Intraseasonal and Interannual Variability of Rainfall over India

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(Manuscript received 20 August 1999, in final form 21 February 2000)

ABSTRACT

A gridded daily rainfall dataset prepared from observations at 3700 stations is used to analyze the intraseasonal and interannual variability of the summer monsoon rainfall over India. It is found that the major drought years are characterized by large-scale negative rainfall anomalies covering nearly all of India and persisting for the entire monsoon season. The intraseasonal variability of rainfall during a monsoon season is characterized by the occurrence of active and break phases. During the active phase, the rainfall is above normal over central India and below normal over northern India (foothills of the Himalaya) and southern India. This pattern is reversed during the break phase.

It is found that the nature of the intraseasonal variability is not different during the years of major droughts or major floods. This suggests that a simple conceptual model to explain the interannual variability of the Indian monsoon rainfall should consist of a linear combination of a large-scale persistent seasonal mean component and a statistical average of intraseasonal variations. The large-scale persistent component can be part of low-frequency components of the coupled ocean–land–atmosphere system including influences of sea surface temperature, snow, etc. The mechanisms responsible for the intraseasonal variations are not well understood. This simple conceptual framework suggests that the ability to predict the seasonal mean rainfall over India will depend on the relative contributions of the externally forced component and the intraseasonal component. To the extent that the intraseasonal component is intrinsically unpredictable, success in long-range forecasting will largely depend on accurate quantitative estimates of the externally forced component.

1. Introduction

Subsequent to the highly deficient summer monsoon rainfall over India in 1877 and the accompanying famine, a large network of rain gauge stations was established over India (Walker 1910). This network of rain gauges has provided a valuable source of data to analyze the space–time structure of the monsoon rainfall and its variability over India. Because of the enormous impact of the monsoon rains on the agrarian societies of Asia, a large number of scientific papers and technical reports have been published with descriptions of rainfall variability over different parts of Asia. The long time series of rainfall data over India has become somewhat of a proxy for the interannual variability of the Asiatic monsoon as a whole.

A large number of papers have analyzed the interannual variability of the summer [June–July–August–September (JJAS)] mean monsoon rainfall averaged over India (see, e.g., Parthasarathy and Mooley 1978; Shukla 1987; Parthasarathy et al. 1994). From observations at several thousand stations for the period 1901–70, the long-term mean value of JJAS rainfall averaged over India is about 923 mm and the interannual standard deviation of the seasonal mean rainfall is about 10 percent (87 mm) of the long-term mean value, as will be shown later. For brevity, years with seasonal mean rainfall in excess of one standard deviation over the long-term mean will be referred to as ''flood'' years, and those with more than one standard deviation below the mean will be referred to as ''drought'' years. It is well known that, even during a particular monsoon season, large spatial and intraseasonal variability of the monsoon rainfall over India is evident. This is primarily because the occurrence of the rainfall is associated either with monsoon disturbances (referred to as monsoon depressions) that form over the adjoining seas and move over land, or with an intensification and/or displacement of the so-called monsoon trough (summer season equivalent to the intertropical convergence zone) that generally lies over the northern plains of India during the monsoon season. The day-to-day variability of rainfall is thus characterized by ''active'' periods with high rainfall over central India when the monsoon trough is over the northern plains, and ''break'' periods with weak or no rainfall over central India and high rainfall over

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northern India when the monsoon trough is over the foothills of the Himalaya (Ramamurthy 1969). Each phase lasts several days.

Based on research to date, it has not been possible to establish whether the occurrence of active and break phases of the monsoon rainfall is a manifestation of some form of dynamical instability of the mean monsoon flow, or a mere indicator of the formation, growth, and propagation of monsoon depressions and/or north–south displacement of the monsoon trough. The latter can also occur in association with the eastward-propagating midlatitude disturbances (Ramaswamy 1962). In a spectral analysis of 70-yr daily rainfall data, Hartman and Michelsen (1989) noted a spectral peak at about 40–50 days, corresponding to the Madden–Julian oscillation (MJO; Madden and Julian 1972). Intraseasonal oscillations on the MJO timescale have been linked to the active–break phases of the monsoon in some studies (De et al. 1988; Singh et al. 1992; Goswami et al. 1998). Several studies based on observations (Yasunari 1979; Sikka and Gadgil 1980; Gadgil and Asha 1992) have associated the active and break phases with fluctuations in two convergence zones, one over the Indian continent and the other over the Indian Ocean. Idealized modeling studies (Goswami and Shukla 1984; Nanjundiah et al. 1992) have suggested that the intraseasonal quasiperiodic fluctuations in the monsoon region can occur from interactions between large-scale dynamics and moist convection.

The motivation for this study is to investigate whether droughts and floods over India are a manifestation of large-scale persistent rainfall anomalies, or are due to a change in the nature of the intraseasonal variability. The main purpose of this paper is to analyze the nature of the intraseasonal variability using the daily rainfall data for 3700 stations over India, which were gridded by Hartman and Michelsen (1989), for the period 1901–70. This study addresses the following questions.

1) Is there a distinct difference in intraseasonal variability between the flood years and the drought years?
2) Are the spatial structures of the dominant modes of the intraseasonal variability over India different from those of the interannual variability of the seasonal means?

While it is difficult to address these questions by analyzing observations, it may be possible to gain some insight into the role of intraseasonal variability in producing interannual variability and vice versa. Current general circulation models (GCMs) are so deficient in simulating the monsoon variability (Sperber and Palmer 1996) that it is difficult to draw reliable inferences on the mechanisms of interannual and intraseasonal variability using GCM simulations. An analysis of observations also cannot provide definite answers to the questions posed above. In the present study, two a priori postulates are put forward, and their validity is tested using observed data.

1) There is no seasonally persistent, externally forced component of rainfall over India, and the entire interannual variability is a manifestation of the changes in the nature of the intraseasonal variations. This postulate is not inconsistent with the suggestions of Palmer (1994) and Webster et al. (1998) that slowly varying boundary conditions (''external forcings'') change only the nature of the intraseasonal variability.
2) The seasonal mean monsoon rainfall consists of an externally forced large-scale (nearly all of India), persistent (nearly the entire season) component and an intraseasonal component that is independent of external forcing. This postulate is an extension of an earlier hypothesis by Charney and Shukla (1981) who suggested that the interannual variability of monsoon rainfall is largely determined by changes in the boundary forcings at the earth's surface.

Webster et al. (1998) have suggested that there is no contradiction between the hypotheses of Charney and Shukla (1981) and Palmer (1994) because the boundary forcings change the probability density function of the intraseasonal variations, giving rise to different seasonal means. The second postulate described above goes beyond a reconciliation of the hypotheses of Charney and Shukla (1981) and Palmer (1994), and suggests that the nature of the intraseasonal variations (viz., frequency of active and break phases) is statistically indistinguishable from year to year, and that the seasonal mean for any given year is a linear combination of the externally forced seasonally persistent component and the mean of the intraseasonal variations. It is recognized that, even in the absence of an externally forced seasonally persistent anomaly, the seasonal mean of the intraseasonal variations will be different from one year to the other. Therefore, in the context of this postulate, the predictability of seasonal mean monsoon rainfall will depend on the relative magnitudes of the externally forced, seasonally persistent component and the seasonal average of the intraseasonal component.

It is difficult to test these postulates using observed data because of the difficulty in separating the seasonal and intraseasonal variability. For example, even if it were true that the daily rainfall is an algebraic sum of a large-scale seasonally persistent component and an intraseasonal component that is independent of the large-scale seasonally persistent component (postulate 2), an analysis of the daily time series of observed rainfall cannot unambiguously isolate the seasonally persistent component because the variance of the daily rainfall is about two orders of magnitude higher than that of the seasonal mean rainfall. Thus, the daily variances remain nearly the same whether the seasonal mean for each year is included or excluded in defining the daily rainfall anomalies.

In addition, an a priori separation of the daily and seasonal anomalies makes it difficult to validate the first postulate. Because, even if it were true that there is no externally forced seasonally persistent component, any method used to isolate the intraseasonal variability by removing the seasonal mean will impact the internal variability of the intraseasonal variations itself. Due to these difficulties, an analysis of the observed rainfall can only give an indication of the degree to which each of the proposed postulates is evident.

The data used in this study and the method of analysis are described in section 2. The features of the variability of rainfall over India on daily and seasonal timescales are discussed in section 3. In section 4, the dominant modes of the intraseasonal and interannual variations of the monsoon rainfall, as determined by the empirical orthogonal function (EOF) analysis, are described. The relationship between the intraseasonal and interannual variations is established in section 5 by two different methods of analysis. Section 6 provides summary and conclusions, and discusses the implications of the results on the predictability of the monsoon rainfall.

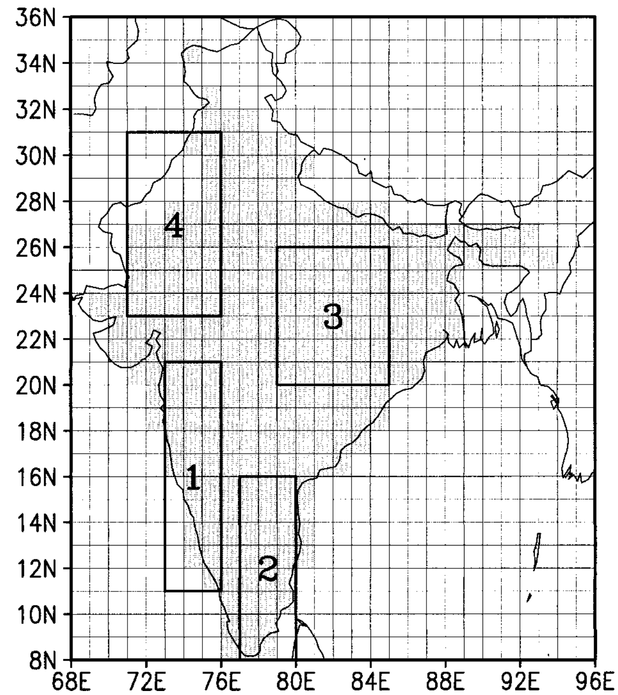

FIG. 1. Map of 1° longitude × 1° latitude grid over India. The daily rainfall data (1901–70) used in this study are located in shaded grid boxes. The labeled regions (1–4) are used in area averages of rainfall presented in Fig. 3.

2. Data and method of analysis

The daily rainfall data used in this study originally came from observations made at more than 3700 rain gauge stations by the India Meteorological Department (IMD). A brief historical account and some description of the rainfall data collection by the IMD are given by Walker (1910) and Parthasarathy and Mooley (1978). The daily station data for the period 1901–70 are available from the National Center for Atmospheric Research (NCAR). For their study of the intraseasonal periodicity of the Indian rainfall, Hartman and Michelsen (1989) converted the IMD data into a gridded dataset by grouping the station data into 1° latitude × 1° longitude grid boxes shown in Fig. 1. They reconstructed data at 293 grid points over India by computing simple averages of all available station observations within each grid box. As described by Hartman and Michelsen, the availability of station data within each grid box is quite good, with 92% of the grid boxes composing three or more stations while 75% of the grid boxes including seven or more stations. About 90% of the grid boxes contain at least one station in each grid box that has data available for more than 60 years. In the present study, the daily rainfall data gridded by Hartman and Michelsen for the period 1901–70 have been used and are referred to as the IMD data. In order to make the data continuous for the entire 70 yr, missing data points have been filled by linear interpolation in space. However, as the data cannot be interpolated at grid boxes on the boundaries, the final continuous dataset consists of 260 grid boxes that are shaded in Fig. 1. Discontinuous data, at grid points mostly in extreme north and northeast India, were excluded.

The seasonal mean is defined as the mean of the rainfall over the 122 days of JJAS. The daily and seasonal anomalies are defined as follows. If $R(m, n)$ is the total rainfall for the nth day of mth year of the 70-yr IMD data, then

the daily rainfall climatology,

$$R_c(n) = \frac{\sum_{m=1}^{70} R(m, n)}{70},$$

the daily rainfall anomaly including seasonal anomaly,

$$R'(m, n) = R(m, n) - R_c(n),$$

the seasonal anomaly,

$$R'_s(m) = \frac{\sum_{n=1}^{122} R'(m, n)}{122}, \quad \text{and}$$

the daily rainfall anomaly,

$$R''(m, n) = R'(m, n) - R'_s(m).$$

Prior to these calculations, very high frequency fluctuations in the daily rainfall data have been removed by applying a 5-day running mean filter to the daily rainfall data in order to obtain more coherent results. Unless otherwise specified, the daily rainfall means and anomalies referred to hereafter are 5-day running means.

To study the dominant modes of the intraseasonal and

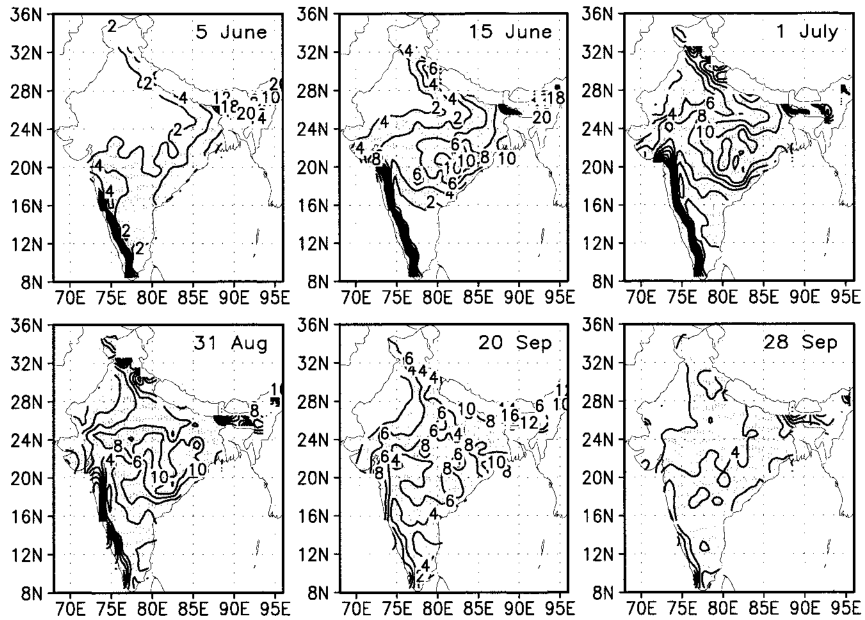

FIG. 2. Daily climatological mean (mm day^{-1}) of rainfall for selected days showing the onset (5 Jun, 15 Jun), persistence (1 Jul, 31 Aug) and withdrawal (20 Sep, 28 Sep) of the Indian summer monsoon rainfall. The daily climatology is based on onset composites formed by shifting the onset date of each year to the climatological mean onset date (2 Jun) of monsoon in Kerala for the 1901–70 period. Contours >2 are shaded.

interannual variability of the rainfall, EOF analyses of the daily anomalies and the seasonal anomalies are performed. The EOFs and the associated principal components (PCs) are determined by performing singular-value decomposition of the covariance matrices of the anomalies. Correlations between the spatial patterns (consisting of 260 grids over India) of the daily and seasonal anomalies are also calculated.

The circulation associated with the rainfall has been examined by using daily mean horizontal winds at 850 hPa from the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis dataset (see Kalnay et al. 1996 for details).

3. Variability of daily and seasonal rainfall

In this section, the main features of the variability of rainfall over India on both daily and seasonal timescales based on the IMD rainfall data for the period 1901–70 are described. Specifically, the climatological means and the variances of daily and seasonal mean rainfall over India's land region are examined.

a. Onset, persistence, and withdrawal of summer monsoon rainfall

As discussed in several studies (see review by Mooley and Shukla 1987), the summer monsoon rainfall first arrives in Kerala, a state in southwest India, between late May and early June every year, and gradually advances over all of India during June. Using the IMD data on the onset dates of rainfall over various parts of India during 1901–84, Mooley and Shukla (1987) determined that the climatological onset date of the summer monsoon over Kerala was 2 June, with a standard deviation of 8 days. Because of this variability in the onset date, the 70-yr gridded daily rainfall data were reconstructed by shifting each year's actual onset date over Kerala to the climatological onset date (2 June) in order to examine the onset, advance, persistence, and the withdrawal of the monsoon rainfall over India. From these 70 yr of 1 May–30 September daily data (hereafter referred to as onset composites), daily climatological means [defined as $R_c(n)$ in section 2] were computed. In Fig. 2, the daily climatological mean of the onset composite is shown for six selected days. After the initial onset over Kerala on 2 June, the monsoon covers the Western Ghats with heavy rainfall by 5 June, and a rainfall of about 2 mm day^{-1} covers the southern and eastern parts of India. By 15 June, the rainfall intensifies and extends over a larger area including central India, where the maximum rainfall is about 10 mm day^{-1}. Almost all of India experiences monsoon rainfall by 1 July with heavy rainfall over the Western Ghats and the eastern hilly regions, and with considerable rainfall over central India. This pattern persists with active and break spells (which can be seen in each individual year but not in the 70-yr climatology) through 31 August and into the beginning of September. The withdrawal of the summer monsoon becomes apparent by about 20 September when much of India experiences less intense

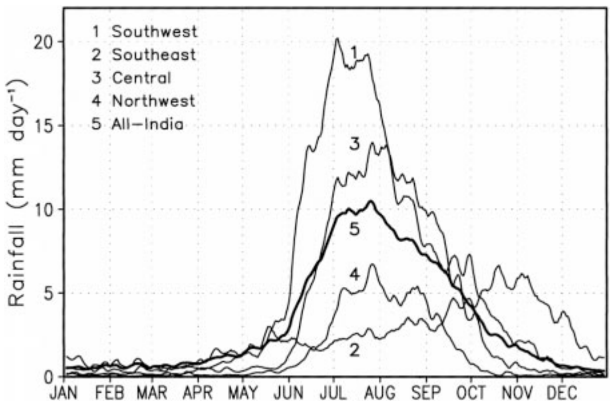

FIG. 3. Daily climatological mean (mm day^{-1}) of 5-day running mean of rainfall area averaged over 1) southwest, 2) southeast, 3) central, 4) northwest India (regions as indicated in Fig. 1) and over 5) all India. The daily climatology is based on rainfall for actual days (not onset composites) of the 1901–70 period.

rainfall, and the withdrawal is almost complete with rainfall of only about 2–4 mm day^{-1} by 28 September.

b. Climatology of daily and seasonal mean rainfall

The daily climatology maps of rainfall for the entire year were examined, but to summarize the day-to-day changes in the daily climatological mean rainfall, four regions over India have been considered, as shown in Fig. 1: southwest (11°–21°N, 73°–76°E), southeast (8°–16°N, 77°–80°E), central (20°–26°N, 79°–85°E), and northwest (23°–31°N, 71°–76°E). The selection of these regions was based on geographical uniformity in the rainfall. The daily climatological mean $R_c(n)$ for the nth calendar day of the year was area averaged over the four above-mentioned regions and over entire India (all-India). Grid boxes without data are excluded from the area averages. The time series of the area averages for the five regions are shown in Fig. 3. Except for the southeast region, the rainfall season lasts from June to September. The southeast region receives less than 3 mm day^{-1} during JJAS but receives higher rainfall during the months of October, November, and December, generally referred to as the winter monsoon. With rapid onset, the southwest region covering the Western Ghats receives the maximum amount of rainfall throughout the summer season, with average peak around 20 mm day^{-1}. The central region of India also receives a substantial amount of rainfall, between 10 and 15 mm day^{-1}, during July and August. The ascent to the peak value during June is more gradual in the central region. The all-India average closely follows the average of the central region, with the main difference being that the peak values differ by about 2–5 mm day^{-1}. It is not surprising that the northwest region, which is partly desert, receives the lowest amount of rainfall throughout the summer season, with a peak value around 5 mm day^{-1}. Except for the southeast region, the rainfall over all the regions rapidly decreases during the withdrawal phase of the summer monsoon in September.

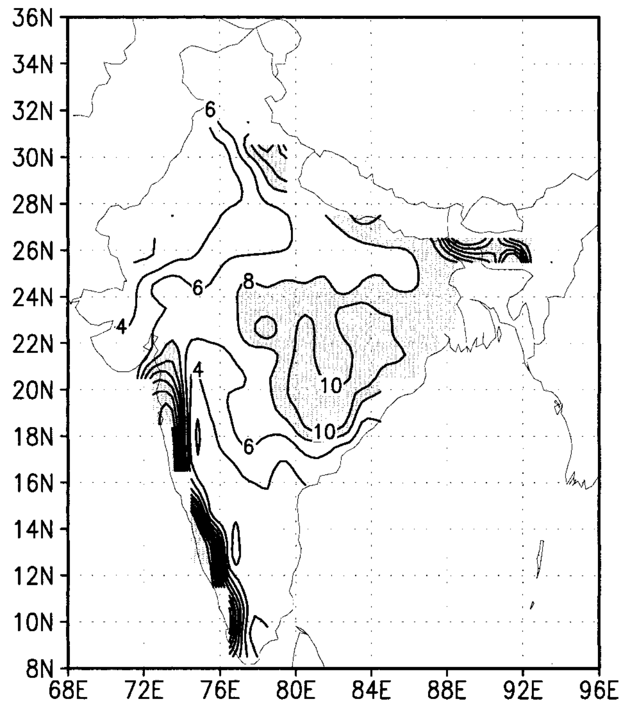

FIG. 4. Climatological mean (mm day^{-1}) of JJAS seasonal rainfall based on the 1901–70 period. Contours >8 are shaded.

The climatological mean rainfall for the JJAS season is shown in Fig. 4. Several features of the daily climatological mean over different regions, discussed earlier, are also evident in the seasonal climatology. The Western Ghats in the southwest and the hilly regions of the northeast receive the maximum amount of rainfall with a seasonal climatological mean of about 25 mm day^{-1}. Over the rest of India, the bulk of the seasonal rainfall occurs in central India with climatological mean values greater than 8 mm day^{-1}. The seasonal mean values of the northwest and southeast regions are about 4 mm day^{-1} or less. The area average of the climatological mean rainfall over all-India is 7.57 mm day^{-1} (or a total of 923 mm for the JJAS season). One of the most remarkable, yet least remarked, features of the seasonal rainfall climatology over India is the occurrence of a distinct local maximum over the land in the eastern part of central India. Some of the existing global rainfall datasets (e.g., Xie and Arkin 1996) do not include this climatological feature.

c. Variances of daily and seasonal rainfall anomalies

The variances of unfiltered daily anomalies and seasonal anomalies for the JJAS season of 1901–70 are presented in Fig. 5. The anomalies are computed according to the definitions given in section 2 (the daily anomalies do not include the JJAS seasonal anomaly).

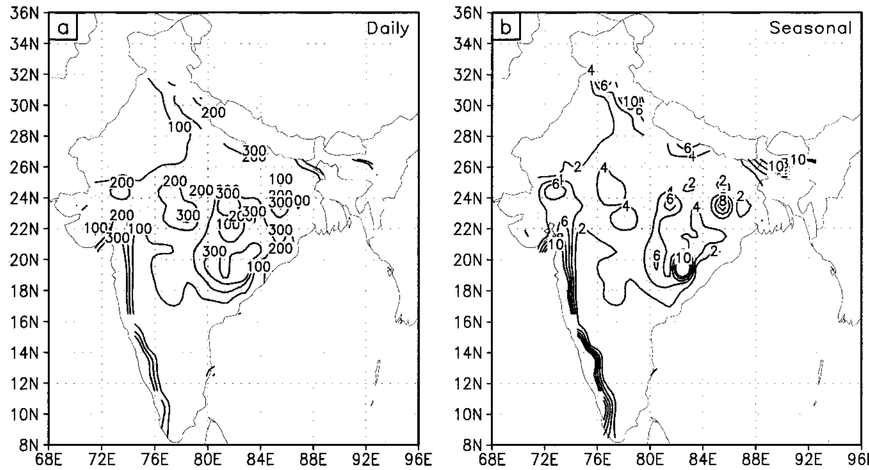

FIG. 5. Variances [(mm day^{-1})^2] of (a) unfiltered daily anomalies and (b) seasonal anomalies of rainfall for JJAS of the 1901–70 period. Contours >100 are shaded in (a) and contours >2 are shaded in (b).

The most striking feature in Fig. 5 is the difference in the magnitudes of the daily and seasonal variances. The variance of the daily anomalies is about 50–100 times larger than that of the seasonal anomalies over most of India. The variances of both daily and seasonal anomalies have maximum values over the same regions. The standard deviation of the JJAS seasonal mean rainfall area averaged over all of India for the period 1901–70 is 0.72 mm day^{-1} (or 87 mm per season).

It is difficult to distinguish between the nature of the intraseasonal variability during a season and the interannual variability of the seasonal means because of the large difference between their respective variances. This large difference makes it difficult to interpret the results of EOF analyses that maximize the variance. To partially alleviate this problem, the daily and seasonal rainfall anomalies at each grid point are normalized by their respective standard deviations before calculating the EOFs.

4. Dominant modes of daily and seasonal variations of rainfall

The dominant modes of daily and seasonal anomalies are determined by EOF analyses of the IMD rainfall data for the period 1901–70. Composite rainfall anomaly maps are also examined.

a. EOFs of daily and seasonal anomalies

EOF analysis was performed on the standardized daily and seasonal anomalies for JJAS season of the 1901–70 period. The daily anomaly examined here, $R''(m, n)$, does not include the seasonal anomaly, as defined in section 2. The leading EOFs of the standardized daily anomalies and standardized seasonal anomalies are shown in Fig. 6. The first EOF (EOF 1) of the daily anomalies explains 15.2% of the daily variance while that of the seasonal anomalies explains 20.7% of the seasonal variance. The spatial pattern correlation between the two EOFs (after multiplying with the standard deviations of the corresponding fields) is quite high (0.75) because both the seasonal and daily standard deviations have their maxima over central India. However, there are important structural differences between the two patterns. The main difference between the two EOFs is that EOF 1 of the seasonal anomalies (Fig. 6b) has the same sign over almost all of India, but EOF 1 of the daily anomalies (Fig. 6a) has opposite signs over the foothills of the Himalaya and central India. The daily pattern is typical of active and break spells when the monsoon trough is displaced northward from its climatological position to the foothills of the Himalaya and the rainfall anomaly over central India is of the opposite sign to that of northern and southern India. EOF 1 of the seasonal anomalies (Fig. 6b) covers a large part of India with uniform values (1.2–1.8). EOF 1 of the daily anomalies (Fig. 6a) shows a less uniform structure with large positive values confined only along the Western Ghats and the western parts of central India and negative values to the north and south. An EOF analysis of the daily and seasonal anomalies without standardization also reveals (figures not shown) dominant patterns with features similar to the corresponding patterns in Fig. 6. However, the patterns in Fig. 6 are enhanced in certain regions such as the southeast. The EOF of the seasonal anomalies shown in Fig. 6b is in agreement with Fig. 14.5 of Shukla (1987).

b. PCs of daily and seasonal variations

The PCs, or the time coefficients of the EOFs, of standardized daily and seasonal rainfall anomalies were also obtained. The leading PC (PC 1) of the standardized

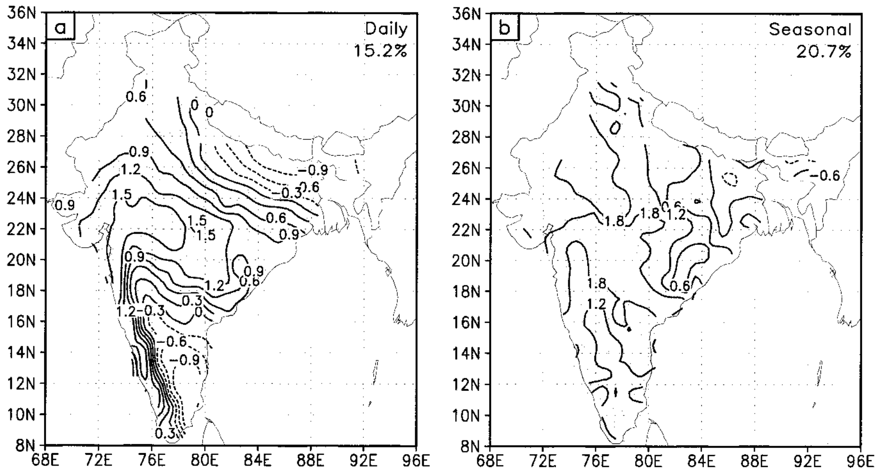

FIG. 6. EOF 1 of (a) standardized daily anomalies (5-day running means) and (b) standardized seasonal anomalies of rainfall for JJAS of the 1901–70 period. Positive contours are shaded.

seasonal anomalies is shown in Fig. 7a along with the actual JJAS seasonal mean rainfall area averaged over all-India for the period 1901–70 in Fig. 7b. The striking correspondence between the two time series in Figs. 7a and 7b, and the fact that the correlation between the two time series is 0.96, confirm that EOF 1 is a good representation of the dominant mode of the JJAS seasonal variation of the rainfall. PC 1 of the seasonal anomalies (Fig. 7a) captures all the strong (flood) and weak (drought) years of the Indian monsoon between 1901 and 1970.

The first PC of the standardized daily rainfall anomalies also shows a very good correspondence with the actual daily anomalies, and captures the active and break phases in both duration and amplitude. As an example, PC 1 of the standardized daily rainfall anomalies and the actual daily rainfall anomalies for 1941 are plotted

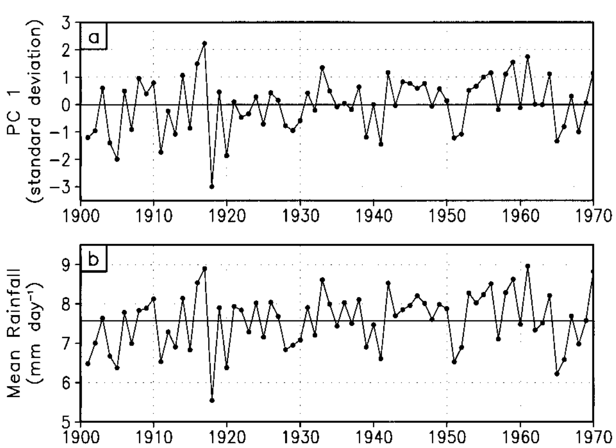

FIG. 7. Time series of (a) PC 1 (standard deviation unit) of standardized JJAS seasonal anomalies of rainfall (corresponding to EOF 1 shown in Fig. 6b) and (b) JJAS seasonal mean of rainfall (mm day^{-1}) area averaged over all-India for 1901–70. The horizontal line in (b) represents the 70-yr mean of the area average (7.57 mm day^{-1}).

in Figs. 8a and 8b, respectively. The figure shows a very close correspondence between the two time series. The correlations between the two time series for each year's JJAS season for the entire period 1901–70 were calculated (shown in Fig. 8c). It was found that, out of 70 yr, 59 yr have correlations greater than 0.7 and 34 yr have correlations greater than 0.8.

c. Comparison with composites of actual anomalies

The leading EOF of the seasonal rainfall anomalies presented in the previous sections fluctuates according to the corresponding PC from year to year, and especially brings out the strong (flood) and weak (drought) years of the Indian monsoon. Similarly, the active (wet) phases and break (dry) phases of the intraseasonal variations are represented by the fluctuations of the leading EOF of the daily rainfall anomalies according to the corresponding PC. To further substantiate the finding that the leading EOFs are good representations of the daily and seasonal variations, composites of the actual daily and seasonal rainfall anomalies were analyzed. From the JJAS seasonal rainfall anomalies, a strong monsoon composite and a weak monsoon composite were constructed on the basis of 8 strong monsoon years and 8 weak monsoon years, respectively. The selection of the strong (weak) monsoon years was based on whether PC 1 of the standardized seasonal rainfall anomalies (shown in Fig. 7a) was greater (less) than one positive (negative) standard deviation unit. With this criterion, 1914, 1916, 1917, 1933, 1942, 1959, 1961, and 1970 were selected as strong monsoon years and 1904, 1905, 1911, 1918, 1920, 1941, 1951, and 1965 as weak monsoon years. The composites of the daily rainfall anomalies were constructed by identifying the active and break phases based on PC 1 of the standardized daily anomalies. The active (break) phase was defined by using the criterion that daily PC 1 should be

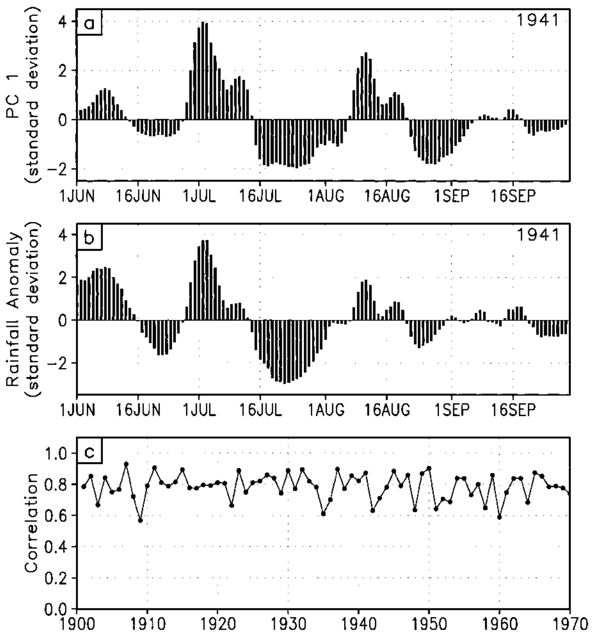

FIG. 8. Daily time series of (a) PC 1 (standard deviation unit) of standardized daily anomalies of rainfall (corresponding to EOF 1 in Fig. 6a) and (b) daily rainfall anomalies area averaged over all-India (standard deviation unit) for JJAS 1941. (c) Correlation between PC 1 of standardized daily anomalies and area averages of daily anomalies for each year's JJAS season of the 1901–70 period. The daily anomalies are 5-day running means.

above (below) a certain positive (negative) threshold value for at least 5 consecutive days. After experimenting with several values, the threshold value was selected to be one-half of the standard deviation of daily PC 1. The active and break composites were then constructed by averaging the actual daily rainfall anomalies for all the days of JJAS 1901–70 that satisfied the specified criterion.

The difference between the active phase composite and break phase composite of the standardized daily rainfall anomalies is shown in Fig. 9a, and the difference between strong year composite and weak year composite of the standardized JJAS seasonal rainfall anomalies is shown in Fig. 9b. The structures of the two composite differences in Fig. 9 have striking resemblances to the leading EOFs of the corresponding anomalies shown in Fig. 6. The strong and weak seasonal composites and the active and break daily composites were also examined separately (not shown) and were found to possess the same structures as the corresponding difference composites. For example, the active (break) phase composite of the daily anomalies has almost the same structure with the same (opposite) sign as in Fig. 9a but with half the magnitude. Similar behavior was also found in the case of strong and weak seasonal anomaly composites.

These results confirm that the leading EOFs shown in Fig. 6 indeed represent the dominant modes of the standardized daily and seasonal anomalies of rainfall over India. In both Figs. 6 and 9, the daily and seasonal patterns have important structural differences. The daily pattern is dominated by positive values over central India and negative values over the foothills of the Himalaya and southeast India. This is a typical break pattern long recognized by the IMD forecasters (Ramamurthy 1969). In contrast, the seasonal pattern has the same sign over nearly all of India and the opposite sign in the east. At least over the Indian land region, these results, based on observed rainfall data, differ from the model-based results of Ferranti et al. (1997) who concluded that the fluctuations within a season and within different years have similar dominant structures. The differences in the structures of the daily and seasonal patterns found in the present study support the sugges-

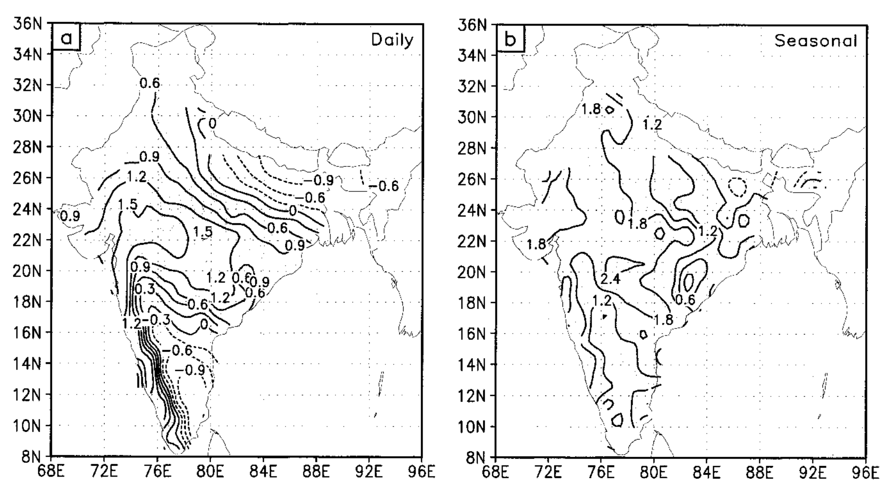

FIG. 9. (a) Difference between active phase composite and break phase composite of standardized daily rainfall anomalies during JJAS of 1901–70. (b) Difference between strong years composite and weak years composite of standardized JJAS seasonal rainfall anomalies during 1901–70. The daily anomalies are 5-day running means. Positive contours are shaded.

tion that the mechanisms for intraseasonal and interannual rainfall variations may be different.

5. Relation between intraseasonal and interannual variability

In the previous section, it was shown that the structures of the dominant modes of variability of standardized daily and seasonal rainfall anomalies are different. In this section, it is shown that, during flood and drought years, the rainfall anomalies persist for the entire season. This is done by two different analyses: the spatial pattern correlation between the daily and seasonal anomalies, and the projection of the daily anomalies on the leading EOF of the seasonal mean anomalies.

a. Correlation between daily and seasonal anomalies

The definitions of the daily anomaly including seasonal anomaly $R'(m, n)$ and the daily anomaly $R''(m, n)$ for the nth day of the mth year were provided in section 2. In order to show the persistence of the seasonal rainfall anomaly $R'_s(m)$ throughout the JJAS season of the mth year, the pattern correlation coefficient for the nth day, denoted by $C'(m, n)$, between the fields of standardized seasonal anomaly $R'_s(m)$ and standardized daily anomaly (including the seasonal anomaly) $R'(m, n)$ was computed for each day of JJAS, separately for each year of the 1901–70 period. Similarly, the pattern correlation coefficient, denoted by $C''(m, n)$, between the fields of standardized seasonal anomaly $R'_s(m)$ and standardized daily anomaly (without the seasonal anomaly) $R''(m, n)$ was also computed. The two correlation coefficients are analyzed to infer whether or not the seasonal anomaly of rainfall persists throughout the summer monsoon season.

The time series of the correlation coefficient between the seasonal anomaly and the daily anomaly that includes seasonal anomaly, $C'(m, n)$, for 1961, 1963, and 1965, three selected years representing strong, normal, and weak monsoon, respectively, are presented in Fig. 10. According to statistical significance tests, a correlation value of 0.16 is at the 99% confidence level and a value of 0.12 is at the 95% level. For all three years, the correlations are positive for nearly the entire JJAS season. It is noteworthy that the same behavior, showing predominantly positive correlations, is true whether the monsoon season is strong, normal, or weak. The time series of the correlation coefficient $C''(m, n)$ between the seasonal anomaly and the daily anomaly (without the seasonal anomaly) of rainfall were also examined (figures not shown). The striking feature found in these time series was that, with the removal of the seasonal anomaly from the daily anomaly, the correlations were now both positive and negative, with sign changes being distributed throughout the season for all years.

The persistence of the seasonal anomaly (Fig. 10) is remarkable considering the fact that the seasonal anomaly $R'_s(m)$ [difference between $R'(m, n)$ and $R''(m, n)$] is quite small compared to the daily anomalies. This result is consistent with previous results of Webster et al. (1998) and Shukla (1987) who examined monthly rainfall anomalies.

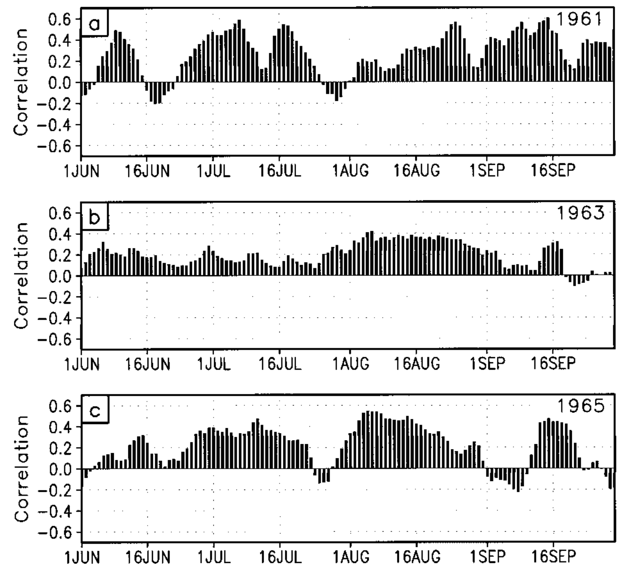

FIG. 10. Daily time series of spatial pattern correlation (C') between standardized JJAS seasonal anomalies and standardized daily anomalies that include the seasonal anomaly of rainfall over India for (a) strong monsoon (1961), (b) normal monsoon (1963), and (c) weak monsoon (1965) years. The daily anomalies are 5-day running means.

The persistence of the positive correlation throughout the season seen in Fig. 10 also occurs for all years of the IMD data that were examined. To summarize the result, the frequency distributions of both $C'(m, n)$ and $C''(m, n)$ were computed. These frequency distributions, as percentage of occurrence, are presented in Fig. 11 for eight strong monsoon years and eight weak monsoon years, separately, and for strong and weak years combined together. The weak and strong monsoon years are the same as those selected for the composites discussed in section 4c. The frequency distribution of $C'(m, n)$ (Fig. 11a), which involves the correlation with the daily anomaly that includes the seasonal anomaly, is skewed toward positive correlations. However, the distribution of $C''(m, n)$ (Fig. 11b) shows no such preference and is close to being Gaussian about zero correlation. Both Figs. 11a and 11b suggest that the relation between the intraseasonal variations (active/break phases) and the seasonal variations has no statistical difference between strong and weak monsoon years.

b. Projection of daily anomalies on the dominant mode of seasonal anomaly

To further examine the results of the previous section, the standardized daily anomalies were projected onto EOF 1 of the standardized seasonal anomalies. The nor-

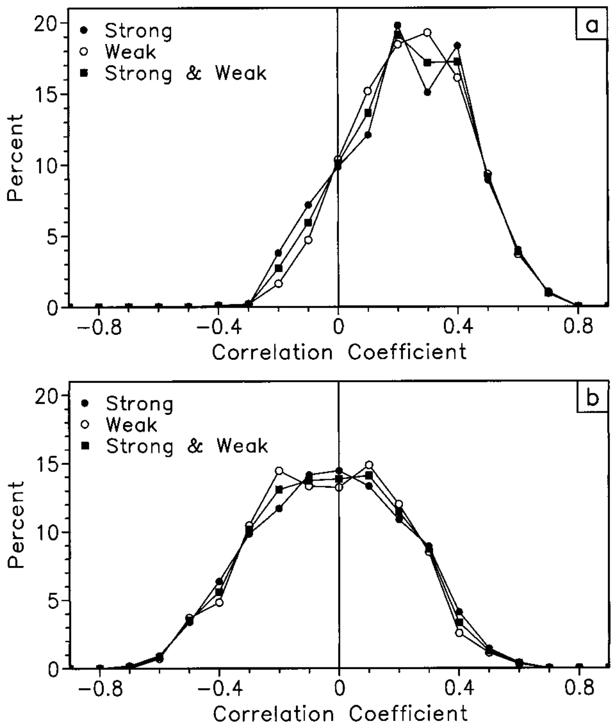

FIG. 11. Frequency distribution of spatial pattern correlation (a) C' between standardized JJAS seasonal anomalies and standardized daily anomalies that include the seasonal anomaly and (b) C'' between standardized JJAS seasonal anomalies and standardized daily anomalies of rainfall over India for eight strong monsoon years (filled circle), for eight weak monsoon years (unfilled circle) and for strong and weak years combined together (filled square). The daily anomalies are 5-day running means.

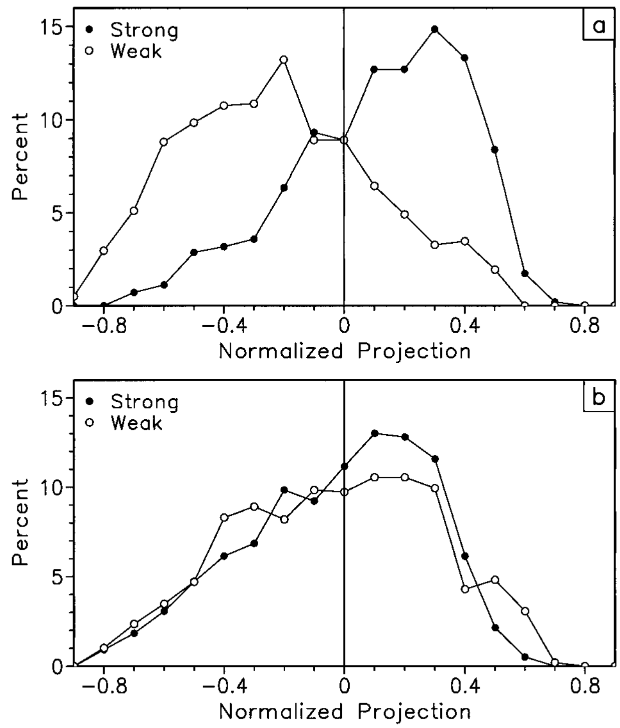

FIG. 12. Frequency distribution of (a) normalized projection (A') of standardized daily anomalies that include the seasonal anomaly and (b) normalized projection (A'') of standardized daily anomaly on EOF 1 of standardized JJAS seasonal anomalies of rainfall over India for eight strong monsoon years (filled circle) and for eight weak monsoon years (unfilled circle). The daily anomalies are 5-day running means.

malized projection, denoted by $A'(m, n)$, of $R'(m, n)$ on EOF 1 of the standardized seasonal anomalies, and the normalized projection, denoted by $A''(m, n)$, of $R''(m, n)$ on the same EOF 1 were computed.

The frequency distributions of $A'(m, n)$ and $A''(m, n)$ for eight strong monsoon years and eight weak monsoon years during 1901–70 are plotted in Fig. 12. The strong and weak monsoon years are same as those used earlier. From Fig. 12a, it is clear that the distribution for weak years is skewed toward negative amplitudes whereas that for strong years is skewed toward positive amplitudes. This further supports the results of the correlation analysis because it shows that the seasonal mean rainfall anomaly pattern has opposite signs during flood and drought years. The projection of the daily anomaly $R''(m, n)$ on the dominant mode of the seasonal anomaly has no such clear preference (Fig. 12b).

6. Summary and conclusions

A long record of observed high-resolution daily rainfall data over India for the period 1901–70 has been analyzed to determine the relationship between the intraseasonal and interannual variability of the Indian summer monsoon. It was found that there is considerable variability in the spatial patterns of the rainfall anomalies over India on both daily and seasonal timescales. The variances of the daily rainfall anomalies over India are about 50–100 times larger than those of the seasonal rainfall anomalies. Therefore, the dominant modes of the daily and seasonal variability are obtained by normalizing the anomalies by their respective standard deviations. The EOF analysis of the standardized anomalies shows that the dominant mode (leading EOF) of the daily rainfall anomalies has a spatial pattern different from that of the dominant mode of the seasonal anomalies. The dominant modes of the daily and seasonal variability show remarkable correspondence to the composites of actual rainfall anomalies (strong and weak composites for the seasonal anomalies and active and break composites for the daily anomalies). The principal component of the dominant mode of the seasonal anomalies was found to be a remarkably good representation of the seasonal mean monsoon variability, in particular capturing all the drought and flood years. Similarly, the leading principal component of the daily anomalies represents the daily variability quite well, capturing the observed active and break phases.

Analysis of the correlation between the daily rainfall anomalies and the seasonal rainfall anomalies shows

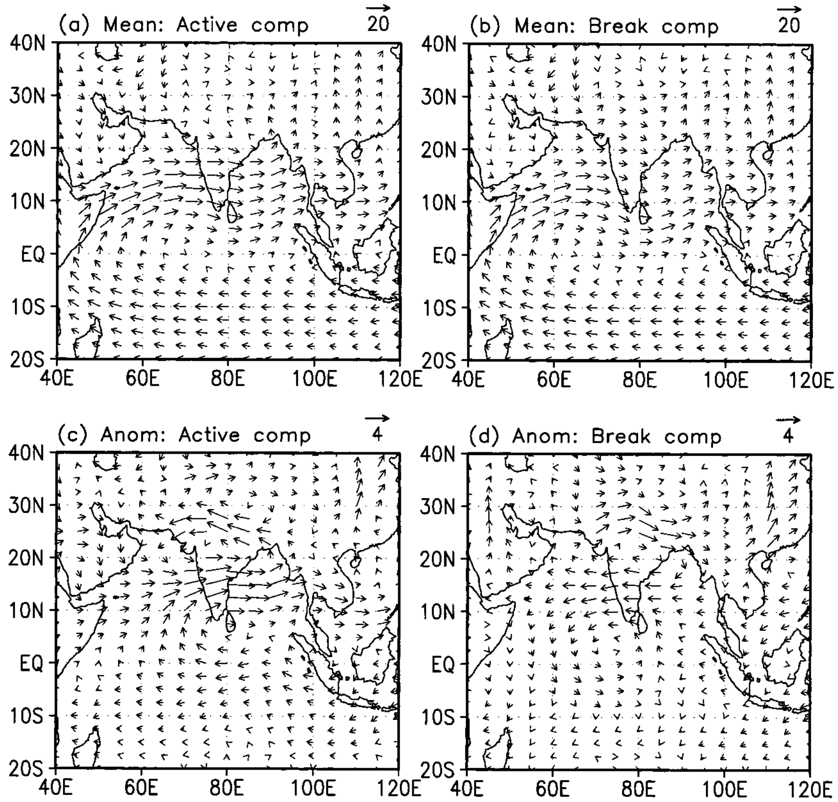

FIG. 13. Composites of daily horizontal wind at 850 hPa during JJAS 1948–70: mean composite for (a) active phase and (b) break phase, and anomaly composite for (c) active phase and (d) break phase. The unit vectors for mean and anomaly composites are 20 m s^{-1} and 4 m s^{-1}, respectively.

that there is a signature of the seasonal anomaly pattern throughout the monsoon season. This result was further confirmed by the analysis of the projection of the daily anomalies on the leading EOF of the seasonal anomalies. The dominant mode of the seasonal anomalies persists throughout the monsoon season. The frequency distributions of the correlations involving the daily anomalies that include the seasonal anomalies clearly show a bias toward positive correlations and do not reveal any bimodality. The frequency distributions of the projections of the daily anomalies on the dominant mode of the seasonal anomalies clearly brought out the signature of the seasonal anomalies in strong and weak monsoon years. These distributions also did not show any bimodality.

In section 1, two opposite postulates were put forward. The first postulate stated that the Indian monsoon rainfall does not have a seasonally persistent (externally forced) component. Both the correlation analysis between the daily and seasonal rainfall anomalies, and the frequency distribution of the projection of the daily anomalies on the leading EOF of the seasonal anomalies do not support this postulate. The results of this study and two previous studies [Shukla (1987) using monthly mean data and Webster et al. (1998) using pentad data] strongly support the notion of a seasonally persistent rainfall anomaly pattern. Whether this seasonally persistent rainfall anomaly is forced by surface boundary conditions (sea surface temperature, snow mass, etc.), or is an integral part of a low-frequency coupled ocean–land–atmosphere fluctuation is not yet established. It is also found that the seasonal rainfall anomalies have a large spatial scale with anomalies of one sign covering the entire Indian land region, whereas the daily anomaly pattern has one sign over central India and opposite sign over parts of south and north. The results of this paper collectively suggest a simple conceptual model supporting the second postulate: The seasonal mean monsoon rainfall over India consists of a large-scale persistent rainfall anomaly and a fluctuating intraseasonal component.

The nature of the fluctuating intraseasonal component of the rainfall does not show any remarkable difference between strong and weak monsoon years. An examination of the circulation at 850 hPa (Fig. 13) shows that the entire monsoon flow (the easterlies to the south of the equator and the westerlies to the north of the equator) gets strengthened or weakened during the active and break phases of the monsoon over India. Figures 13a and 13b show the composite mean horizontal vector wind at 850 hPa for the active and break phases, respectively, and Figs. 13c and 13d show the corresponding anomaly fields. The active and break phases in Fig. 13 are the same days of the period 1948–70 as those used in preparing the rainfall composites in Fig. 9a. It is clearly seen that the active and break phases do not change the character of the mean monsoon flow but merely represent strengthening and weakening of the entire flow. The easterlies to the south of the equator and the westerlies to the north of the equator get stronger (weaker) during active (break) episodes.

The implication of these results concerning the predictability of monsoon rainfall over India is clear and important. If the spatial and seasonal average of the intraseasonal component were small, and the externally forced component were large, the seasonal rainfall anomaly averaged over India would be more predictable. This may explain why the India Meteorological Department has had such a remarkable success in predicting the all-India rainfall using empirical methods (Gowariker et al. 1991; Thapliyal and Kulshrestha 1992). On the other hand, these results also suggest that it would be difficult to predict the intraseasonal rainfall anomalies over smaller regions (e.g., districts and subdivisions). For regions smaller than the scale of the intraseasonal fluctuations, it would be quite difficult to detect the seasonally persistent component. In general, the success in predicting the monsoon rainfall over India will depend on the relative magnitudes of the large-scale seasonally persistent component and the intraseasonal component. If future research, either by analysis of observed data or by model experiments, could establish a predictable relationship between the large-scale seasonally persistent anomalies and intraseasonal variations, prospects for making more accurate forecasts of monsoon rainfall over India will surely be increased.

Acknowledgments. This work was supported by grants from the National Science Foundation (ATM-9321354), the National Oceanic and Atmospheric Administration (NA76-GP0258), and the National Aeronautics and Space Administration (NAGW-5213). The authors thank Marc Michelsen for providing the gridded rainfall data and Mike Fennessy for helpful comments.

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