stratification and principal component analyses suggests that the respective patterns have physical significance. Other patterns without such demonstrated correspondence may or may not have a physical meaning.

The combination of the various analysis techniques applied here permitted to identify pronounced and organized rainfall anomaly patterns over the Indian subcontinent. Various patterns appear to have a physical reality. This exercise in pattern identification may serve as a basis for subsequent investigations into the general circulation mechanisms of hydrometeorological anomalies in the Indian Ocean domain.

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