Long-Term Variability of Asian Summer Monsoon Rainfall during 1946–1988

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Abstract

An observational study has been made of the long-term variability of Asian summer monsoon rainfall for the period 1946–1988 and its relationship to global sea-surface temperatures (SSTs) and geopotential height fields.

The trend analysis of June–September rainfall for the recent four decades shows a distinct long-term trend in rainfall over several Asian regions; increasing trends in southwest India, and decreasing trends in northwest and central India, on the south side of the Himalayas, and in the western Indochina peninsula facing the Bay of Bengal.

A rotated empirical orthogonal function (R-EOF) analysis was applied to global SSTs for the above 43-year period (Shinoda and Kawamura, 1994). The second R-EOF (R-EOF2) mode exhibits the warming trend of the Indian Ocean. The correlation analysis between the time coefficients of the R-EOF2 mode and monsoon rainfall shows that the trend components which are observed in both the R-EOF2 mode and rainfall for the above areas are responsible for the high correlation between them.

The R-EOF2 mode is highly correlated not only with monsoon rainfall, but also with tropical 850 hPa geopotential heights. This correlation pattern exhibits an east-west contrast having positive correlations over Africa and the western Pacific Ocean and negative correlations over the northern Indian Ocean. The above positive and negative correlations coincide with the increasing and decreasing trends in 850 hPa heights.

Over the Indian subcontinent, areas having negative and positive trends of 850 hPa heights coincide with those having increasing and decreasing trends in regional rainfall, respectively. On a monthly basis, for June and August, the Indian subcontinent is extensively covered with areas having increasing trends in rainfall and decreasing trends in 850 hPa heights, whereas the areas are limited to southwest India during July and September.

1. Introduction

Recently, much attention has been paid to the long-term climate change over the century in relation to global warming. As for the tropics and subtropics, precipitation has decreased, especially since the mid-century, over large regions extending from northern Africa to southeast Asia and Indonesia (IPCC, 1996).

Numerous attempts have so far been made to investigate the long-term variability of all-India rainfall. Mooley and Parthasarathy (1984) pointed out significant 14 and 2.8 year periodicities in all-India rainfall through spectral analysis, while Parthasarathy *et al.* (1991; 1994) suggested a transition between two climatic regimes with a period longer than 30 years. The two regimes are related to the “meridional monsoon” and “zonal monsoon”

circulation (Fu and Fletcher, 1988). These studies, however, agree on the point that the long-term trend is hardly found over a long period of nearly one century. On an interannual time scale, Ropelewski and Halpert (1987) showed that summer rainfall uniformly fluctuates over most of India, being closely related to the El Niño/Southern Oscillation (ENSO). Therefore, all-India rainfall is a useful index for examining ENSO-related monsoon variability.

On the other hand, it should be noted that an obvious trend in Asian monsoon rainfall is observed over several regions (Jagannathan and Parthasarathy, 1973; Alvi and Koteswaram, 1985). For example, increasing trends in summer rainfall were found along the Indian west coast during 1871–1984, while decreasing trends exist over the areas adjoining northeast India (Kumar *et al.*, 1992). The summer rainfall averaged over Indian administrative subdivisions, which is often used, does not represent the reality of the regional rainfall variability (Kumar

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et al., 1992). Thus, this study is aimed to investigate, on the basis of station rainfall data, the regional difference in the long-term variability of Asian monsoon rainfall. The focus of this investigation is placed not only on India but also on the Indochina peninsula, since the summer monsoon over these two regions is regarded as one unit in the global monsoon system, judging from rainfall and OLR distributions (Murakami and Matsumoto, 1994; Kripalani and Singh, 1993).

It is well known that sea-surface temperatures (SSTs) over the Arabian Sea have a significant negative correlation with the monsoon westerlies related to Indian summer rainfall due to air-sea interaction (Shukla and Misra, 1977; Ghosh *et al.*, 1978; Raghavan *et al.*, 1978; Weare, 1979; Cadet and Diehl, 1984; Rao and Goswami, 1988). That is, the strong westerlies over the Arabian Sea lead to the upwelling of the sea-surface layer, namely, negative SST anomalies and sufficient Indian rainfall (Shukla, 1987). On the other hand, the Indian Ocean reveals a dominant warming trend during recent decades (Nitta and Yamada, 1989; Kawamura, 1994). Shinoda and Kawamura (1994) and Shinoda (1995) concluded that the recent reduction in Sahelian rainfall is closely related to the warming trends of the Indian Ocean.

Motivated by the question as to how the warming trends of the Indian Ocean affect Asian summer monsoon rainfall, the present study explores through correlation and trend analyses the relationships between global SSTs, especially their trend components, Asian monsoon rainfall, and the tropical east-west circulation. The period of analysis is confined to 43 years from 1946 to 1988 because the warming trends of the Indian Ocean have been observed since the 1950s.

2. Data

The data used in this study consist of Asian rainfall, global upper-air, and global sea-surface temperature observations on monthly and seasonal (June–September) base.

The monthly precipitation data are obtained from the Global Historical Climatology Network (GHCN), compiled by the Carbon Dioxide Information Analysis Center (CDIAC), and available only before 1990. The data observed at each of 375 rain-gauge stations in the extensive area of 60°E–110°E, the equator–40°N for the period 1946–1988 are analyzed because the data after 1989 have less observations.

The upper-air observation data are obtained from the Monthly Climatic Data for the World, compiled by the National Oceanic and Atmospheric Administration (NOAA). Although these data are available from the early 1950's to 1987, only the data after 1957 are used because the ascent times of rawin-

sonde were changed in April 1957 (Parker and Cox, 1995).

The SST dataset consists of monthly mean SSTs at a spatial resolution of a 5° latitude-longitude regular-rectangular mesh, compiled at the UK Meteorological Office. The data over the latitudes extending from 55°N to 30°S during the years 1946–1988 are analyzed in this study, since the spatial distribution of the SST observations is dense enough to perform a rotated empirical orthogonal function (R-EOF) analysis. This analysis deals with the global domain because the Asian summer monsoon may be coupled not only with SSTs over the Indian Ocean but also with the Pacific SSTs through the tropical east-west (Walker) circulation. The results of the R-EOF analysis used in the present analysis are performed by Kawamura (1994), which gives a further explanation and discusses robustness of the R-EOFs.

3. Relationship between monsoon rainfall and global SSTs

3.1 Monsoon rainfall

Over the Asian domain analyzed in this study, summer monsoon rainfall is defined as that summed from June to September, because the arrival and withdrawal of the summer monsoon over most of the domain occur within these four months.

Figure 1 shows June–September rainfall averaged over the period 1946–1988 (mm/month) (a) and the linear trends of the rainfall during this period (b). In Fig. 1b, the statistical significance of the linear trends is determined in accordance with Suzuki (1968). That is, the significance level for a given linear trend is determined by examining the possibility that we obtain, by chance, a linear trend whose real value is zero. The summer precipitation exceeds 200 mm/month over most of India and the western Indochina peninsula (Fig. 1a). In particular, rainfall is concentrated on the Indian west coast, the northeastern area of the Bay of Bengal, and the west coast of the Indochina peninsula. On the other hand, the map of the linear trends (Fig. 1b) illustrates that monsoon rainfall increases over southwest India and the northern part of India and Pakistan, while it decreases over central India, the western Indochina peninsula, and the southeastern side of the Himalayas.

All-India rainfall for the period 1850–1990 (Fig. 2) is calculated by averaging June–September rainfall for 50 stations that are uniformly distributed over India. The interannual variability is dominant throughout the period, while no distinct long-term trend is found in the five-year running mean (broken curve) and in the linear trend for the period 1946–1988 (broken line), respectively.

Fig. 1. Asian summer monsoon rainfall averaged over the period 1946–88 (a) and the linear trends for the same period (b). The contour intervals in Fig. 1a and b are 100 mm/month and 2×10^{-2} SD/yr, respectively. The stippling denotes areas exceeding rainfall of 300 mm/month (Fig. 1a) and areas having a decreasing trend (Fig. 1b). The closed circles in Fig. 1a reveal rain-gauge stations, while the closed triangle in Fig. 1b indicates a station which shows a linear trend significant at the 5 % level. The broken line represents altitude and has an interval of 1000 m.

Fig. 2. All-India monsoon rainfall (a) and number of stations used for calculating the time series (b). Normalized rainfall for each station is averaged over India. The broken curve denotes the five-year running mean, while the broken line indicates the linear trend for 1946–88.

3.2 Global SSTs

As mentioned above, the results of the R-EOF analysis for global SST anomalies (Shinoda and Kawamura, 1994) is used in this study. The loading patterns and time coefficients of the first and second R-EOF mode (hereafter referred to as R-EOF1 and R-EOF2, respectively) are shown in Figs. 3 and 4, respectively. The R-EOF1 mode (Fig. 3), which explains 7.7 % of the total variance, represents the ENSO phenomenon. In the loading pattern, large positive anomalies are found over the tropical central-eastern Pacific Ocean and dominant maxima

in the time coefficients coincide with the occurrences of the El Niño events.

The R-EOF2 mode (Fig. 4), which explains 4.3 % of the total variance, has two large signals in the loading pattern: negative anomalies over the north Pacific Ocean and positive anomalies over the Indian Ocean. The time coefficients indicate a significant increasing trend since the late 1950's.

3.3 Correlation between monsoon rainfall and SST

The correlation analysis between monsoon rainfall and SST R-EOF modes for June to September are performed in this subsection.

Fig. 3. Loading pattern (upper) and time coefficients (lower) of the R-EOF1 mode of global monthly SST anomalies for 1946-1988. The contour interval is 2.0 in relative units. The dark (light) stippling indicates values of more than +4.0 (+4.0 to 0), while the hatching denotes values of less than -4.0. The broken line in the time coefficients reveals the 13-month running mean.

Fig. 4. As in Fig. 3, except for the R-EOF2 mode.

In order to separate the interannual and long-term variations, the original time series of June-September rainfall (O_r) is divided into two components: long-term (L_r) and year-to-year (E_r) variation. Thus

$$O_r = L_r + E_r,$$

where L_r denotes the five-year running mean, while E_r indicates the residual between O_r and L_r . Over most of the Asian domain analyzed here, the variances of E_r are three to four times as large as

those of L_r (not illustrated). The same procedure is applied to the time coefficients averaged over the summer season (June-September) for each R-EOF mode:

$$O_s = L_s + E_s.$$

Figure 5 shows the pattern of correlations between the interannual components of summer rainfall (E_r) and the R-EOF1 mode (E_s). Both time series (E_r and E_s) exhibit a wide-spread negative correlation over the study area. In Fig. 5, the absolute values

Fig. 5. Correlation between the interannual components of the summer rainfall (E_r) and R-EOF1 mode (E_s). The contour interval is 0.2 and areas having negative correlations are shaded. The closed square (triangle) indicates a station which shows the correlation coefficient significant at the 1 % (5 %) level.

of the correlation coefficient at 1 % and 5 % significance levels are 0.40 and 0.31, respectively. It is found that summer rainfall over southwest-central India is negatively correlated, at the 1 % level, with the ENSO-related R-EOF1 mode. The uniform pattern of correlation over India shown in Fig. 5 results in the high correlation between all-India rainfall and the R-EOF1 mode (-0.55). These results coincide with previous studies on the relationship between summer monsoon rainfall and ENSO (Rasmusson and Carpenter, 1983; Yasunari, 1990; among others).

The correlation pattern between the long-term variations of summer rainfall (L_r) and the R-EOF2 mode (L_s) (Fig. 6) reveals a pattern different from that shown in Fig. 5. The significance levels of the correlation coefficient become higher (0.71 and 0.58 at 1 % and 5 %, respectively) because an effective sample size (Madden, 1976) of L_r becomes smaller than E_r due to running mean. Positive correlations are found over southwest India, while negative correlations occur over northwest-central India and the western part of the Indochina peninsula. It should be noted that this pattern resembles the pattern of linear trends of the summer rainfall (Fig. 1b). Contrary to Fig. 6, the correlations between the interannual components of summer rainfall (E_r) and the R-EOF2 mode (E_s) are less than ± 0.2 almost over the domain (not shown). Therefore, the high correlation presented in Fig. 6 is attributed to the trend components which are observed in both the R-EOF2 mode and rainfall. Hastenrath and Rosen (1983)

Fig. 6. As in Fig. 5, except for the correlation between the long-term variations of the summer rainfall (L_r) and R-EOF2 mode (L_s).

Fig. 7. Regional division according to the long-term variability of summer monsoon rainfall.

found similar overturning patterns of rainfall variability in central India and the west coast regions. They claimed that the pattern is related to the frequency of cyclonic storms in the Bay of Bengal and the Arabian Sea.

4. Regional characteristics of the long-term variability

Trend and correlation analyses suggest that the linear trend is dominant in the long-term variability of rainfall for recent decades. Then, several stations which exhibit a similar long-term variation are subjectively grouped into one region, as shown in Fig. 7, according to Figs. 1b and 6.

The rainfall time series for areas (a)–(e) (Fig. 8)

Fig. 8. Normalized June-September rainfall anomalies for the regions shown in Fig. 7. The broken lines denote the five-year running mean.

are produced by averaging the normalized rainfall anomalies for stations included in each region (8, 8, 9, 9, 12 stations for the areas (a)–(e), respectively).

It is found that rainfall is increasing in southwest India (b), while it is decreasing in northwest India (a), central-eastern India (c), and western Indochina (e) after the late 1950s. No significant long-term trend is observed in Bangladesh (d). The long-term component of R-EOF2 is correlated with those of rainfall over the area (b) and (c) at 5 % and the area (e) at 1 % significant levels, respectively (Table 1). It should be noted that the long-term trend is not manifested when averaging the rainfall data over

entire India. This results from an offset of different signs of trends that are observed in each regional rainfall.

The above-mentioned regional characteristics of the long-term variability of Asian summer monsoon rainfall are confirmed by a composite analysis. Figure 9 shows two composites of rainfall anomalies for two periods of continuous 11 years; 1950–60 (Fig. 9a) and 1975–85 (Fig. 9b). The two composites show a pattern having opposite signs of anomalies, being particularly pronounced over southwest India, central-eastern India and the western Indochina peninsula.

Table 1. Correlation coefficients between the long-term component of the R-EOF2 mode and those of rainfall over five areas shown in Fig. 8. The single and double asterisks denote the 5 % and 1 % significance levels, respectively.

	Regional rainfall				
	a	b	c	d	e
R-EOF2	-0.523	0.680*	-0.706*	0.318	-0.822**

5. Long-term trends in 850 hPa heights

Figure 10a illustrates the correlation between tropical 850 hPa heights and the time coefficients of the R-EOF2 mode for June–September. This map exhibits an east-west contrast having positive correlations over Africa and the western Pacific Ocean, and negative correlations over western South America and the Indian west coast. A similar pattern is found in the linear trends of 850 hPa heights (Fig. 10b). This suggests that the high correlations between tropical 850 hPa heights and the time coefficients of the R-EOF2 mode over several tropical regions would be accounted for by the trend components in both time series. For instance, over Africa, the positive correlations of 850 hPa heights with the R-EOF2 mode, which reveals a marked trend, are closely related to the increasing trends in the 850 hPa heights. These trends may result in the decline of Sahelian rainfall (Shinoda and Kawamura, 1994). Similar increasing trends in 850 hPa heights are found over the western equatorial Pacific, coinciding with a decreasing trend of SOI since the mid-1970s (Nitta and Yamada, 1989).

It should be noted that the negative trends in 850 hPa heights over the Indian west coast (Fig. 10b) correspond to the increasing trends in rainfall over southwest India (Fig. 6). This results in the high correlation between summer rainfall and 850 hPa heights over the area (Fig. 10c). These results suggest that the warming trends of the Indian Ocean, identified as the R-EOF2 mode, may be linked to the decreasing trends of 850 hPa heights and the corresponding increasing trends of rainfall over southwest India.

6. Monthly trends

On a monthly basis, summer rainfall and associated geopotential heights reveal different long-term variations. The linear trends of monthly 850 hPa heights for June to September are shown in Fig. 11. Similar increasing trends in 850 hPa heights are found over Africa and the western Pacific Ocean throughout June–September. However, the patterns differ from month to month over the Indian subcontinent: negative trends over most of the India-

Fig. 9. Composite anomalies of summer monsoon rainfall for the period 1950–60 (a) and 1975–85 (b). The units are the percentage deviation from the average for 1946–88. The contour interval is 10 % and the stippling denotes areas having negative anomalies.

Indochina regions during June and August and positive trends over the western Pacific to central India during July and September.

Figure 12 shows a map of the correlation between the five-year running means of monthly rainfall (L_r) and the R-EOF2 mode (L_s) for June–September. For June and August, positive correlations are predominantly observed over India, while negative correlations occur over western Indochina. On the other hand, during July and September, negative correlations cover the India-Indochina peninsula regions except southwest India.

The trends of rainfall and associated trends of 850 hPa heights over the India-Indochina region are schematically shown in Table 2. The rainfall over southwest India increases not only for June–September but also for each month, corresponding

Table 2. Schematic representation for trends of rainfall and 850 hPa height. Double signs in the trends of 850 hPa height indicate the 5 % statistical significance level.

	Rainfall			850 hPa height	
	southwest India	central-eastern India	western Indochina	Indian west coast	central India-Indochina
Jun-Sep	+	—	—	—	+
Jun	+	+	—	--	—
Jul	+	—	—	—	++
Aug	+	+	—	—	+
Sep	+	—	—	+	++

Fig. 10. Correlation between tropical 850 hPa heights and the time coefficients of the R-EOF2 mode (a), linear trends of 850 hPa heights for 1957–87 (b) and the correlation between the 850 hPa heights and summer rainfall over southwest India (c). In Fig. 10a and c, the contour interval is 0.2, the hatching (cross-hatching) indicates areas having a correlation coefficient of +0.2 to +0.4 (more than +0.4) while the light (dark) stippling denotes areas having a correlation coefficient of –0.2 to –0.4 (less than –0.4). The absolute values of correlation coefficients at the 5 % and 1 % significance levels are 0.39 and 0.50, respectively. In Fig. 10b, the units are gpm per year and the contour interval is 2.0 gpm/yr. The open circle (cross) denotes an observing station which shows the linear trend significant (non-significant) at the 5 % level. Areas having a decreasing trend are stippled.

Fig. 11. As in Fig. 10b, except for the monthly (June to September) linear trends.

to the decreasing trends of 850 hPa heights over the Indian west coast. Similarly, the decreasing trends of rainfall over the western Indochina peninsula coincide with the increasing trends of 850 hPa heights over the central India–Indochina region during the summer monsoon season. On the other hand, the trends of rainfall over central-eastern India change their sign month to month: increasing trends dur-

ing June and August when the decreasing trends of 850 hPa heights are manifested over the Indian west coast, and decreasing trends during July and September when the increasing trends of 850 hPa heights are predominant over the region between central India and the Indochina peninsula. Although several local areas are not consistent with the relationship between rainfall and 850 hPa

Fig. 12. As in Fig. 5, except for the correlations between the long-term variations of the rainfall and R-EOF2 mode for (a) June, (b) July, (c) August, and (d) September.

heights on the seasonal and monthly time scales shown in Table 2, these discrepancies may be attributed to two reasons: sparse network of rawinsonde stations relative to the network of rain-gauge stations and/or some small-scale effects on the rainfall pattern such as orography.

7. Summary and discussion

The present study has shown the regional difference of the long-term variability of Asian summer monsoon rainfall during 1946–1988 and its relation to global SST anomalies and geopotential fields. The summer monsoon rainfall indicates a distinct long-term variability over several Asian regions—increasing trends in southwest India and decreasing trends in northwest India, central-eastern India, and the western Indochina peninsula. This regional difference causes no significant long-term trend in all-India rainfall. The correlation analysis between R-EOF modes of global SSTs and Asian summer rainfall shows that the interannual component of the summer rainfall is closely related to the ENSO-related R-EOF1 mode, while the long-term variation is associated with the R-EOF2 mode which represents the warming of the Indian Ocean.

Also the regional difference of the long-term variability of rainfall is associated with the tropical east-west contrasting pattern of tropical 850 hPa heights having increasing trends over Africa and the western Pacific-Indochina region and decreasing trends over the Indian subcontinent, especially on the Indian west coast. This pattern may be related to the warming trend of the Indian Ocean.

The GCM study (Kitoh, 1992) has shown that the westerly moisture flux over the Arabian Sea shifts further southward when SSTs are above normal over the tropical Indian Ocean. This leads to increased rainfall over the southern tip of India and southward and decreased rainfall over the region extending from central India to the Indochina peninsula. These results seem to correspond to our results, although Kitoh's study focused on the interannual variability, not the long-term trend. Thus, the simultaneous occurrence of increased rainfall over southwest India and decreased rainfall over central-eastern India and western Indochina (Fig. 8) may result from the southward shift of the moisture flux linked to the warming trend of the Indian Ocean.

The recent warming of the Indian Ocean, as manifested as the R-EOF2 mode, may result in enhance-

ment of the convective activity over the Indian west coast and its weakening over tropical Africa and the western Pacific region (Fig. 10a and b). This circulation pattern indicates the weakening of the tropical east-west circulation. The R-EOF2 mode displays the secondary positive signals over the eastern Pacific (Fig. 4), as has also been pointed out by Nitta and Yamada (1989). These signals may be physically coupled with the negative anomaly over the north Pacific Ocean shown in the R-EOF2 mode (Trenberth and Hurrell, 1994; Graham, 1994).

Figures 11 and 12 show the monthly characteristic of the long-term trends for both summer rainfall and 850 hPa heights over the central India-Indochina regions—dominances of the increasing trends of rainfall and decreasing trends of 850 hPa heights during June and August and those of nearly opposite signs during July and September. This monthly difference is a remarkable feature of the long-term variability of the Asian summer monsoon. This implies that the long-term variability of the monthly rainfall is related to the active/break cycle of the summer monsoon having a periodicity of 30–40 days.

It is difficult to explain the long-term variability of the Asian summer monsoon simply by the warming effect of the Indian Ocean. The decreasing trends of the Eurasian snow cover during the past 20 years have been pointed out by Robinson *et al.* (1993) and Groisman *et al.* (1994). It should be further investigated how the Eurasian snow cover, which is strongly correlated with Indian summer monsoon rainfall on an interannual basis (Hahn and Shukla, 1976), affects the long-term variability of the Asian summer monsoon.

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1946–1988年の夏季アジアモンスーンの長期変動

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1946–1988年の夏季アジアモンスーン降水量の長期変動を解析し、全球の海水面温度(SST)および下部対流圏の等圧面高度との関係を調べた。最近の数十年で、夏季アジアモンスーン降水量は地域により傾向の異なる長期変動を示す。すなわち、6–9月の降水量はインド南西部で増加、北西および中部インド、ヒマラヤ南麓、そしてベンガル湾に面したインドシナ半島西部で減少している。上記の43年間の全球のSSTアノマリに回転経験的直交関数(R-EOF)解析を行なうと(Shinoda and Kawamura, 1994)、第二成分(R-EOF2)はインド洋SSTの昇温傾向を示す。このR-EOF2と夏季モンスーン降水量との相関解析の結果は、両者の高い相関がそれぞれの線型傾向に依っていることを示している。SSTのR-EOF2モードはモンスーン降水量だけでなく、熱帯の850 hPa等圧面高度とも高い相関をもつ。また、高い相関を示す地域では、850 hPa高度が顕著な線型傾向を示している。線型傾向のパターンは、アフリカと西太平洋で高圧傾向、インド洋北部で低圧傾向という東西対照性を示している。インド亜大陸上では、降水量の増加している地域、減少している地域が下部対流圏の低圧傾向、高圧傾向にそれぞれ対応している。6–9月の各月の解析から、夏季アジアモンスーンの長期変動は興味深い特徴を示すことが分かった。すなわち、6・8月には降水量増加傾向と850 hPa高度の低圧傾向がインド全域に広がる一方、7・9月にはそれらはインド南西部に限られる。

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