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Changes in the Pattern of Distribution of Southwest Monsoon Rainfall Over India Associated With Sunspots

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ABSTRACT—Despite the systematic nature of the monsoon rains over India, large year-to-year variations in the pattern of distribution of rainfall during the season occur. The yearly pattern of rainfall distribution during the monsoon season (May 31–October 2) for each of the years 1901–51 for a network of 105 stations over India is characterized by a set of six distribution parameters. A brief description of the spatial distribution of the different patterns is given to indicate the nature of the component patterns. Polynomial trend analyses of the time series of the distribution parameters indicate oscillatory features. Power spectrum analyses reveal certain significant periods corresponding to the sunspot cycle or some higher harmonics with regional preferences. The variation of distribution parameters in the different parts of the country with the different sunspot epochs is demonstrated. Studies of the distribution of surface pressure anomalies, frequency of storms and depressions, and the frequency of "breaks in monsoon" associated with the contrasting sunspot epochs suggest that the monsoon circulation features as well as the characteristics of the rainfall distribution have a periodicity nearing the sunspot cycle.

1. INTRODUCTION

An average annual rainfall of about 105 cm has been estimated for the plains of India. Even though abundant rain falls over the Indian territory as a whole, the disparity in its distribution over the different parts of the country is so great that some parts suffer from perennial dryness. In other parts, however, so much rain falls that only a small fraction can be utilized. In the worst famine year on record (i.e., 1899), the total annual rainfall was 26 percent below normal; in 1917, the year of very heavy rainfall, it was 29 percent above normal. The variability of rainfall (coefficient of variation, CV, which is equated to the standard deviation expressed as percentage of the mean) exceeds 30 percent over large areas of the country and is over 40–50 percent in parts of Saurashtra, Kutch, and Rajasthan. The variability is more than 100 percent at some stations in the interior tracts in these areas, indicating that these are particularly liable to very heavy rainfall in some years and to very scanty rainfall in others. The variability is least (about 15–20 percent) over Northeast India and the western coast of the peninsula, indicating high reliability of rainfall in these areas. As a general rule, areas having the lowest mean rainfall are also those in which the rainfall is most irregular.

Rainfall amount varies with the season of the year. Except for Assam, Jammu and Kashmir, and the south peninsula, more than 75 percent of India's annual rainfall is received during the southwest monsoon season, June through September. The year-to-year variations in monthly rainfall are much larger than those of the annual rainfall. Table 1 illustrates the extreme variability of the monthly rainfall in the arid and semiarid subdivisions of the country.

The variations are highest during the nonmonsoon months, indicating the highly erratic nature of the rainfall during these months. Even during the monsoon months, the variations are high, the lowest being in the month of July when the monsoon is at its height.

2. THE SOUTHWEST MONSOON SEASON

The southwest monsoon season is the main rainfall season and is also the least variable over most parts of the country.[1] The order of the variability over the drier tracts, where variability is greatest, is given in the last column of table 1.

Rainfall during the monsoon season is not continuous but occurs in spells lasting for about 5–7 days. During the most active monsoon months, July and August, the monsoon trough (equatorial trough) lies over the Gangetic Plains (roughly from 30°N, 75°E to 23°N, 88°E) causing increased rainfall in the plains of India and decreased rainfall near the foot of the Himalaya Mountains and in the southeast peninsula. Interruptions in the monsoon rains occasionally last over a couple of weeks. These interruptions in monsoon rains are known as "breaks" in the monsoon (Raghavan 1973). During these breaks in the monsoon, the monsoon trough shifts from its normal position to the foot of the Himalayas, heavy rainfall occurs along and near the foot of the Himalayas, and rainfall increases in the southeast peninsula and decreases over the rest of the country.

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[1] Hereafter we shall be referring to the southwest monsoon as the monsoon.

TABLE 1.—*Coefficient of variability (%)*

	J	F	M	A	M	J	J	A	S	O	N	D	June-Sept.
West Rajasthan	232	152	157	170	182	96	59	76	146	253	333	180	49
East Rajasthan	107	152	162	231	138	62	38	50	78	150	145	171	28
Rayalseema	207	241	221	81	61	41	52	63	45	56	83	172	38
Madhya Maharashtra	215	175	144	71	76	33	30	37	39	61	101	200	18

Despite the systematic nature of the monsoon rainfall, its behavior during individual years shows considerable variation. The important aspects of the variations are:

1. The timing of the onset or the commencement of the rainy season in the different parts of the country,
2. The pattern of distribution of rainfall including the timing and duration of breaks in the monsoon,
3. The timing of withdrawal of the monsoon from the different parts of the country, and
4. The total amount of rainfall of the season.

For success in crop production, both the total rainfall and its distribution during the rainy season are important. Obviously, late commencement of the monsoon rains, long breaks in the rains, and early withdrawal are harmful to crops. Similarly, excessive rainfall over short periods leads to flooding and waterlogging.

To determine whether the variations in the rainfall from year to year are entirely random or are controlled by some systematic trend, Pramanik and Jagannathan (1956) studied the series of annual rainfalls over an 80-to 100-yr period ending in 1950. They found systematic variations over certain areas in addition to the random fluctuations. In addition, they found that, if the annual rainfall was separated into seasonal rainfall, the southwest monsoon rainfall of Vishakhapatnam exhibited a decreasing trend, and Kozhikode, Bellary, Nagpur, and Jalapaiguri showed a slight increasing trend.

Ananthakrishnan and Gopalchari (1964) presented a descriptive account of some of the salient features of the mean rainfall patterns of several stations in India. Their study gives an idea of the variety of patterns of the monsoon rainfall over the country. Because of the importance of the rainfall distribution during the different parts of the rainy season for deciding the pattern of agriculture, researchers of the Institute of Tropical Meteorology, Poona, as part of their "climatic fluctuations" project, are studying the variations in the pattern of distribution of rainfall. In one such study (Jagannathan and Bhalme 1967), we attempted to relate the precipitation pattern variations with selected physical processes. We found that during the monsoon, rainfall patterns in northeast India differed significantly from one sunspot epoch to another, suggesting differential intensification of the seasonal trough of low pressure over the country. In the present study, we discuss the year-to-year variations in the component patterns that make up the monsoon rainfall, with emphasis on those features that parallel the sunspot cycle. Circulation features typical of the different sunspot epochs are also discussed.

3. DATA AND THE METHOD OF ANALYSIS

The study has been made on a network of 105 stations (fig. 1) distributed over India. The rainfall of the 25 pentads during the period May 31–October 2, corresponding to the 31st and 55th pentads of the "IGY calendar," is the rainfall data used. The variations of the pentad rainfall during the season are represented analytically as a function of time in the form

$$R(t)=A_0F_0(t)+A_1F_1(t)+\dots \qquad (1)$$

where $F_r(t)$ is a function of time of the rth degree and the coefficients, A_r, are independent of time. In addition, the functions chosen have the property of mutual orthogonality such that $\int F_rF_sdt=0$, the integration running over the entire period under consideration. Because of this property of orthogonality of the time functions, the influence of the several functions are independent of each other and the coefficients of the polynomials indicate the extent of the influence of the different components independent of one another. Thus the coefficients can serve as independent parameters of the rainfall distribution for comparison between the different stations and between the different years. Hereafter, we shall refer to the coefficients, A_r, as "distribution parameters" of the rainfall distribution during the monsoon season. These rainfall distribution parameters are readily obtained by correlating the individual patterns represented by $F_r(t)$ with the rainfall series

$$A_r=\int R(t)F_r(t)dt, \qquad r=0, 1, 2, \dots \qquad (2)$$

where $R(t)$ is a discrete function representing 5-day total rainfall and $F_r(t)$ are orthogonal polynomials of time in units of 5 days. Here we use Fisher's orthogonal polynomials to the 5th degree (Fisher and Yates 1963).

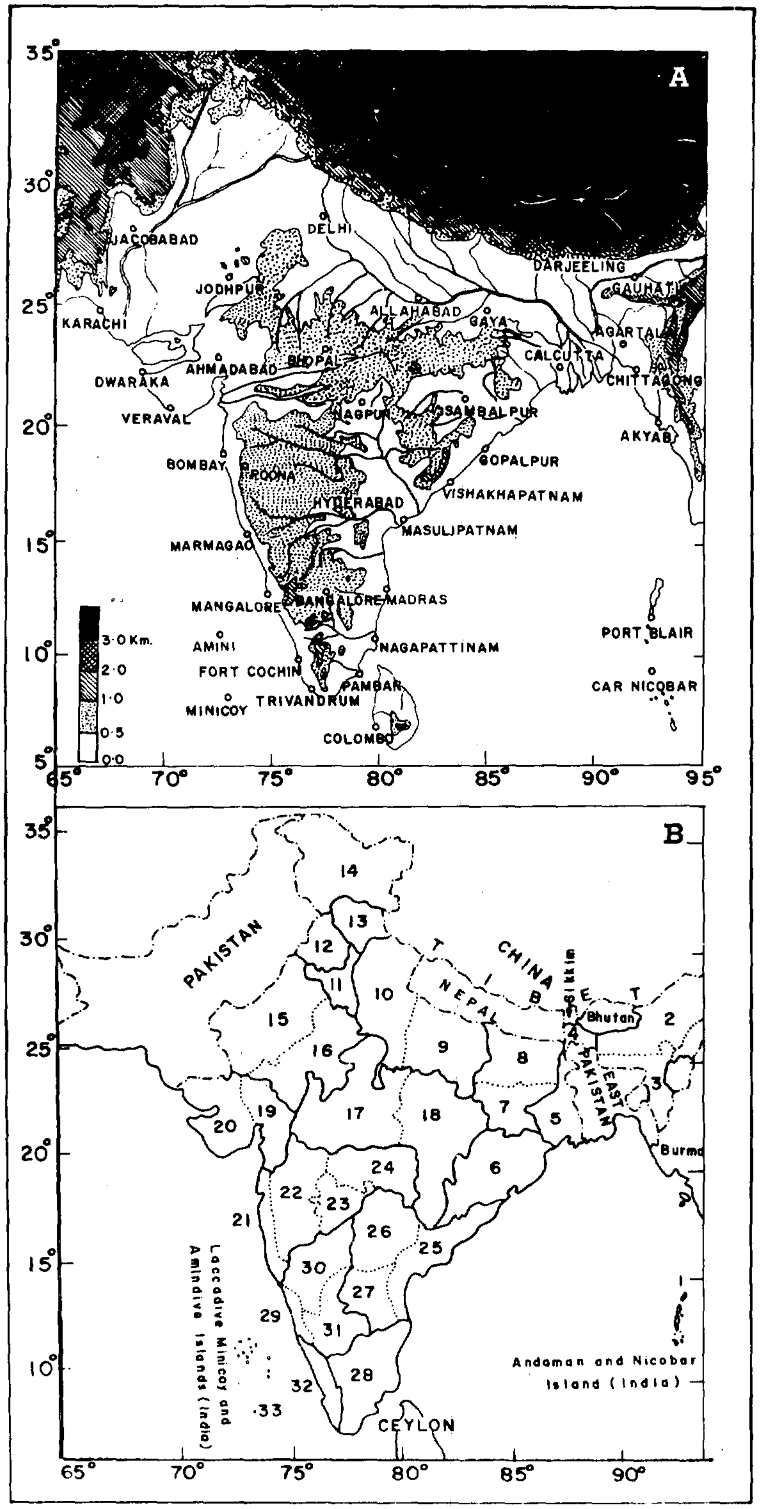
4. DISTRIBUTION PARAMETERS

The parameters representing the pattern of distribution of the rainfall during the monsoon have been calculated for each of the years 1901–51. The patterns of distribution at the different stations show high variability.

Before studying the year-to-year variations in the distribution parameters, we will discuss briefly what these functions represent and how their mean features vary over the area. Even though some of the mean parameters are not significant over certain areas, they exhibit a good deal of continuity revealing their geographic dependence (fig. 2). Areas over which the parameters are significant are shown by stippling (except for A_0). Brief comments on some of the features revealed follow:

A_0—The coefficient in the first term represents the mean level of the pentad rainfall and obviously the areal distribution of A_0 represents the mean rainfall distribution over the country. Since this is so well known, it is not described here.

A_1—This coefficient is a measure of the gradient of the linear trend in the rainfall with the advance of the season.



Index to Subdivision numbering

1. Bay Islands
2. North Assam
3. South Assam
4. Sub-Himalayan West Bengal
5. Gangetic West Bengal
6. Orissa
7. Bihar Plateau
8. Bihar Plains
9. Uttar Pradesh East
10. Uttar Pradesh West
11. Haryana
12. Punjab
13. Himachal Pradesh
14. Jammu and Kashmir
15. Rajasthan West
16. Rajasthan East
17. Madhya Pradesh West
18. Madhya Pradesh East
19. Gujarat
20. Saurashtra and Kutch
21. Konkan
22. Madhya Maharashtra
23. Marathwada
24. Vidarbha
25. Coastal Andhra Pradesh
26. Telengana
27. Rayalaseema
28. Tamil Nadu
29. Coastal Mysore
30. Interior Mysore North
31. Interior Mysore South
32. Kerala
33. Arabian Sea Islands

FIGURE 1.—Maps of India (A) relief, (B) subdivisions. East Pakistan is now Bangladesh.

A positive value indicates a general increase of rainfall with the advance of the season, while a negative value indicates a decrease. Over the west coast of the peninsula and over Assam and Bengal, the rainfall shows a general decreasing trend with the advance of the season; over the southern peninsula, east of the Western Ghats, and over the Ganga Valley, the rainfall of the monsoon season shows a general tendency to increase with the advance of the season. The inverse relationship between the character of the features on the windward and leeward sides of the Western Ghats is worth noting.

A_2—The coefficient of the second-degree term indicates whether the pattern associated with this component is convex (when A_2 is positive) or concave (when it is negative) to the time axis. Thus, when A_2 is positive, the rainfall described by this term attains a minimum during the

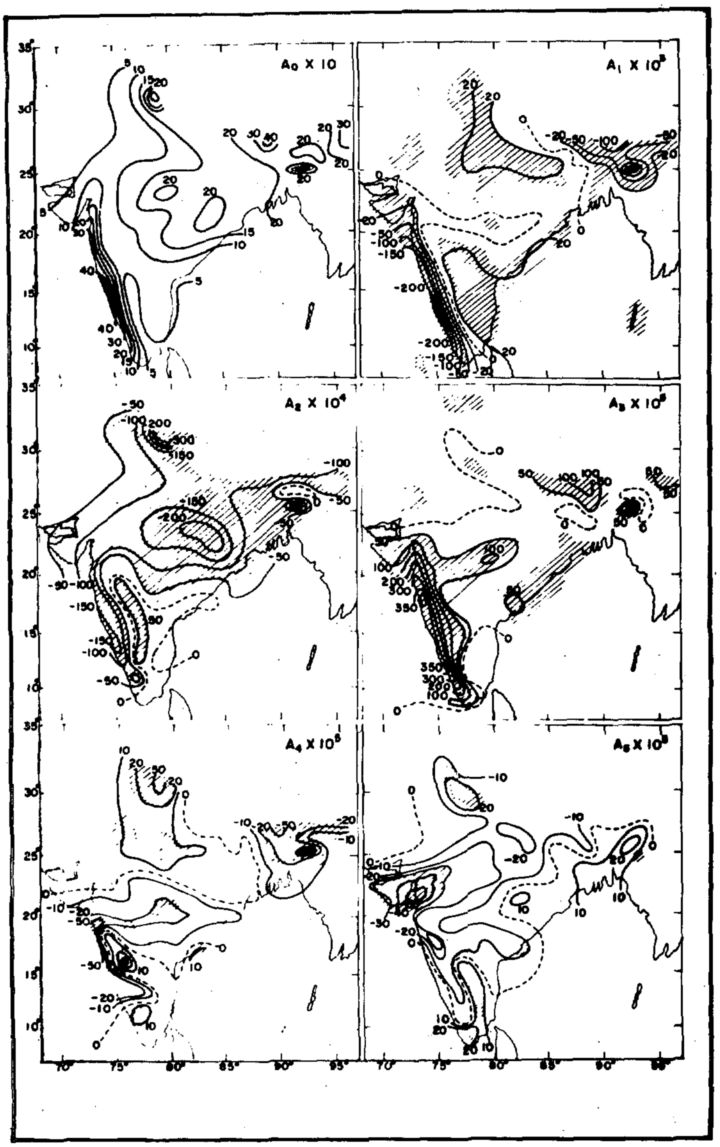


FIGURE 2.—Distribution parameters. Areas over which a parameter is significant are stippled.

TABLE 2.—*Character of polynomial trend of the rainfall distribution parameters*

State	No. of stations	Rainfall distribution parameters					
		A_0	A_1	A_2	A_3	A_4	A_5
Assam	(6)	1(4)+	1(3)−	3(1)+ 1(4)−		1(4)−	1(2)+ 1(5)+
West Bengal	(5)	1(4)−	1(2)+	1(1)− 1(3)+	2(5)+	1(4)−	2(3)+ 1(5)+
Bihar	(6)	−	1(3)−	1(1)−	−	3(3)−	1(2)+ 1(3)+ 3(4)− 1(5)+
Orissa	(5)	1(4)−	−	−	1(1)+ 1(2)+	1(5)−	1(3)+
Uttar Pradesh	(10)	3(1)+ 2(5)−	1(3)− 1(5)−	−	2(2)− 1(3)− 1(4)+	3(4)+ 1(5)−	1(4)− 3(5)+
Jammu and Kashmir	(2)	−	1(1)− 1(5)+	−	−	−	−
Punjab	(4)	−	1(3)+	2(4)−	−	1(3)+ 1(4)+	1(2)− 1(5)+
Rajasthan	(9)	−	1(5)−	1(5)−	−	1(3)+	1(4)−
Madhya-Pradesh	(8)	4(1)+ 1(2)−	2(4)+	3(1)−	1(3)− 1(5)+	1(4)+	−
Gujarat	(5)	−	1(4)+	1(1)− 1(2)− 1(5)−	1(3)−	1(2)+	1(5)−
Maharashtra	(10)	2(1)+ 1(2)− 1(4)−	1(2)+ 1(3)+ 3(4)+	1(2)− 1(3)+	1(5)+	5(3)+ 1(4)+ 1(4)− 1(5)−	1(1)+ 1(4)−
Andhra Pradesh	(6)	1(1)− 1(2)+ 1(3)+	1(4)−	−	1(3)+	−	1(5)+
Mysore	(5)	−	1(3)+	−	1(3)−	1(3)+ 2(3)+	1(4)+ 1(5)+
Kerala	(5)	−	−	−	−	2(3)+	−
Madras	(8)	1(1)− 1(3)+	1(4)−	−	1(3)− 1(5)−	1(4)+	1(2)− 1(4)− 3(5)+

middle of the season; a negative A_2 indicates maximum rainfall. This component is negative over almost the entire country except for a region parallel to the Western Ghats on its lee side and a small area behind the Khasi Hills. The largest negative values (i.e., maximum rainfall) are found over Punjab-Uttar Pradesh Hills, the Khasi Hills, the Western Ghats, and over Orissa-Madhya Pradesh. Therefore, we find that the rainfall associated with this component is highest on the windward side of the hills and lowest on the leeward side.

A_3—This component is positive over practically the whole country, except for northwest India, the southeast peninsula and a small area behind the Khasi Hills. The maximum (positive) values are located over the west coast of the peninsula and over the Khasi Hills. The rainfall value described by this coefficient experiences a full oscillation during the season. Over those regions where the coefficient is positive, a rainfall maximum occurs near the end of June or in early July and a minimum occurs at the beginning of September. Where this component is negative, minimum rainfall is experienced at the end of June and the maximum near the beginning of September. Therefore, if two or more areas have like signs, their rain spells are in phase; if the areas have opposing signs, their rain spells are half a cycle out of phase. Even though the negative values of the parameters over the southeast peninsula and on the lee side of the Khasi Hills are not statistically significant individually, their occurrence in such large groups suggests that the windward and leeward precipitation patterns described by this coefficient may also be inversely related.

A_4—This component is negative over the northern peninsula, over the west coast of the peninsula between 13° and 20° N, and over the north Assam and Bengal hills. Over the rest of the peninsula and the west Uttar Pradesh and Punjab region, the coefficient is positive. This component is significant in the northern portions of northeastern India, the sub-Himalayan regions of West Uttar Pradesh, Punjab, and a few scattered pockets. The rainfall described by this coefficient is periodic, with peaks and troughs alternating every 6 weeks.

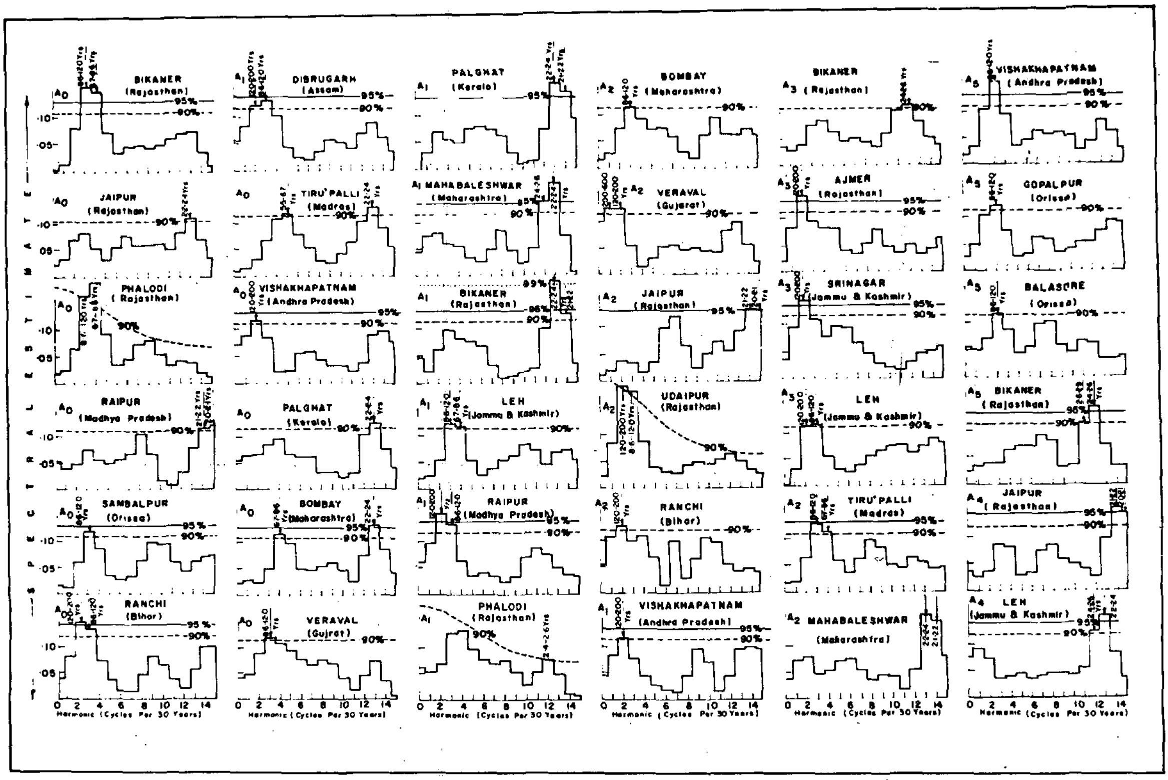


FIGURE 3.—Power spectra of rainfall distribution parameters.

A_5—This component is significant over Gujarat, Punjab, and at a few scattered stations elsewhere. In these areas, the rainfall described by this term is also periodic, with peaks and troughs alternating every 4 weeks.

Previous discussion describes the average behavior of the component patterns in the different parts of the country. What are the physical causes of these patterns? At present, we can only speculate on the answer to this question. We must first look more closely at the time variations of these parameters. This we shall do in the remaining sections of this paper.

5. POLYNOMIAL TRENDS IN THE SERIES OF DISTRIBUTION PARAMETERS

The time series of the distribution parameters for a period of 51 yr at the different stations were subjected to trend analysis by fitting fifth-degree polynomials of time. Fisher's orthogonal polynomials (Fisher and Yates 1963) were used. The character of the polynomial trends of the different distribution parameters are summarized in table 2.

Only significant parameters (5-percent level) are enumerated. The presentation is made in the form $n(D)s$, where n is the number of stations with the specified feature, D is the degree of the polynominal that is significant at the 5-percent level, and s is the sign of the coefficient ($+$ or $-$). A_0, which represents the monsoon rainfall as a whole, shows an increasing linear trend over a part of the west coast of the peninsula, West Madhya-Pradesh, and a few stations in Uttar Pradesh. A decreasing linear trend is shown over a portion of coastal Andhra Pradesh and some areas in Madras State.

TABLE 3.—*Total count of the spectral peaks significant at the 95 percent level*

Parameter	A_0	A_1	A_2	A_3	A_4	A_5	Total count
QBO	10	12	11	11	14	13	71
Sunspot cycle	5	3	6	8	1	3	26
Other cycles	7	5	6	12	15	6	51
Total	22	20	23	31	30	22	148

The higher degree parameters also exhibit, to a significant level, trend features that are consistent over large areas. Thus, the representative parameters of the distribution of rainfall during the monsoon season appear to experience oscillatory tendencies during the first half of this century. We must now determine whether or not the observed fluctuations are systematic oscillations and, if so, to ascertain the frequencies of such oscillations.

6. SPECTRAL ANALYSIS

The time series of all the distribution parameters were subjected to power spectrum analysis on the basis of correlations for 15-lag. The resulting spectra for a few selected stations are shown in figure 3. These spectra exhibit many peaks and troughs. The sampling theory developed by Tukey (1950) was used in an attempt to determine whether these peaks and the troughs are

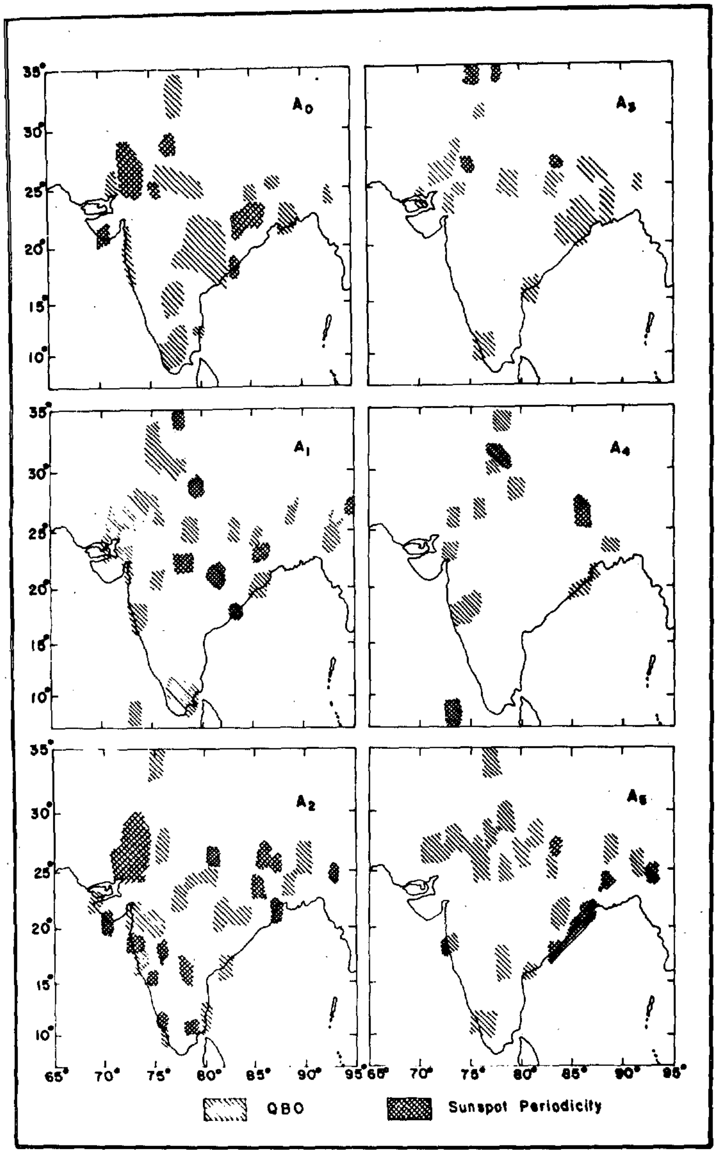


FIGURE 4.—Significant periodicities in rainfall patterns.

accidental occurrences resulting from sampling procedures or in reality represent systematic oscillations. The null hypothesis of red or white noise spectrum was adopted depending on whether or not the series revealed any persistence. If the persistence was of the Markov linear type, the appropriate red noise spectrum and the associated 99-, 95-, and 90-percent limits were calculated, and the individual peaks were tested with reference to these limits. If the 1-lag correlation was significantly greater in magnitude than zero and the higher lag correlations did not taper off exponentially, the spectral estimates were initially tested with reference to the relevant red noise spectrum; later, the existence of other types of nonrandomness was investigated. In the absence of any persistence, the spectral estimates were tested against the white noise spectrum. Before accepting the peaks, the possible higher frequency oscillations, which might throw "aliased power" at the observed frequency, were investigated and suitable allowance was made.

Table 3 gives the total count of significant spectral peaks for six parameters for all the stations. Of the several periodicities exhibited in the individual spectra, the quasi-biennial oscillation (QBO) is predominant; the cycles corresponding to the sunspot cycle are also frequently observed. Since sunspot cycles have been observed in several other atmospheric phenomena, their existence in monsoon rainfall distribution can be considered probable even though the cause-effect relationships are still obscure. The quasi-biennial oscillation, one of a group of cycles in the atmosphere that is related to the sunspot cycle, has gained considerable acceptance in recent years. The other cycles, which have not been anticipated on a priori considerations, fell out as insignificant when tested with more stringent criteria appropriate to the highest observed powers of the several powers calculated.

The following are some of the salient features revealed by the spectral analysis (fig. 4):

A_0—The spectra exhibit significant power over the range of period 2.0–2.9 yr over the west coast (north), interior southern peninsula, a large part of Andhra Pradesh, West Madhya-Pradesh and Madhya Bharat, Jammu and Kashmir, and a few isolated spots in Assam, Bengal, Bihar, and Rajasthan, indicating some periodicities corresponding to the QBO. In addition, a number of stations in Rajasthan and adjoining Uttar Pradesh, Madhya Bharat, and Kathiawar and over Bihar Plateau exhibit oscillations corresponding to the sunspot cycle. Koteswaram and Alvi (1969) and Bhargava and Bansal (1969) also reported QBO in the annual rainfall over the west coast (north) of India.

A_1—The QBO in this component is noticeable over Rajasthan, Punjab, Gujarat, Western Maharashtra, and extreme southern peninsula, and a few stations over southern Uttar Pradesh, Bihar, and Orissa. The sunspot cycle is observed over a few stations in coastal Andhra Pradesh, Madhya-Pradesh, North Assam, West U.P., and Jammu and Kashmir.

A_2—The QBO is noticeable over the area extending from coastal Andhra Pradesh northwestward (except for West Rajasthan) and at a few stations over Assam, Bengal, the extreme southern peninsula, and southern Maharashtra. The sunspot cycle is observed to the north and south of the elongated QBO region and over West Rajasthan and a few stations in Assam and on the extreme southern peninsula.

A_3—The QBO or a subharmonic thereof is present over practically the entire country at different levels of significance; the sunspot cycle is observed over Jammu and Kashmir and at a few stations in Rajasthan and Uttar Pradesh.

A_4—The QBO or a subharmonic thereof is significant over Northwest India, Bengal, and the Orissa coast; the sunspot cycle is significant in the sub-Himalayan region, Bihar, and Uttar Pradesh.

A_5—The QBO is present over practically the entire country at different levels of significance; the sunspot

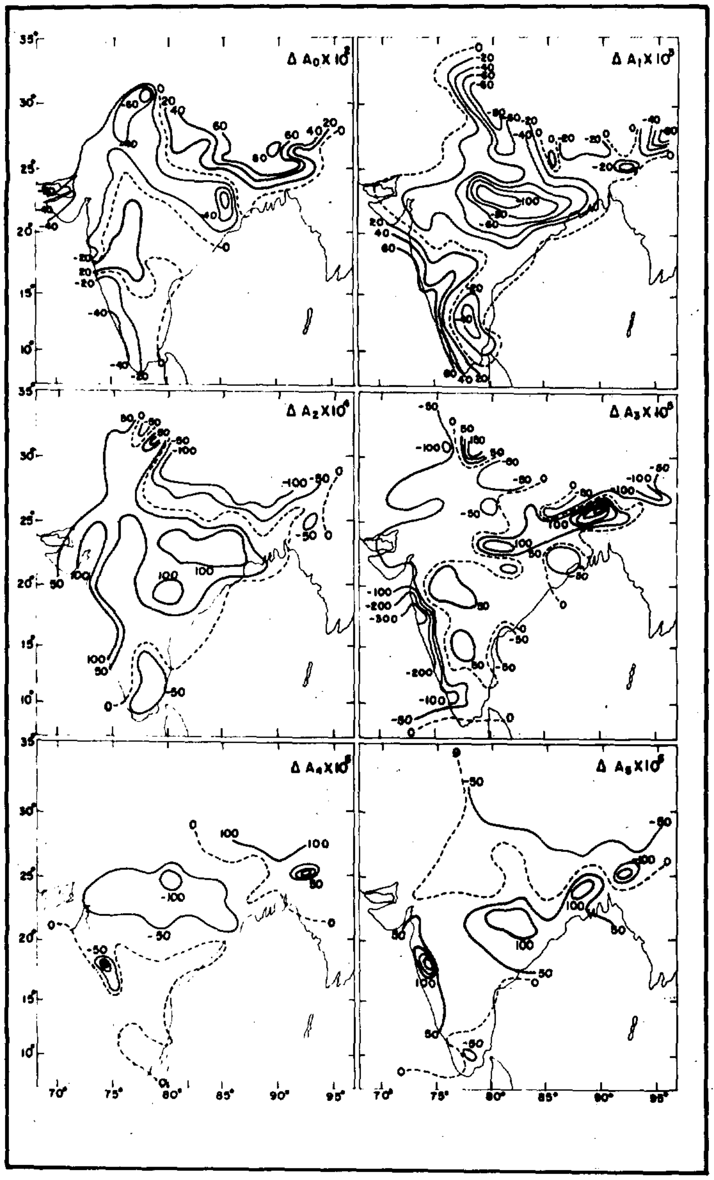


FIGURE 5.—Anomalous variations between sunspot epochs.

cycle is observed over the east coast north of 15°N and over the sub-Himalayan region.

The preceding analysis clearly shows that the characteristic parameters representing the pattern of distribution of monsoon rainfall experience oscillations corresponding to the solar cycle. In the next section, we will examine the contrasting patterns associated with the different phases of the sunspot cycle.

7. VARIATIONS ASSOCIATED WITH SUNSPOT EPOCHS

Composite patterns corresponding to the epochs of sunspot maximum, sunspot minimum, sunspot increasing, and sunspot decreasing have been obtained by pooling the different years of like sunspot character. Only the central years in which the specified feature is observed have been used. The spatial distribution of the anomalous variations between sunspot epochs defined by

$$\Delta A_r = \overline{A_r(\max)} - \overline{A_r(\min)}$$

are shown in figure 5. The contrasting variations in the component patterns of the rainfall distribution associated with the four epochs along with the integrated patterns are shown for a few selected stations (fig. 6).

The salient features of the variations associated with sunspots are as follows:

A_0—The mean rainfall is larger during sunspot maximum than during sunspot minimum (i.e., positive ΔA_0) over North Assam, North Bengal, Bihar, and sub-Himalayan East U.P., and the central parts of the peninsula. Over the rest of the country, the rainfall during the sunspot minimum is larger than that during the sunspot maximum. The significant increase of rainfall during the maximum epoch over the sub-Himalayan northeast India, a decrease over the region extending from Orissa to Punjab, and another increase from Kathiawar-Konkan northeastward with a reversal of the picture during sunspot minimum are suggestive of the role played by the storms and depressions of the season. In addition, the oscillations of the response of A_0 corresponding to the sunspot cycle are dominant in the areas influenced by orography.

A_1—The mean anomalies are positive over the west coast (fig. 5), where the decrease of rainfall with the advance of the season becomes more sharp during sunspot minimum than during sunspot maximum. (See rainfall profiles for Bombay, Ratnagiri, Mangalore, and Trivandrum on fig. 6A.) The anomalies are significantly negative over three areas extending from Orissa; (1) westward to Gujarat, (2) northwestward to Punjab, and (3) northeastward to Assam. The profiles on figure 6B indicate that the rainfall due to this component increases with the advance of the season during the minimum epoch and decreases during the maximum epoch or decreases at a smaller rate during the minimum epoch than during the maximum epoch.

A_2—Over the west coast between 13° and 20°N, Orissa, and Madhya-Pradesh, the rainfall described by this component tends to concentrate more during the middle of the season with higher values occurring during the minimum epoch than during the maximum epoch. Over the north Uttar Pradesh, Bihar, Bengal, and Assam, the anomalies are of opposite signs.

A_3—The anomalies are negative over the western regions with a maximum over the west coast. They are generally positive over the east coast with maximum values over an area extending from North Bengal to East Madhya Pradesh.

A_4—The anomalies are negative over the central regions of the country with a maximum over the Mahabaleshwar area; the anomalies are positive in the extreme northeast with maximum over the Cherrapunji region.

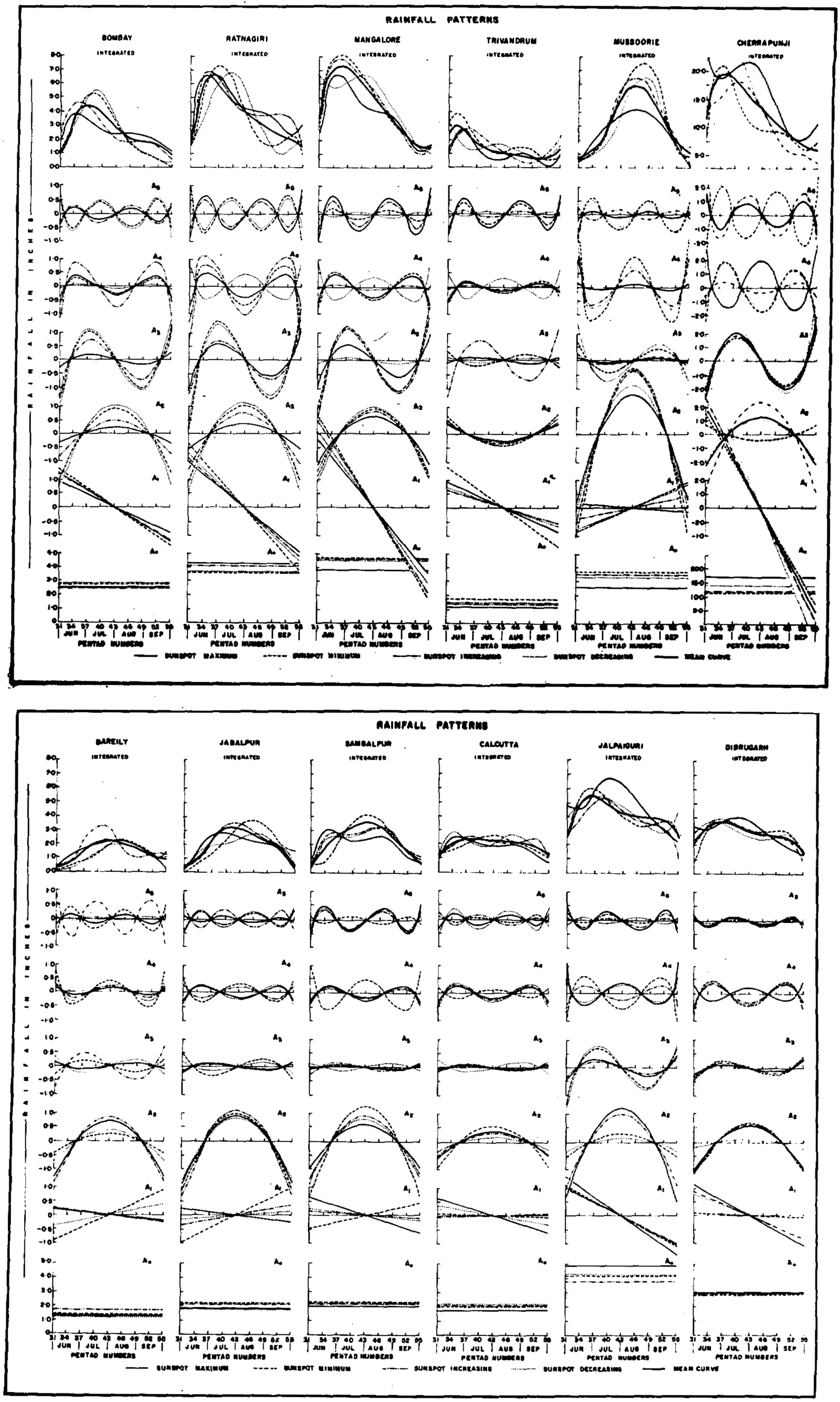


FIGURE 6.—Rainfall patterns associated with four sunspot epochs.

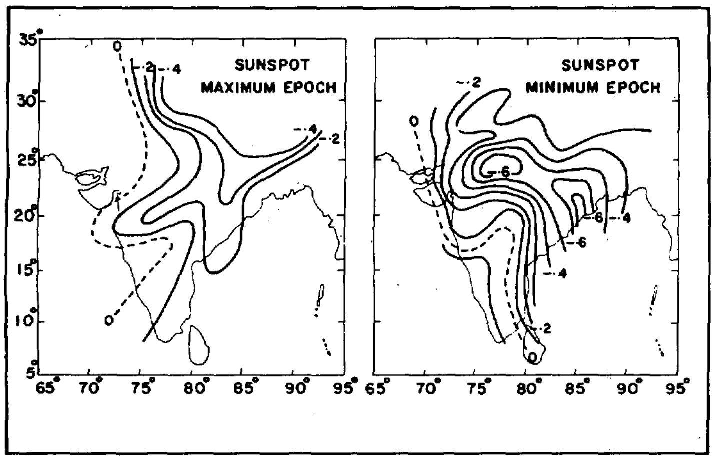


Figure 7.—Surface pressure departure (mb) during monsoon season.

Table 4.—*Number of days of breaks in the monsoon*

Central year (C)	Sunspot minimum epoch			Central year (C)	Sunspot maximum epoch		
	C−1	C	C+1		C−1	C	C+1
1901	8	4	7	1906	13	28	0
1912	11	11	15	1918	10	23	4
1923	7	0	8	1928	15	12	0
1933	20	7	8	1938	8	0	4
1943	4	0	0	1948	12	3	10
Total	50	22	38		58	66	18

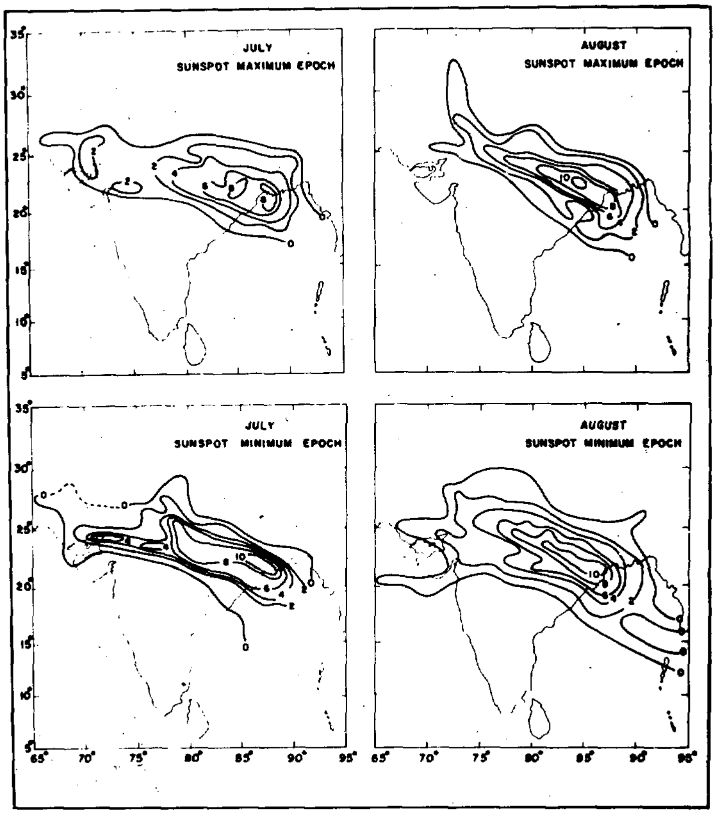


Figure 8.—Frequency of storms and depressions (1901–1950).

A_5—The anomalies over the peninsula are positive with maxima over the west coast and over south Bengal, Orissa, and East Madhya Pradesh; the anomalies are negative over the northern regions with maximum values over the Khasi Hills and the sub-Himalayan region.

The integrated patterns on figure 6 also show significant contrasts between the different sunspot epochs.

8. ANOMALOUS CIRCULATION FEATURES ASSOCIATED WITH SUNSPOT EPOCHS

The foregoing analyses clearly show that the rainfall distribution patterns during the monsoon season vary from one sunspot epoch to another. In addition, the distribution patterns exhibit considerable spatial variations. It appears, therefore, that sunspot influence, as evidenced by the differential rainfall patterns, arises from changes introduced in the circulation features. The composite surface pressure fields associated with the sunspot maximum epoch and sunspot minimum epoch (fig. 7), show that, during the sunspot maximum the core of the negative pressure departures lies near the foot of the Himalaya, a condition usually associated with the break monsoon. During sunspot minimum, this core is situated farther south over Orissa-Madhya Pradesh-East Rajasthan, as in the active monsoon condition.

Table 4 (extracted from Ramamurthy 1969) shows the relative frequency of breaks in the monsoon during July and August of different years. Note that the total number of days of breaks in the monsoon is significantly larger during sunspot maximum than during sunspot minimum.

It is well known that the fluctuations in the intensity of the rainfall during the monsoon season are to a large extent associated with the series of storms and depressions and their movement. The average number of storms and depressions that crossed each 1° square during the two epochs for the normally strong monsoon months of July and August is shown in figure 8. We see that more storms and depressions are observed during the minimum epoch than during the maximum epoch. Also, the length of the tracks as well as the duration of the systems are greater during the minimum epoch than during the maximum epoch.

9. CONCLUDING REMARKS

The year-to-year variations in the characteristic parameters representing the pattern of monsoon rainfall over India are not entirely random. Power spectra of the time series reveal variations corresponding to the sunspot cycle or some higher harmonics thereof; the QBO, for example, is apparent in some of the parameters over extensive areas of the country. The anomalous fluctuations associated with the different phases of the sunspot cycle show characteristic variations in the rainfall patterns. The previous findings of Jagannathan and Raghavendra (1964), wherein they concluded that the duration of "wet spells" in the arid and semiarid Rajasthan are related to sunspot cycle characteristics, receive further support here. The geographical patterns of response to sunspot cycle and the anomalous behavior of certain circulation features associated with the different sunspot epochs suggest that the real cause-effect in the solar-weather relationships may be traceable to changes introduced in the atmospheric circulation. How these energetically minute changes in the solar features could be linked to the energetically large changes in the atmosphere are still major questions to be answered; it is hoped that the dissection of the rainfall features provided here may help in this direction.

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