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PATTERNS AND INTENSITIES OF MARKED RAINFALL-DEFICIT CONDITIONS IN THE STATE OF MAHARASHTRA, INDIA, DURING THE SUMMER (JUNE-SEPTEMBER) MONSOON, 1871 - 1984.

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ABSRTACT: Drought occurrences and frequencies across Maharashtra display a limited number of commonly-occurring basic patterns, which are defined in Figure 4 and illustrated for specific years in Figures 5 and 6. Moreover, differences in fluctuations of summer monsoon rainfall from year to year, including the occurrences of drought and extreme drought conditions, can be structured into five sets of regional conditions (Figures 8 and 9), which are illustrated in Figures 10 to 13. There are marked relationships between these summer monsoon rainfall conditions and SSTs of the Indian Ocean in April to June before the monsoon season, and of the eastern tropical Pacific Ocean (the El Nino phenomenon) in July to September contemporaneously with the monsoon rainfall event, The former of these two conditions is most marked in western areas of the state, whilst the latter is more critical over central and eastern areas. The possible implications of these results in relation to global warming are considered briefly.

INTRODUCTION

Throughout India as a whole the failure of the summer monsoon to provide sufficient rainfall necessarily leads to severe problems for society, with drought and associated famine as the extreme situation. What is "sufficient" varies from place to place, for both the natural environment and society's adjustment to it have developed over time in relation to the local average rainfall and the normal (non-extreme) fluctuations around this. Extreme deviations from average rainfall, especially marked deficits, have therefore attracted much scientific attention not only because of their climatological interest but also because of their critical impact upon Indian society.

Studies of such deficit or drought conditions have mainly been concerned, in recent years, with large-scale units for which the rainfall data have been generalised. Thus in many cases an All-India data set has been used, to provide a view of drought occurrences that is meant to represent the country as a whole, apart from the mountainous extreme north-west and north-east (e.g. Bhalme and Jadhav, 1984; Bhalme et al., 1986; Mooley et al., 1981; Mooley and Parthasarathy, 1983, 1984; Parthasarathy and Pant, 1984, 1985). In more detail, displaying the pattern of conditions across the country, other studies have analysed data generalised for each of 29 Standard Meteorological Sub-divisions (e.g. Mooley et al. 1981;

Parthasarathy et al., 1987). There are also studies at an intermediate scale of generalisation, between these two previous ones, such as for the three regions used by Ananthakrishnan and Parthasarathy (1984) or the ten regions defined by Gregory (1989. a. b.).

All of these data sets are derived from 306 District stations, for which long reliable records exist. These station data can be utilised to provide a more detailed picture of rainfall conditions within any given region or area. In a practical sense, such an area can most usefully be one of the administrative states, rather than a climatologically defined unit based on Meteorological Subdivisions (Gregory, 1989b). It is the state that must cope with the social and economic problems resulting from rainfall-dificit or drought conditions. This present study carries out an analysis for one such state — Maharashtra — for the summer monsoons of the 114 years 1871-1984. Within this state, which incorporates both very wet and very dry environments, lie 26 of these District stations, a number sufficient for the clear specification of both patterns and associated intensities of drought or rainfall-deficit conditions.

The relevance of such conditions to local communities in Maharashtra is illustrated by several quotations from Deshpande (1971). Thus he stressed that "the dominant natural factor that affects basically the life and economy of the people is the rainfall in its regime, amount and variability" (p. 27) and went on to state "But its distressing feature is 'variability," (p. 28). In addition, he made the point that "its impact in terms of economic distress and human suffering is greater in the regions of intermediate and scanty rainfall" (p. 28). The latter essentially comprise the Deccan area of Maharashtra in general, and especially its central and western parts.

With this in mind, the focus of this study is upon markedly below average summer monsoon rainfall conditions over the period 1871-1984, with these being seen as providing some guide to possible future conditions. Such marked rainfall deficits can lead to drought and its associated problems for society. Amongst these are famine, but is must be remembered that famine can be caused, or intensified, by other conditions. Often these are man-made in nature, but excessive rainfall at the wrong time of the year can also lead to crop damage and to an intensification of famine. Thus the account by Subramanian (1975) of what is termed "the Maharashtra drought 1970-73" in fact was concerned with crop shortage and famine over this period, for marked summer monsoon rainfall deficits (i.e. droughts), although characteristic especially of 1972 and partially of 1971, were not so of 1970 and 1973.

THE TERRAIN AND THE STATION NETWORK

The state of Maharashtra (Deshpande, 1971) covers more than 300,000 square kilometres across the north-western Deccan and the coast to the west. This Konkan coastal belt is relatively narrow, being between 50 and 80 kilometres in width, and is represented in the climatic data by four stations (1, 2, 3, 4). To the east of this rises to more than 900 metres the dissected edge of the Deccan in terms of the Western Ghats or the Sahyadris, but none of the stations is located here (for station numbers, names and locations see Figure 1).

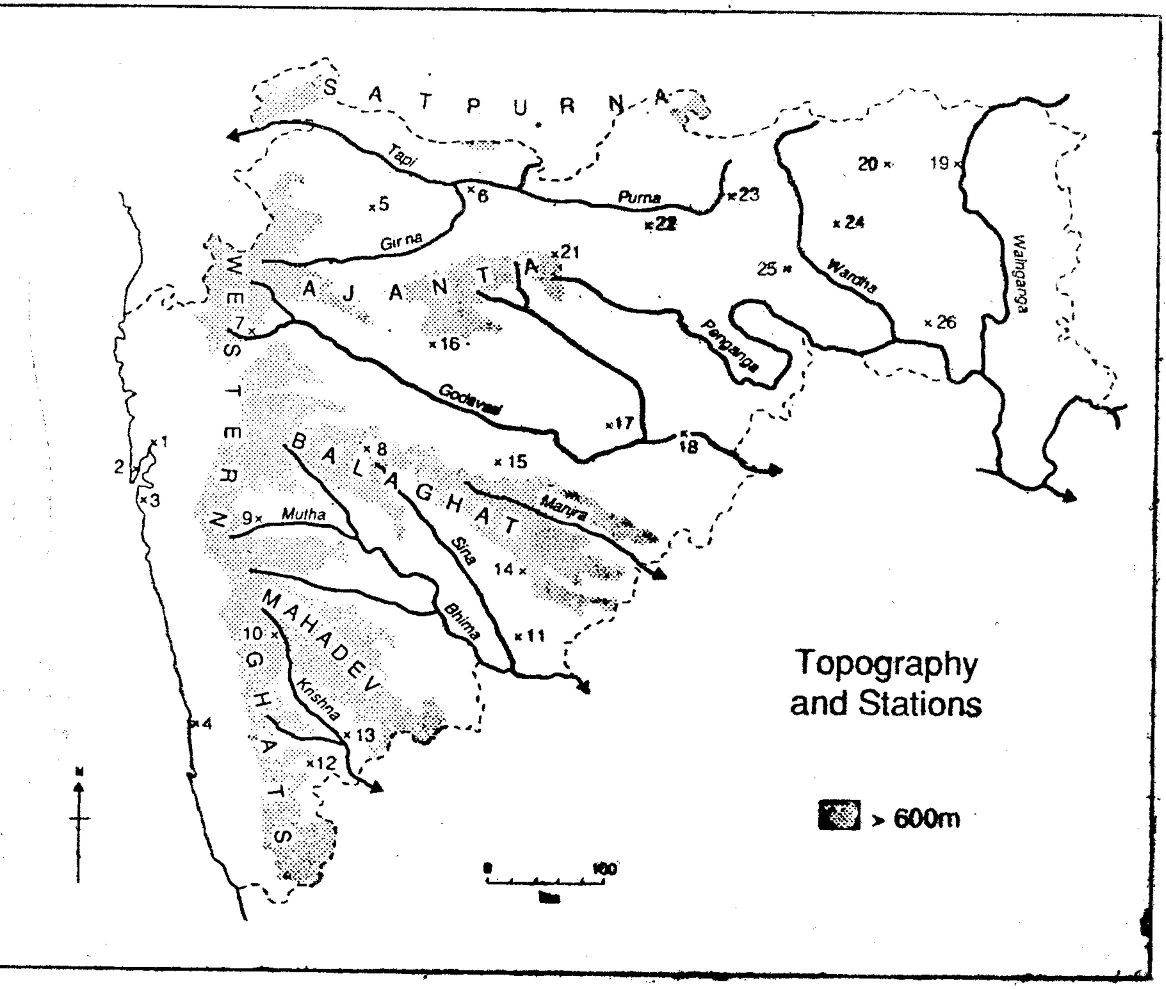

FIGURE 1. Maharashtra state — topography and stations (with mapped station numbers, official reference numbers, and station names listed below)

1. (2101) Thana
2. (43057- Bombay/Colaba
3. (43058) Alibag
4. (43110) Ratnagiri
5. (2203) Dhulia
6. (42851) Jalgaon
7. (42921) Nasik
8. (43009- Ahmednagar
9. (43063) Pune
10. (43113) Satara
11. (43117) Sholapur
12. (43157) Kolhapur
13. (43158) Sangli
14. (2302) Osmanabad
15. (43011- Bhir
16. (43013) Aurangabad
17. (43017) Parbhani
18. (43021) Nanded
19. (2401) Bhandara
20. (42866) Nagpur/Mayo Hosp.
21. (42931) Buldana
22. (42933- Akola
23. (42937) Amravati
24. (42939) Wardha
25. ((42943) Yeotmal
26. (43029) Chanda

The Maharashtra area of the Deccan plateau east of the Western Ghats is mainly drained by the Godavari river and its tributaries, the Krishna, the Bhima, the Wardha and the Wainganga. In the western and central areas the basins lie between 500 and 300 metres above sea level, whilst above these basins the plateau tracts, declining in general from west to east, vary between 600 and 450 metres. Major ranges rising from the plateau to between 700 and 900 metres ASL extend eastwards from the Western Ghats, especially between the Krishna and Bhima basins (the Mahadev Range), the Bhima and Godavari basins (the Balaghat Range) and north of the Godavari (the Ajanta Range). The valley basins immediately east of the Western Ghats contain station 7 in the Nasik catchment of the upper Godavari, station 9 in the Mutha valley of the Bhima, and stations 10, 12 and 13 in the Krishna basin. Further east the Sina basin (parallel to the Bhima) is represented by stations 11 and 14, whilst the Godavari catchment proper contains stations 15, 17 and 18. On the edges of the higher ranges lie stations 8 (the Balaghat Range) and 16 (the Ajanta Range).

To the north of the Ajanta Range the land falls to heights between 150 and 300 metres above sea level, and drains westwards via the Tapi basin with its tributary, the Purna. The plateau immediately south of this basin contains stations 5 and 21, whilst in the basin itself are stations 6, 22 and 23. Northwards along and beyond the Maharashtra border rises the Satpudas Range, but this is not represented in the station network. Finally, east of the Tapi basin over the north-east of Maharashtra state the Wardha and the Wainganga basins (again at between 150 and 300 metres) drain southwards to the main Godavari system. Stations 24 and 25 lie in the upper Wainganga basin, station 19 in the upper Wardha basin, and station 26 between the lower reaches of both these rivers, whilst the intervening Nagpur plateau in the north (rising to about 450 metres) is represented by station 20.

AVERAGE PATTERN OF RAINFALL

This area receives its summer (June to September) monsoon rainfall partially from the west and partially from the east. The systems moving inland from the Arabian Sea bring heavy rainfall to the Konkan coast, with average values between 2000 and 2500 mm, and even higher totals over the western slopes and crests of the Western Ghats (see Figure 2). A marked rain-shadow effect is found eastwards to the lee of this area, which is aceentuated by the decrease in rainfall from east to west as the monsoon lows cross the Deccan from the east during the retreat of the monsoon. As a result, average summer monsoon rainfall decreases to between 400 and 600 mm along a north-south belt east of the Western Ghats. Such values would be seen to produce semi-arid or perhaps even arid conditions in an Indian context (Mather, 1974; Singh, 1984), where an average annual value of approximately 560 mm is taken to be the boundary between these two conditions. Across central and eastern Maharashtra, however, average summer monsoon values increase steadily to more than 1200 mm over the Wainganga basin, where conditions become sub-humid. Moreover, the variability of summer monsoon rainfall, as expressed by the coefficient of variation, is less in the wetter west and east (values below 25 per cent) whilst it rises to 30-35 per cent over the drier areas (Figure 2).

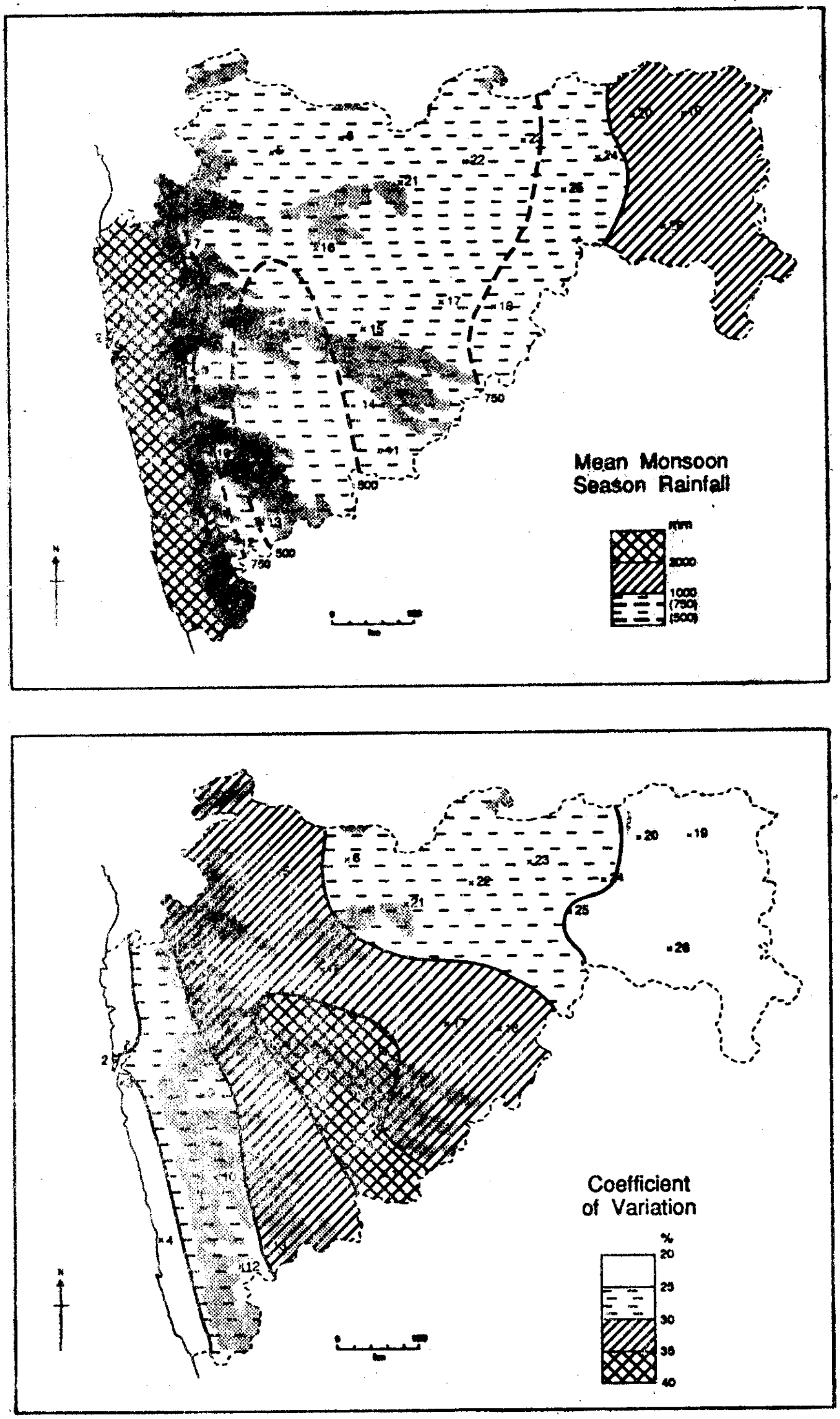

FIGURE 2. Monsoon season (June to September ra'nfall, 1871-1984, across Maharashtra state: (upper map) mean rainfall: (lower map) coefficient of variation.

Although the pattern of rainfall in absolute terms is similar in each of the monsoon moths to that of the monsoon period as a whole, the percentage of the total monsoon rainfall falling on average in each of these months varies between different parts of the state. The percentage proportions can be seen in Figure 3, where it can also be noted that on average:

i) the onset of the monsoon rainfall in June is far more marked along the Konkan coast than elsewhere;

ii) the peak falls tend to be in July over much of the state, but over the central plateau area it is September that is the wettest month;

iii) August is a relatively dry month over the western half of the state;

iv) relatively drier conditions also occur in September over the Konkan area in the west and the Wainganga catchment and the Nagpur plateau in the north-east;

v) about 60 per cent of the total summer monsoon rainfall occurs in June and July over western areas, 55 per cent over northern areas, but only about 45 per cent over southern plateau areas.

COMMON SPATIAL PATTERNS OF RAINFALL FLUCTUATIONS

The most common spatial patterns of summer monsoon rainfall fluctuations can be defined and evaluated from a principal components analysis of these 26 data sets over the 114 years of record. This was effected not only for the season as a whole but also for each of the four months individually. In each case five components each yielded an eigenvalue greater than unity, and collectively they incorporated between 67 per cent (June) and 74 per cent (August) of the overall variance of the data set (see Table 1 for the monsoon season itsefl). In all cases Component 1 was clearly the dominant one, however, and it displayed a similar pattern in all months and the season as a whole.

The maps of the Loadings on Component 1 (Figure 4) indicate a pattern where either rainfall deficits or rainfall surpluses occurred everywhere over Maharashtra. They were at their greatest, however, along the Konkan coast and over central Maharashtra, with rather less marked deficits or surpluses over the area east of the Western Ghats and over the Wainganga catchment in the north-east.

The maps of the Loadings on Component 2 for June. September and the monsoon season, and on Component 3 for July and August (Figure 4) indicate a gradient between the north-east and the south-west, suggesting that in some years the north-east experienced markedly drier (wetter) conditions than did the rest of the state. In several of these drier cases (i.e. with negative scores) the north-east would still have been wetter than average but without the excessive surpluses of other areas; in other cases, however, real deficits would have occurred in the north-ast but not elsewhere.

In contrast, the maps of Loadings for Component 2 in July and August, and Component 3 in September and the monsoon season as a whole (Figure 4), display a pattern with marked gradients between the area immediately east of the Western Ghats and both the coastal area to the west and the main plateau area to the east. As for Component 3 in June, this suggests a coast/interior gradient

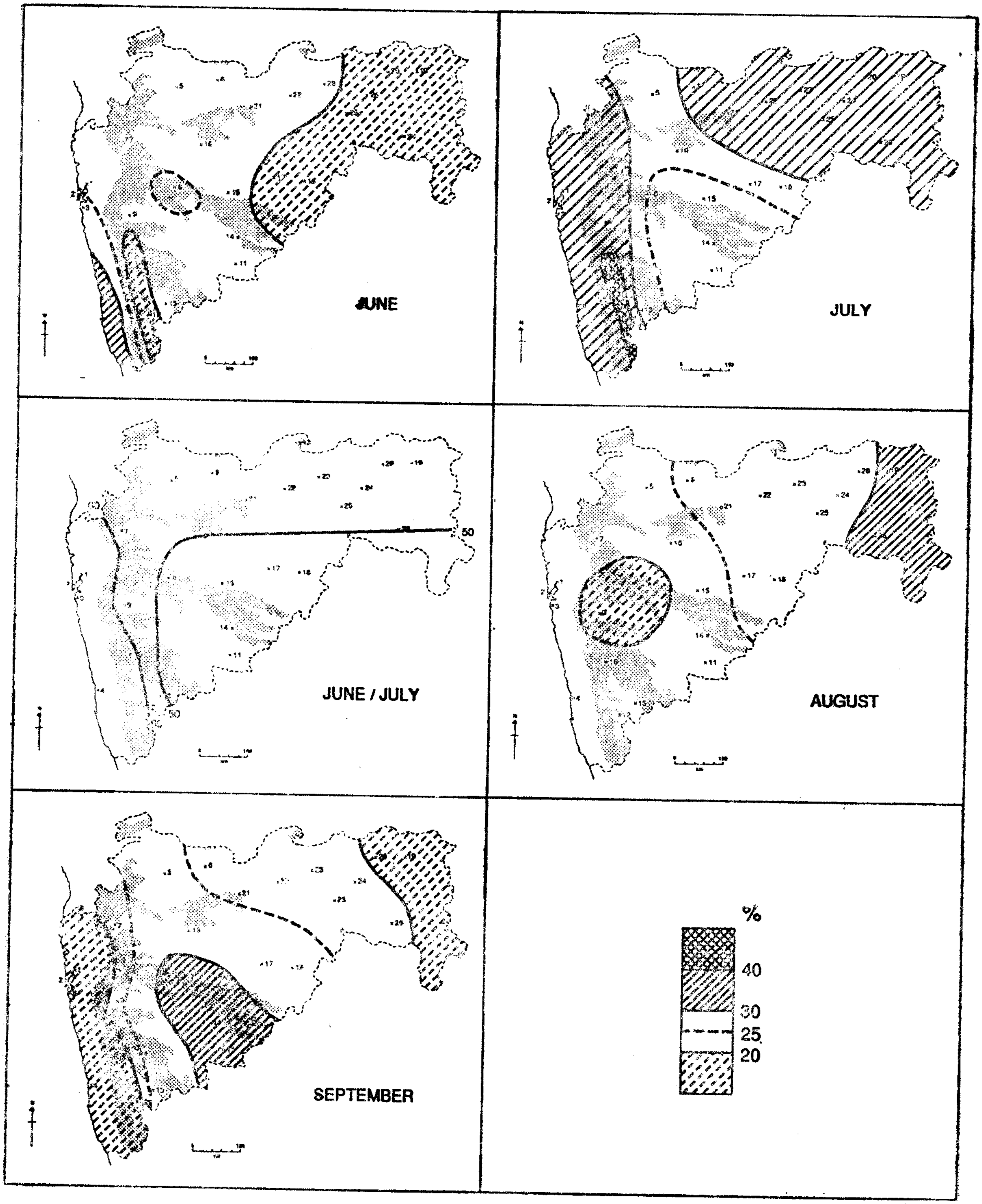

FIGURE 3. The percentage of the mean monsoon season (June to September) rainfall, 1871-1984, across Maharashtra state, occurring in each of the months June to September, and in June and July together.

Table 1. Loadings on the first five principal components from an analysis of monsoon season (June to September) rainfall for Maharashtra state, India, for 26 stations over 114 years (1871-1984)

	COMPONENTS				
Stations	1	2	3	4	5
1	0.64	−0.05	0.16	−0.54	−0.05
2	0.66	−0.32	0.02	−0.53	−0.12
3	0.76	−0.26	0.01	−0.45	−0.04
4	0.68	−0.31	−0.13	−0.33	−0.03
5	0.67	−0.19	−0.17	−0.02	−0.44
6	0.75	0.07	−0.01	0.09	−0.28
7	0.53	0.00	0.40	0.33	−0.31
8	0.62	−0.32	−0.23	0.37	−0.13
9	0.55	−0.22	0.56	0.17	−0.04
10	0.44	0.03	0.70	0.05	−0.10
11	0.62	−0.32	−0.26	0.09	0.08
12	0.50	−0.20	0.62	−0.05	0.29
13	0.56	−0.24	0.52	0.23	0.09
14	0.73	−0.25	−0.26	0.13	0.27
15	0.68	−0.22	−0.27	0.27	0.17
16	0.75	−0.22	−0.18	0.19	0.06
17	0.77	−0.18	−0.08	0.04	0.24
18	0.75	−0.01	−0.20	0.10	0.31
19	0.52	0.51	0.14	−0.01	0.36
20	0.59	0.57	0.13	0.07	0.07
21	0.78	0.10	−0.23	0.01	−0.02
22	0.73	0.35	−0.09	0.13	−0.16
23	0.71	0.35	−0.13	0.08	−0.26
24	0.65	0.57	−0.09	−0.01	−0.12
25	0.73	0.37	−0.11	−0.05	0.09
26	0.60	0.49	0.01	−0.27	0.12
Eigenvalue	11.28	2.39	2.16	1.47	1.04
Percent variance	43.4	9.2	8.3	5.6	3.3
Cumul. percent	43.4	52.6	60.9	66.5	69.8

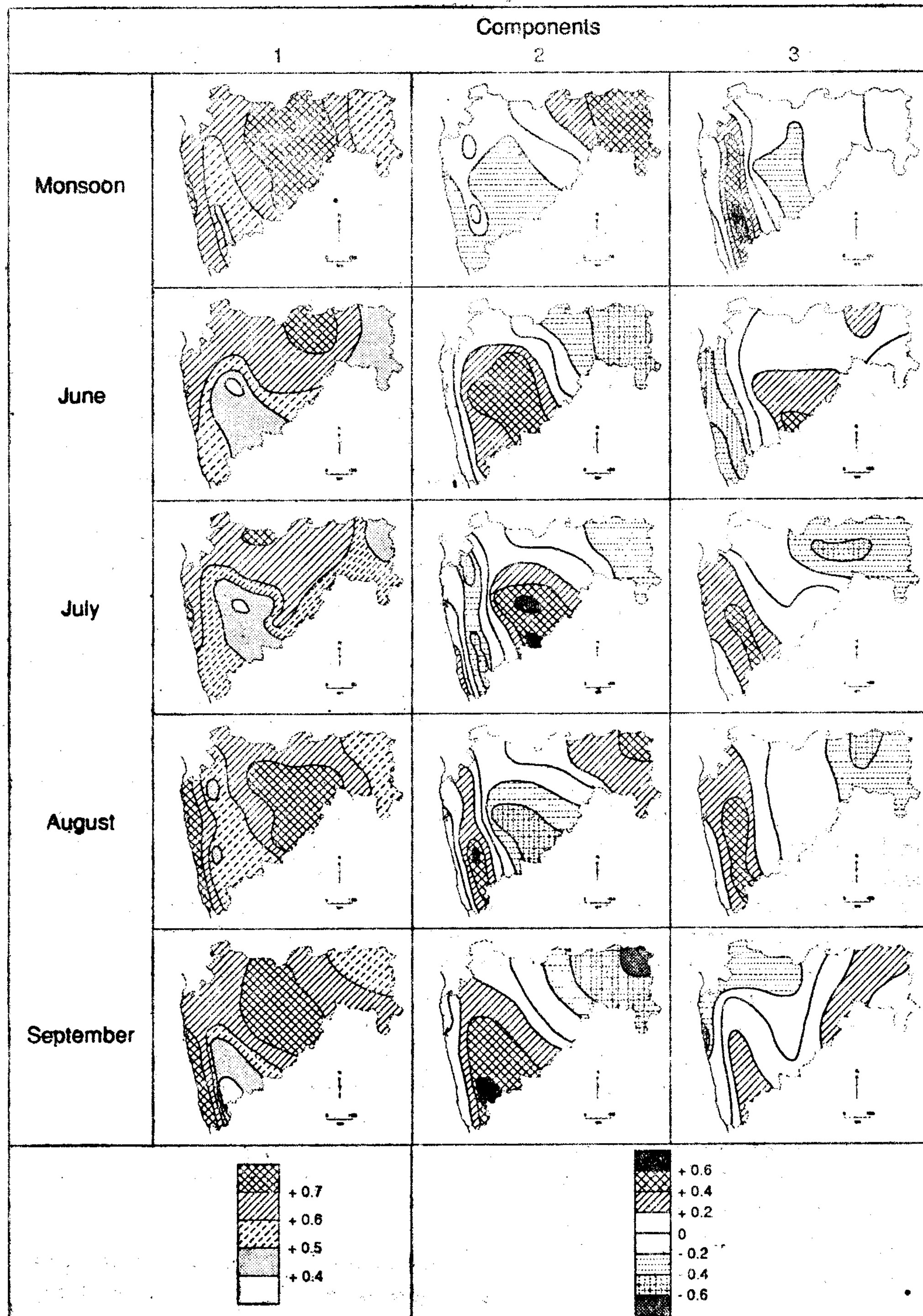

FIGURE 4. Loadings on the first three principal components across Maharashtra state, from analyses of rainfall, 1871-1984, for the monsoon season (June to September) as a whole and for each of these four months separately.

that does not appear in the three main patterns for the other periods.

When considering droughts as major phenomena, the monsoon season as a whole represents the most effective time unit, rather than conditions in any one month alone. On this basis, if standardised scores are computed for each of the 114 years on Component 1, five years had negative scores greater than —2.0 standard deviations i.e. five years with the most widespread rainfall deficits and the most universal drought conditions. These were 1899, 1918, 1920, 1972 and 1871 in order of their scores. The detailed patterns (Figure 5), when the fall for that year at any station is expressed as a percentage of the 114 year average for that station, do not perfectly match the general component pattern, but they each have much in common with it.

If Component 2 is considered, the five years with the most marked gradients, as represented by the largest negative scores, were 1892, 1928, 1967, 1974 and 1983. Of these, in 1928 and 1967 drier than average conditions dominated in the north-east, but it was only in 1974 that drought conditions (falls below 75 per cent of the average) distinguished this area (Figure 5). As for the spatial gradients of Component 3, such relationships were found in several years when large deficits or drought conditions were effectively limited to the rain-shadow zone. However, in 1935, 1948 and 1949 these were very localised, and it was only in 1951 that the whole of this area was affected by drought whilst the rest of the state was not (Figure 5).

Years with common patterns of surplus or deficit can also be evaluated by applying a classification procedure to the Scores recorded on each of the five critical components metioned earlier as having an eigenvalue greater than unity. If Ward's grouping algorithm is used (Ward, 1963), ten groups of years with considerable internal coherence are defined. Two of these groups comprise years in which drought conditions were widespread. The first group consists of 1871, 1899, 1918, 1920 and 1972 (the patterns for these have already been displayed – Figure 5). The second such group involved the years 1876, 1877, 1904, 1905, 1911, 1925, 1929, 1941, 1952 and 1984. The patterns for these ten years are shown in Figure 6.

An alternative approach to scheduling major drought years would be as follows. If drought at a station is taken as a monsoon rainfall which is less than 75 per cent of the long-term average (i.e. a deficit of more than 25 per cent), then this occurred at three-quarters or more of the stations (19 or more out of 26) in the same five years specified earlier as having the largest negative loadings on component 1 (see Figure 5). If, however, the critical number of stations is taken as more than 10 out of 26 (i.e. more than 40 per cent of them) then all of the stations specified by the earlier classification procedure, except for 1929, are included, plus the year 1912. Collectively, these 16 years (i.e. those, apart from 1951 and 1974, shown in Figures 5 and 6) can be seen as the major widespread drought years across Maharashtra within the 114 years of the analysis.

The relationship between these two sets of evaluation, and the relative intensities of drought in the various years, are graphed in Figure 7. At the same time are shown the four years in which severe

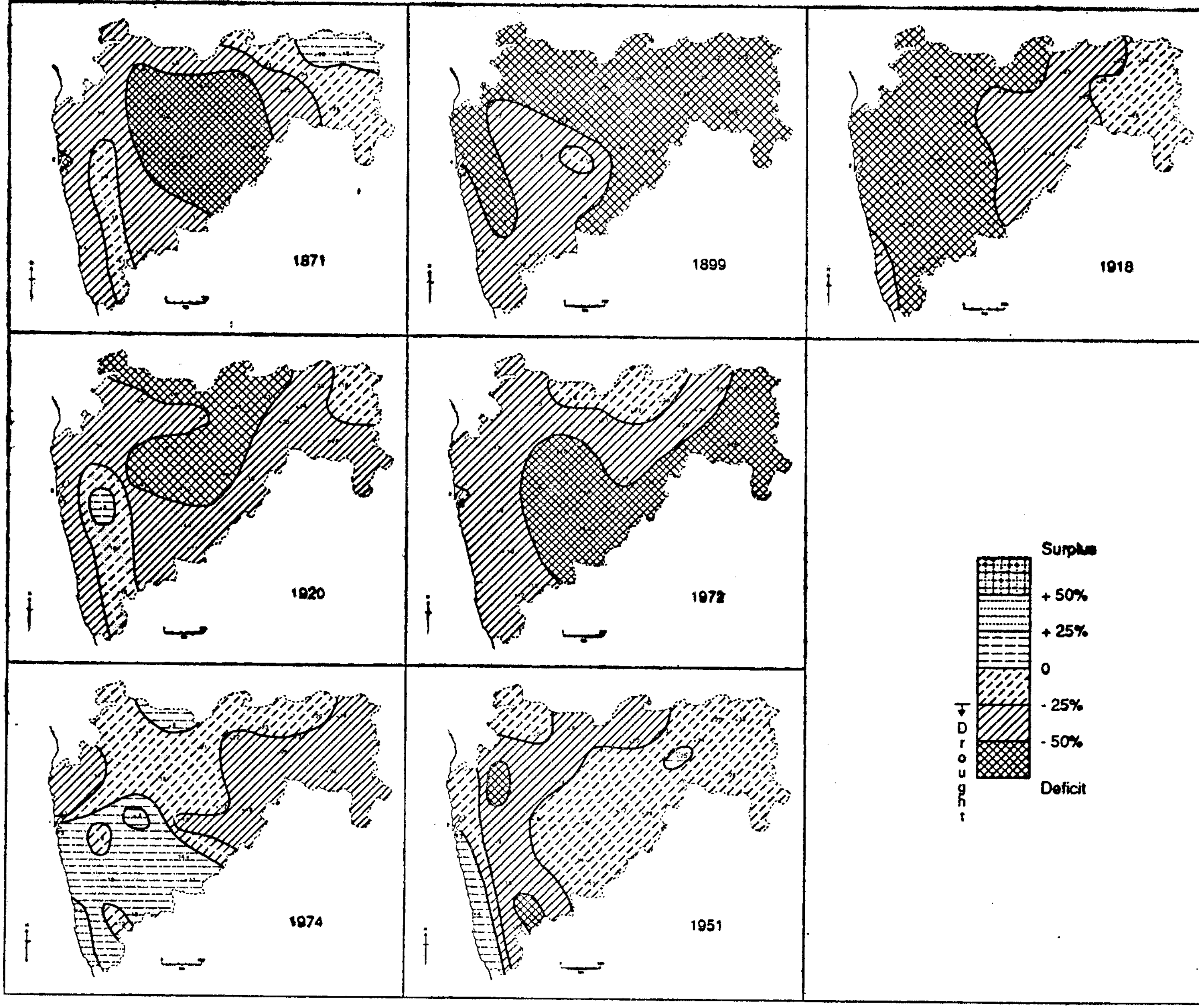

FIGURE 5. Monsoon season (June to September) rainfall across Maharashtra state as a percentage of the 1871-1984 mean monsoon rainfall, for seven drought years: the five years with negative scores larger than —2.0 on Component 1, plus 1974 (large negative scores on Component 2) and 1951 (large negative scores on Component3).

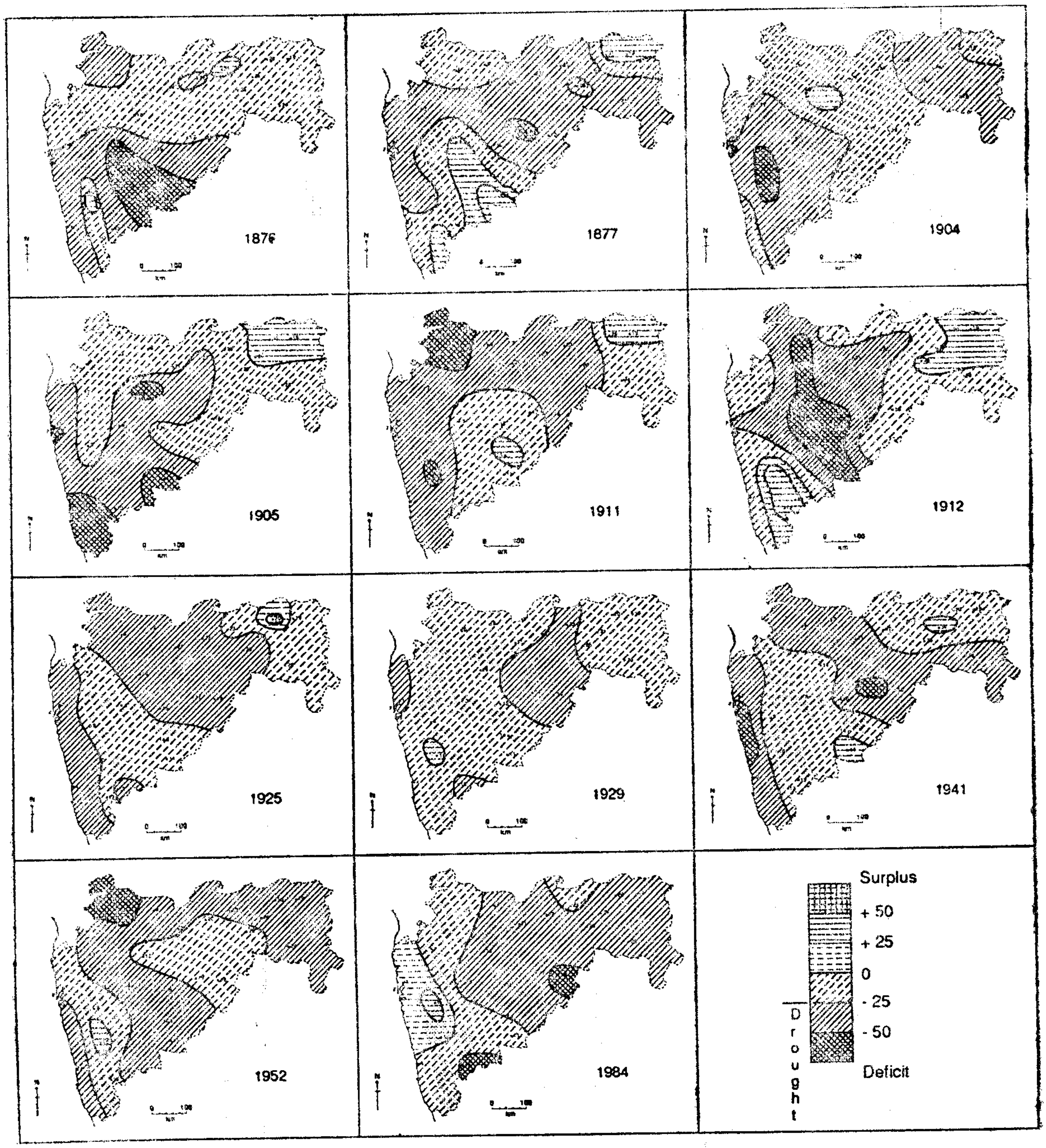

FIGURE 6. Monsoon season (June to September) rainfall across Maharashtra state as a percentage of the 1871-1984 mean monsoon rainfall, for a further 11 years with widespread drought conditions, as indicated in Figure 7.

drought (i.e. rainfall less than 50 per cent of the average) occurred over a relatively wide area (i.e. at more than five, or more than 20 per cent, of the 26 stations). This Figure suggests that these widespread drought years were especially concentrated in the approximately 30 years period from the end of the last century through to the late 1920s. In contrast, there was a 20 year period before the end of last century when none of these widespread droughts occurred, whilst between 1930 and 1970 only two such events were recorded.

If these apparent temporal concentrations are tested by the hypergeometric frequency distribution (Gregory, 1979, 1989b), the number of widespread droughts in each of the two decades 1903-1912 and 1904-1913 (i.e. four) was greater than might be expected at random (at the 0.05 level of significance). Again, in terms of 30-year periods the occurrence of eight widespread droughts in each of the periods 1896-1925 to 1904-1933 was also significantly greater than random (at the 0.05 level). In contrast, if the 29 years in which no station experienced drought conditions (i.e. no station with rainfall below 75 per cent of the average) were considered these were effectively randomly distributed in time. No decade or 30-year period displayed a concentration significantly greater than random. If simply the four years with widespread extreme drought are considered, they display no significant concentration in time, neither at the decade nor the 30-year level. If, however, the 86 years are considered in which no station recorded such extreme drought (i.e. no station with a deficit of more than 50 per cent of the average), then the 30-year period 1921-1950, with 27 such years, displayed a concentration of such years at a level (0.05) significantly greater than random. These more formally tested and established temporal phases confirm the subjective interpretation made earlier from Figure 7.

COMMON TEMPORAL PATTERNS OF RAINFALL FLUCTUATIONS

If individual stations are compared in terms of the timing and intensity of drought conditions, or of rainfall conditions as a whole, then each station will display some characteristics peculiar to itself. However, there may well be certain basic underlying tendencies which mean that several stations are essentially alike in terms of their temporal fluctuations, whilst others differ from these conditions. By applying Ward's classification procedures (Ward, 1963) to the loadings of the 26 stations on the five significant components delimited earlier, groupings of stations can be defined each of which displays considerable homogeneity in terms of temporal fluctuations from year to year.

The resultant hierarchical pattern for the monsoon season as a while is shown in Figure 8. Five distinct groups of stations can be seen, within each of which internal variance is very limited. Moreover, when these are mapped (Figure 9) a coherent regional structure appears. Similar classifications were carried out for each of the four months separately, and the results are also mapped in Figure 9. Effectively the same five regions are defined for August and September as for the monsoon season, whilst for July the only difference is that the two northern regions are merged into one. It is in June that a somewhat different regional pattern emerges, with a progressive change from the coast to the north east.

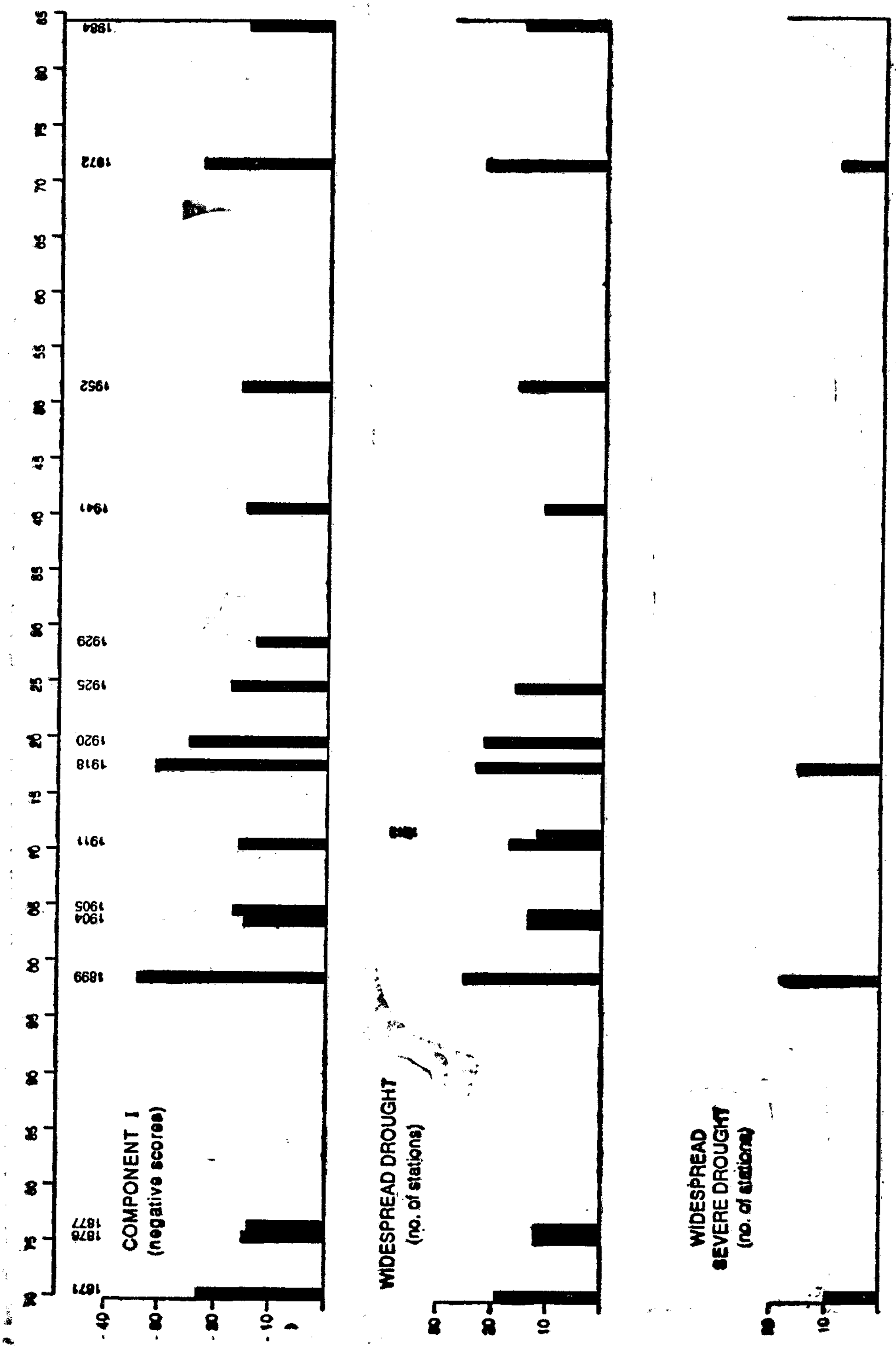

FIGURE 7. Three different specifications of the years with most widespread drought conditions across Maharashtra state, 1871-1984.

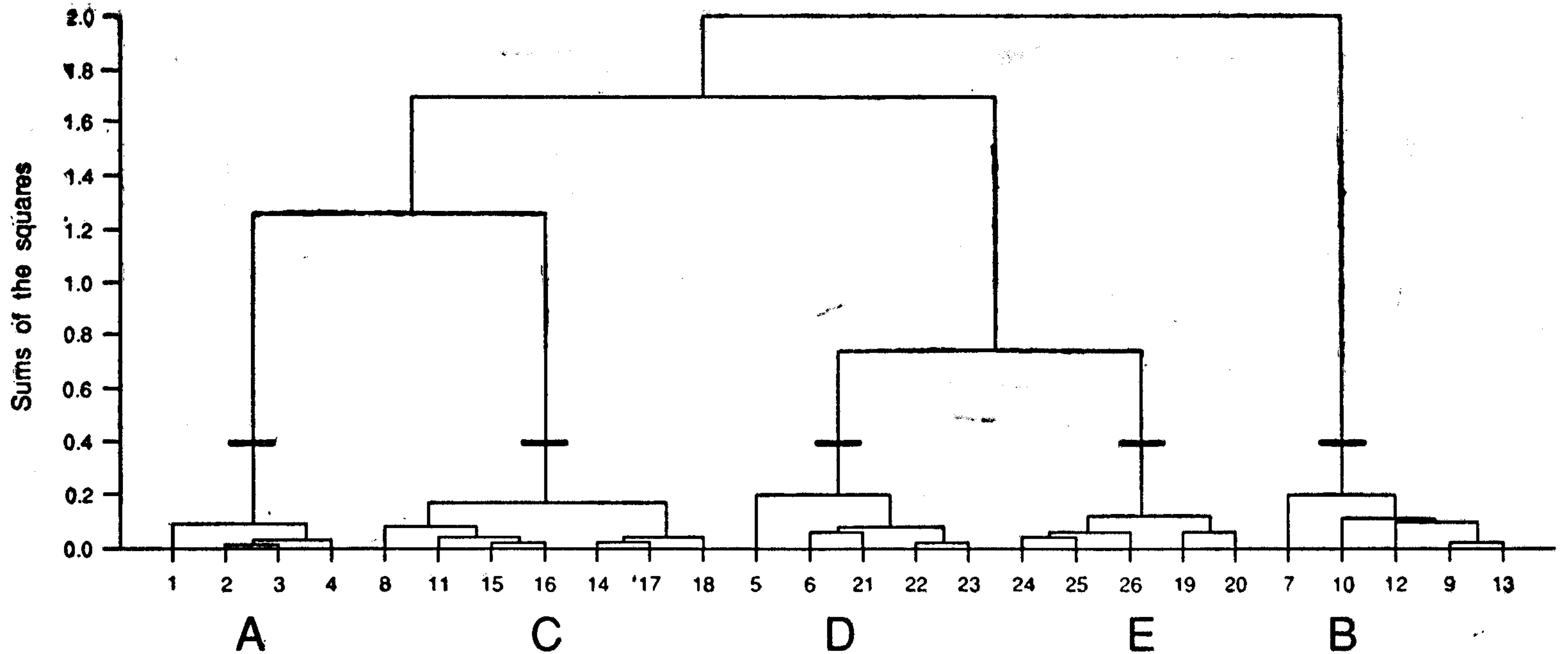

FIGURE 8. Groupings of stations across Maharashtra state in terms of a principal components analysis of monsoon season (June to September) rainfall for the period 1871-1984, classified by Ward's method (Ward, 1963) applied to the loadings on the first five principal components.

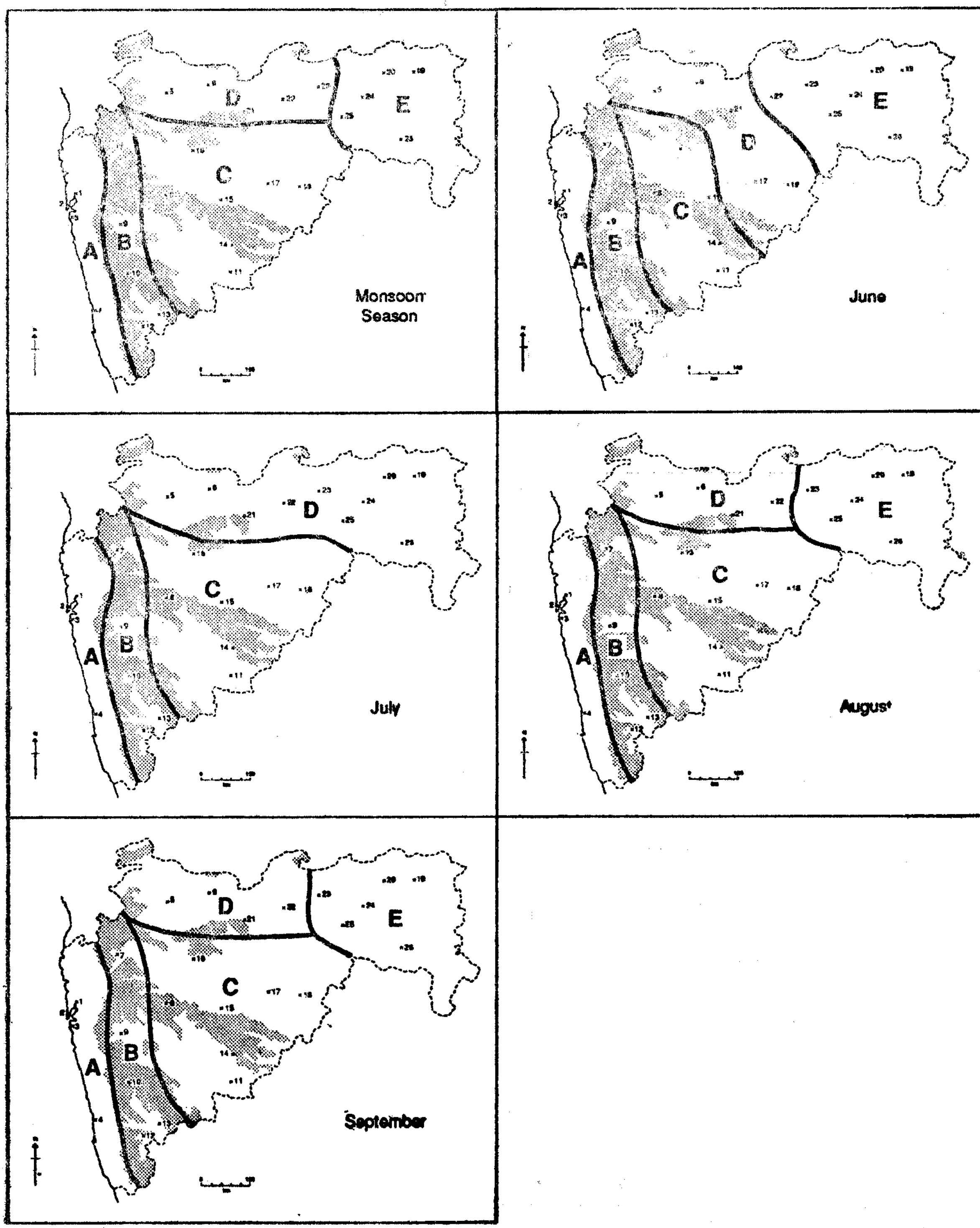

FIGURE 9. Regions of rainfall fluctuations (1871-1984) across Maharashtra state, for the monsoon season (June to September) as a whole (see Figure 8) and for each of the four months separately.

The monsoon (and August and September) patterns comprise:

Region A — the Konkan Coast and the western slopes of the Western Ghats;

Region B — part of the dry area to the east of the Western Ghats along the western edge of the Deccan;

Region C — the Central and Eastern Maharashtra uplands, incorporating the upper Godavari Valley and most other tributary valleys of the Godavari system:

Region D — the Tapi Basin, northwards from the Ajanta Range:

Region E — the Wardha and Wainganga catchments and the Nagpur Plateau in the north-east.

It is a combination of regions D and E into one northern Region D that distinguishes the July pattern.

The distinctiveness of these five regions in terms of year to year fluctuations can be illustrated (Figure 10) by correlating the 114 monsoon rainfall values for one central station in each region with the equivalent values for each of the other 25 stations used in Maharashtra. To provide a more general picture of conditions, and although the spatial distribution of stations within any one of these five regions is far from regular, it is perhaps reasonable to average the annual monsoonal rainfall of these district stations to yield regional rainfall values for each of the monsoon seasons 1871-1984. These can then be converted to percentage of the 114-year average value for that specific region. The resultant regional percentages for the monsoon season as a whole are presented graphically in Figure 11, in terms of years that are very dry (a deficit of more than 50 per cent), dry (a deficit of between 25 and 50 percent), below average (a deficit of between 0 and 25 per cent), above average (a surplus of between 0 and 25 per cent), wet (a surplus of between 25 and 50 per cent) and very wet (a surplus of more than 50 per cent).

Analysis will show (Table 2) that the years of marked monsoon season rainfall deficit or drought in regional terms are effectively the same as those defined earlier in station terms. Apart from the final group in Table 2, with only two drought regions within four below average regions, these years repeat those shown in Figure 7. The one year from the latter figure that is missing here is 1912. In this year only three of the regions had below average rainfall, but two of these were drought regions. This was the only year in which these circumstances occurred.

These characteristics are reflected in temporal changes as shown by cumulative percentage deviation curves (Figure 12). Thus in Regions A and C, years with below average rainfall dominated from the late 1890s through to 1930. Then a period of fluctuating conditions was followed by mainly above average conditions from the early 1950s to the mid-1960s, when fluctuating conditions returned for the rest of the period. The main difference between the two regions was the frequent above average rainfall years early in the period in Region C. Region D had patterns much in common with these until 1930. Above average years tended to occur from then until about 1950, after which below and above average conditions seemed to fluctuate randomly. As for Region E, this differed from Region D by the run of wetter years from the mid-1900s to about 1920, and by the run of drier years from the early 1960s

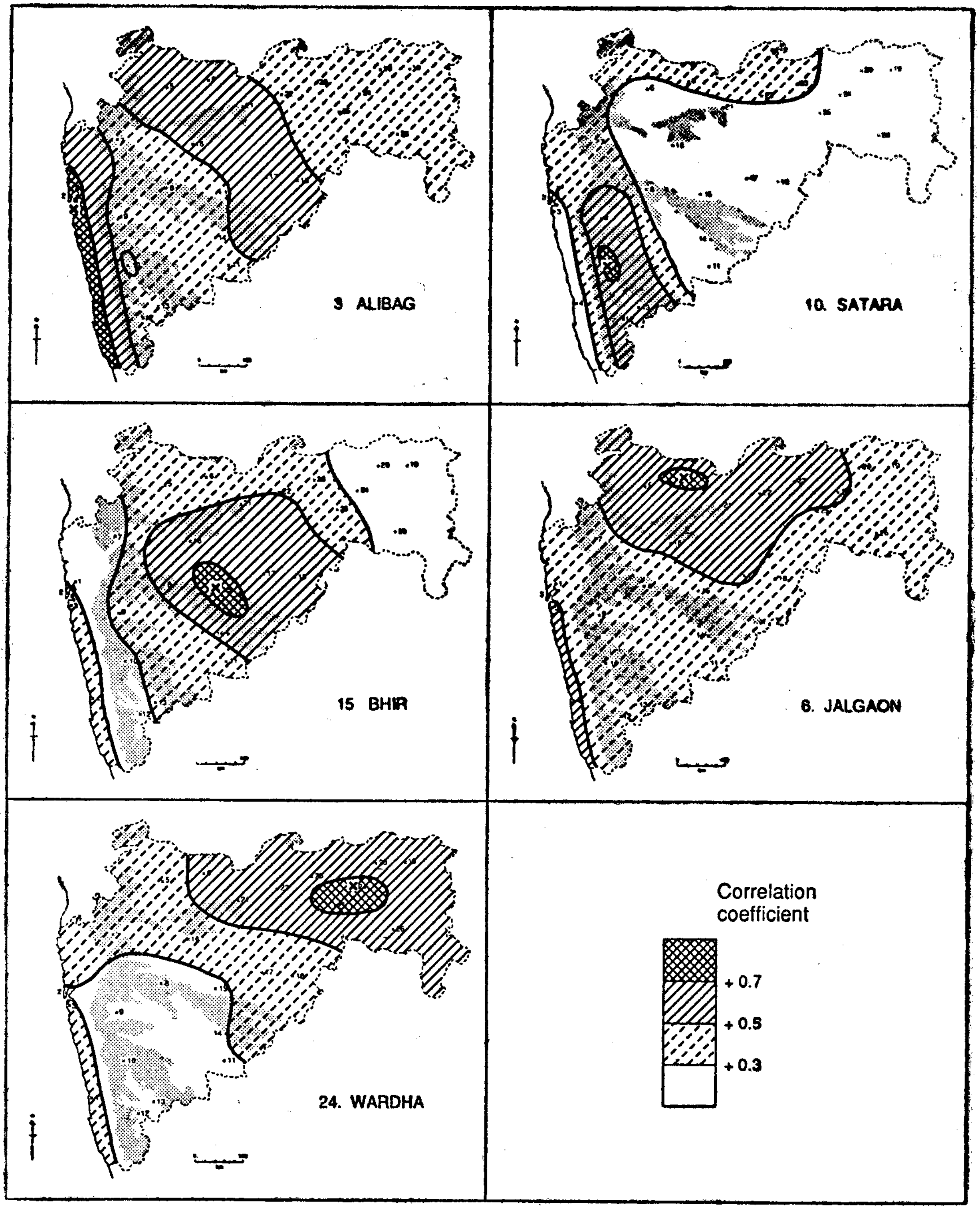

FIGURE 10. The correlation between each of five stations (one in each of the five regions mapped in Figure 9) and all the other 25 stations listed in Figure 1, in relation to monsoon season (June to September) rainfall across Maharashtra state, for period 1871-1984. All correlation coefficients are statistically significant at the .0.05 level (by a one-tailed t test-, and at the 0.01 level for all shaded areas.

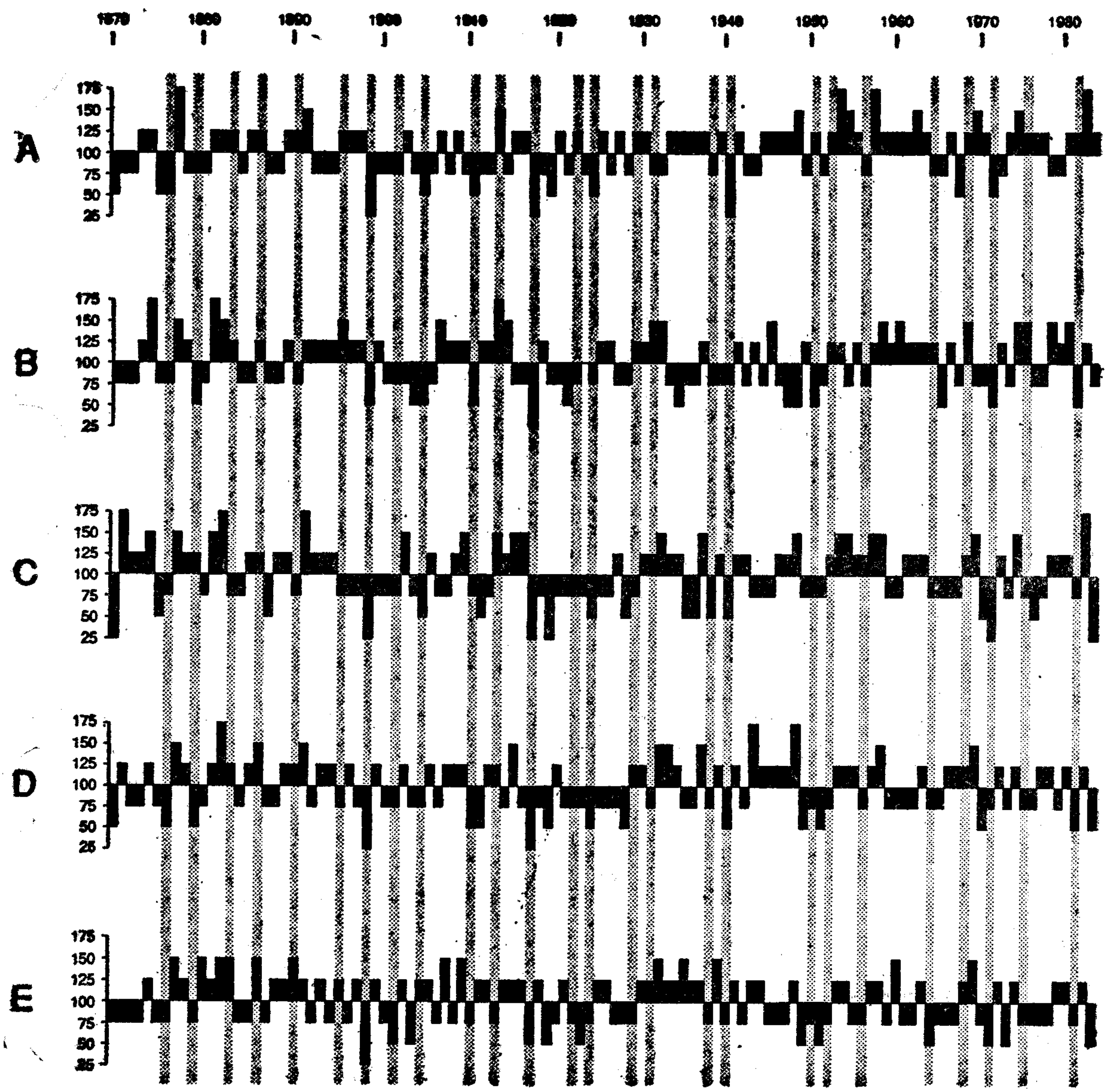

FIGURE 11. Monsoon (June to September) rainfall fluctuations from year to year to year (1871-1984) for each of the five regions in Maharashtra state mapped in Figure 9. Each year's regional rainfall is expressed as a percentage of the regional 1871-1984 mean monsoon season rainfall, and generalised into 25 per cent categories. Years with a strong El Nino phenomenon are stippled.

Table 2. Monsoon season (June to September) drought years (deficit > 25 per cent) affecting two or more of the five regions defined in Maharashtra, when at least four of them received less than the average rainfall, in the period 1871-1984.

ALL FIVE regions below average	FOUR regions below average
FIVE regions < 75% of average 1899. 1918	
FOUR regions < 75% of average 1920, 1972	
THREE regions < 75% of average 1871, 1911, 1925, 1941	THREE regions < 75% of average 1905, 1984
TWO regions < 75% of average 1876, 1877, 1904, 1929, 1952	TWO regions < 75% of average 1880, 1950, 1971, 1982

Table 3. Estimates of (i) the probability and (ii) the recurrence interval of summer monsoon drought conditions (rainfall deficits > 25 per cent) and extreme drought conditions (rainfall deficits >50 per cent) occurring somewhere within Maharashtra state, and in each of the five regions previously defined, based on conditions in 1871-1984.

	State	A	B	C	D	E
Probability						
Drought (>25 per cent deficit)	.72	.29	.42	.50	.38	.35
Extreme Drought (>50 per cent deficit)	.26	.05	.09	.18	.105	.04
Return Period						
Drought (>25 per cent deficit)	1.4	3.5	2.4	2.0	2.6	2.9
Extreme Drought (>50 per cent deficit)	3.9	20.0	11.1	5.6	9.5	25.0

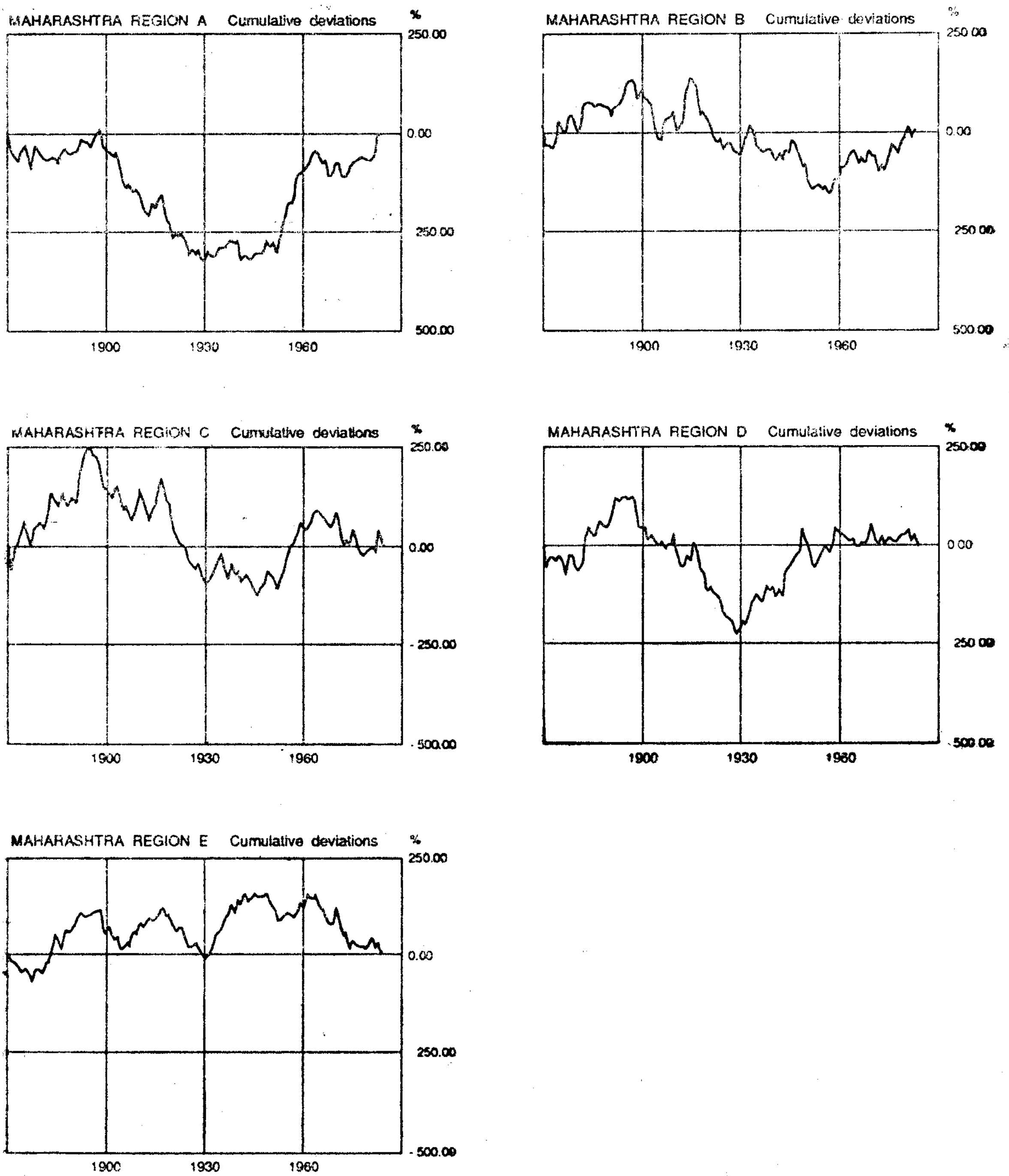

FIGURE 12. Graphs of cumulative percentage deviations from the 1871-1984 mean for regional monsoon season (June to September) rainfall for the five regions of Maharashtra state mapped in Figure 9.

to the mid-1970s. Finally, the distinctive features of Region B are the run of dominantly drier years between the mid-1910s and the late 1950s, and the frequent wetter years to the end of the period.

Another approach to regional drought frequencies is in terms of extreme event theory, applied on a spatial basis (Gregory and Parthasarathy, 1986; Gregory, 1987). Thus it is possible to present estimates of the probability (and return period) of drought in general and any intensity of drought in particular, occurring somewhere within Maharashtra or any one of the defined regions. The resultant curves are presented in Figure 13. These are conservative estimates of extreme events, for they are necessarily based solely on the stations used in the analysis and not on all possible locations in the areas involved. On this basis, however, the probabilities and return periods of both drought (a deficit greater than 25 per cent of the average) and extreme drought (a deficit greater than 50 per cent of the average) are listed in Table 3. Thus in Maharashtra as a whole, for example, an extreme drought can be expected somewhere at least one year in four, whilst a simple drought will occur about two years out of three.

REGIONAL MONSOON RAINFALL AND SSTs

These fluctuations in regional rainfall, and especially in drought conditions, are at least partially influenced by fluctuations in sea-surface temperatures (SSTs), especially for the Indian Ocean and the eastern tropical Pacific Ocean. The former is the ocean surface over which the monsoon system blows towards India, whilst the latter, via the El Nino system and the related Southern Oscillation, is seen to influence atmospheric circulation patterns over large areas of the world, and especially the tropics.

Most sources (e.g. Mooley and Parthasarathy, 1983; Rasmussen and Carpenter, 1983; Bhalme and Jadhav, 1984) recognise 26 El Nino years (i.e. with higher than average SSTs over the eastern tropical Pacific Ocean) during the 114 years of the present record — see Figure 11. If these are related to the number of stations in the Maharashtra network experiencing drought conditions (i.e. monsoon rainfall less than 75 per cent of the average) in any given year, the following relationships appear (Table 4).

There appears to be a relatively higher concentration of El Nino years in the high drought frequency, and a lower concentration in the very low drought frequency group. These concentrations differ significantly from random at the 0.05 level, with a Chi-squared value of 11.7. Nevertheless, it is still true that in 18 of the 26 El Nino years fewer than 40 per cent (i.e. ten or less) of the stations experienced rainfall that was below 75 per cent of the average.

For a more effective assessment, however, the Meteorological Office data on SST anomalies for major oceanic units can be used. The five sets of regional rainfall data were each correlated with six SST data sets, namely those for the Indian Ocean and the eastern tropical Pacific Ocean for each of three season — January to March, before the monsoon season; April to June, before and overlapping the start of the monsoon season; and July to September, contemporaneous with the bulk of the monsoon season. The simple correlation coefficients are listed in Table 5.

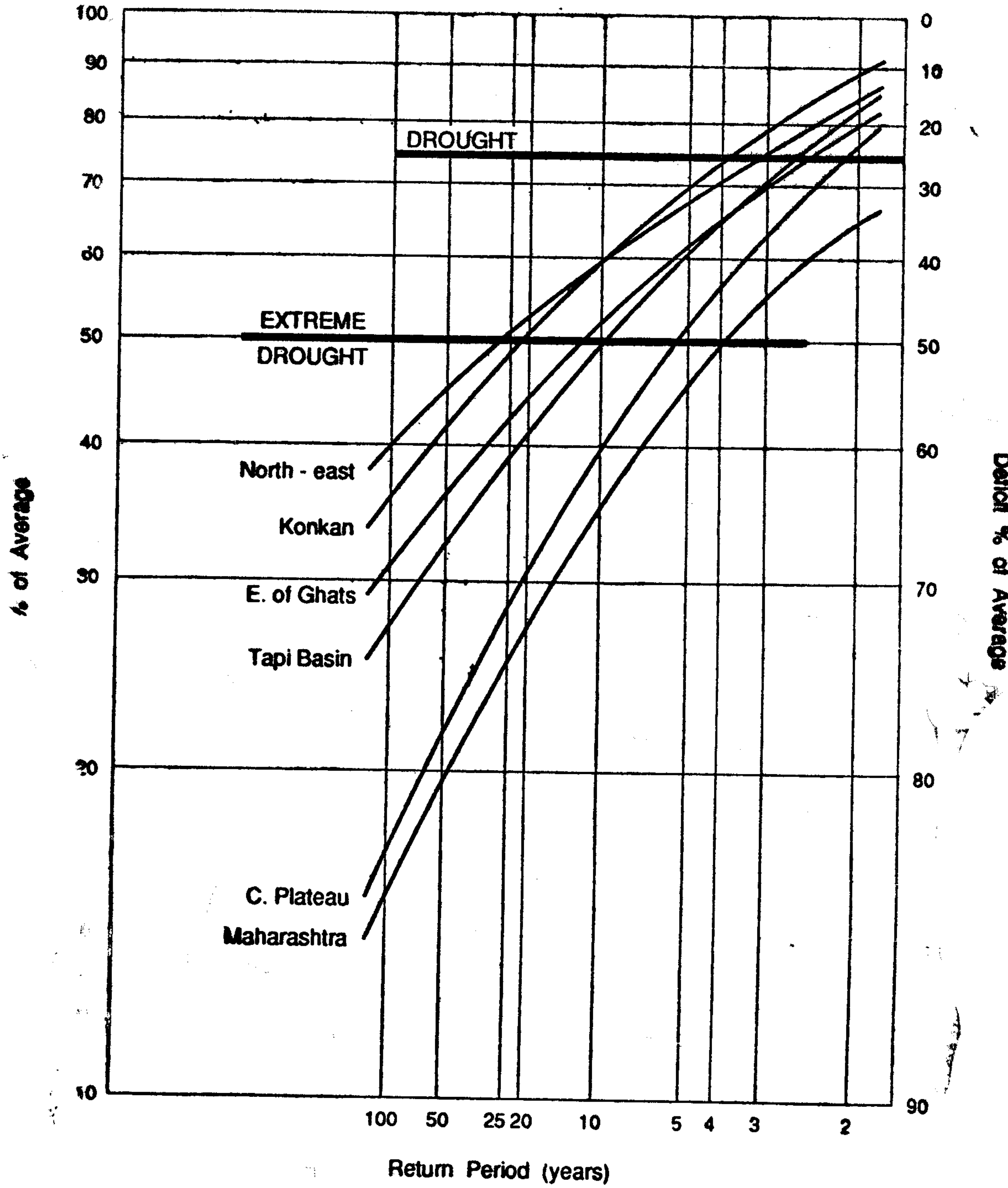

FIGURE 13. Graphs of the Return Periods of extreme low monsoon season (June to September) rainfall within Maharashtra state as a whole, and within each of the regions mapped in Figure 9, based on rainfall data for 1871-1984 and on the stations listed in Figure 1.

Table 4. The number of stations in the Maharashtra network experiencing drought conditions (a monsoon season rainfall deficit > 25 per cent) in El Nino and non-El Nino years, 1871-1984.

Number of stations	El Nino years	non-El Nino years	Total years
0 — 1	6	45	51
2 — 10	12	36	48
11 — 25	8	7	15
Total	26	88	114

Table 5. Correlation coefficients between regional monsoon season (June to September) rainfall and three seasonal sea surface temperatures (SSTs) for the eastern tropical Pacific Ocean (P. O.) and the Indian Ocean (I. O.), for the period 1871-1984.

Sea surface	Regions				
	A	B	C	D	E
P. O. jfm	+.13	+.11	+.01	+.09	+.13
P. O. amj	—.00	—.03	—.19(*)	—.08	—.02
P. O. jas	—.20(*)	—.18	—.45(**)	—.36(**)	—.28(**)
I. O. jfm	+.29(**)	+.22(*)	+.32(**)	+.23(*)	+.23(*)
I. O. amj	+.40(**)	+.34(**)	+.24(*)	+.25(**)	+.21(*)
I. O. jas	+.26(**)	+.16	+.14	+.18	+.11

(*) correlation coefficient statistically significant at the 0.05 level, in a two-tailed test.

(**) correlation coefficient statistically significant at the 0.01 level, in a two-tailed test.

Thus statistically significant relationships with a positive sign occurred between the regional rainfalls and antecedent Indian Ocean SSTs, and significant relationships with a negative sign between the rainfalls and contemporaneous eastern tropical Pacific Ocean SSTs. Appreciating that considerable levels of correlation could exist between these several SST data sets, multiple regression and correlation analyses were carried out to find the highest level of multiple correlation coincident with all the independent variables being statistically significant at least at the 0.05 level. In each case (Table 6) it was a combination of April to June SSTs

Table 6. Multiple regression relationships between monsoon season (June to September) rainfall of the five regions defined in Maharashtra (Figure 9), and the SSTs for (i) July to September over the eastern tropical Pacific Ocean (P. O. jas) and (ii) April to June over the Indian Ocean (I. O. amj). Multiple correlation coefficients are given for the regression, and signs and F values for each of the independent variables (i. e. the SSTs): in all cases significance levels are also given.

		REGIONS				
		A	B	C	D	E
regression	: corr. coef.	.46	.40	.53	.46	.37
	: signific.	.001	.001	.001	.001	.001
	: sign.	—	—	—	—	—
P. O. jas	: F value	7.7	5.9	34.7	20.7	11.9
	: signific.	.01	.05	.001	.001	.001
	: sign.	+	+	+	+	+
I. O. amj	: F value	25.0	17.0	12.5	11.5	7.4
	: signific.	.001	.001	.001	.001	.01

in the Indian Ocean with July to September SSTs in the eastern tropical Pacific Ocean that best satisfied these criteria.

Thus for all five regions the regression relationship was significant at the 0.001 level, whilst both variables (SSTs) were significant at the 0.05 level or better. For Regions A and B, in the west, the April to June SSTs of the Indian Ocean were the more important, whilst for Regions C, D and E (in the centre and east) the July to September SSTs of the eastern tropical Pacific Ocean were the more important. It would thus appear that a warmer/cooler Indian Ocean immediately prior to the monsoon season, which would affect the moisture-holding capacity of the monsoon airflow and perhaps also the intensity and frequency of monsoon lows, was associated with an increase/decrease in monsoon rainfall, especially over the areas closest to the Arabian Sea area of the Indian Ocean. Conversely, the change in atmospheric circulation systems related to warmer/cooler SSTs over the eastern tropical Pacific Ocean were associated with a decrease/increase in monsoon rainfall, especially over the more inland areas.

IMPLICATIONS FOR THE FUTURE

The occurrences, frequencies and patterns of large summer monsoon rainfall deficits over Maharashtra state have been analysed and summarised for the 114 year period 1871-1984. What are the implications of these relationships for an appreciation of possible future drought occurrences in Maharashtra?

The spatial distributions of below average, drought and extreme drought conditions have been shown to vary in detail from one drought year to another (Figures 5 anl 6): moreover, it was only in 1899 that drought conditions occurred over the whole of the state. Such a universally occurring drought in the future is obviously a possibility, but the probability of it is very low. On the other hand, monsoon seasons in which considerable areas of drought conditions are spatially embedded in widespread below average rainfall conditions are likely to recur with a frequency of one or two per decade. The pattern reflected by Component 1 in Figure 4 will no doubt contine to be the commonest pattern of monsoon rainfall distribution, especially for such very dry (drought) years.

Over the past, years of complete drought absence have been virtually random in occurrence, as have been widespread extreme droughts. In contrast, periods have occurred when droughts have been more frequent than might have been expected by chance whilst such relationships have varied between one region and another. There is no guarantee that these characteristics will persist into the future, however, and this must also be partially true of the longer term drought return periods (Figure 13)

Whether or not the monsoon season rainfall characteristics that have been established for the period 1871-1984 will continue into the future depends markedly on the issue of man-induced global warming. Whilst the future occurrence of this during the coming decades is now widely, though not universally, accepted throughout the relevant scientific community, there is as yet no reliable assessment of probable regional, as distinct from global, impact (Houghton et al., 1990). However, it is to be expected that the observed relationships (modest though they are in magnitude) between SSTs and monsoon season rainfall in Maharashara will be sustained, as they are physically based. If, therefore, global warming leads to a rise in sea surface temperatures over the Indian Ocean and the eastern tropical Pacific Ocean, a concomitant impact on these rainfall conditions must be expected.

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