On the Relationship between Tropical Chinese Rainfall and the Indian Summer Monsoon

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Abstract

We explore the relationships between monthly tropical Chinese rainfall (TCR) and June–September Indian summer monsoon rainfall (ISMR) for the 35-year period from 1954 to 1988. The largest positive correlations between the TCR and the ISMR occur during the months of May and September, with the May correlation exceeding the 99 % level of significance. The TCR between June and August, the most intense period of rainfall in tropical China, shows no apparent relationship with the ISMR. Similar behavior is found in composite anomaly patterns of outgoing longwave radiation (OLR). Repeating the rainfall computations for four subdomains in tropical China supports these results.

The significant correlation between the May TCR and the ISMR suggests that the May TCR may be a precursor of the ISMR, consistent with the westward migration of the onset of the Asian summer monsoon seen in climatological mean patterns of OLR.

1. Introduction

Asian monsoon is a prominent feature of the annual precipitation cycle for a widespread area of the southern and eastern Asia. Because of its economic and scientific importance, the characteristics of the monsoon have been studied extensively (*e.g.*, Ramage, 1971; Murakami, 1976; Yasunari, 1981; Rasmusson and Carpenter, 1983; Shukla and Paolino, 1983; Ropelewski and Halpert, 1987, 1989; Lau *et al.*, 1988). During the past few decades, our knowledge about the monsoon's variability on various time scales and its association with other low-frequency phenomena such as El Niño/Southern Oscillation has increased rapidly. However, because of the distinct regional features of the Asian monsoon, we face many difficulties in measuring adequately the variability in the broad-scale monsoon phenomenon (*e.g.*, Webster and Yang, 1992). Without considering these regional features, the Indian monsoon rainfall has often been used as a proxy for the Asian monsoon as a whole. This can sometimes cause trou-

ble in understanding the broad-scale features of the Asian monsoon and its association with other atmospheric circulation systems. Within the Asian monsoon region, India and China are the only two countries that are large in size and that have long-term records of rainfall data. Thus, knowledge about the relationship between the Indian and Chinese monsoon rainfall will be useful for having a better presentation of the large-scale Asian monsoon.

The distinctiveness of the tropical Chinese monsoon from the Indian monsoon is manifested in several respects. The onset of the Chinese monsoon tends to be more gradual than that of the Indian monsoon (*e.g.*, Liang *et al.*, 1990). Indeed, whereas 75–90 % of the total annual rainfall for India typically occurs during June–September (Mooley *et al.*, 1981), only about half of tropical China's rainfall occurs during this period (Fig. 1). Also, the winter monsoon appears more prominently in China than in India (*e.g.*, Tao and Chen, 1987), suggesting different annual cycles of monsoon for the two countries. In addition, the Chinese and Indian monsoons appear to be associated with different atmospheric

Monthly Tropical Chinese Rainfall

Fig. 1. Monthly mean rainfall for tropical China averaged over a 31-station network (see Fig. 3) for the years 1954–1988. 56 % of the rainfall occurs during June–September.

circulation systems (Chen and Li, 1983; Tao and Chen, 1987).

Despite the distinctive regional monsoon features described above, however, a possible linkage between the Indian and Chinese monsoons may exist during particular periods due to the seasonal migration of the Asian monsoon. Rao (1976) and Meehl (1987), among others, have observed an annual migration cycle of strong tropical convection along a roughly southeast-northwest path between Australia (boreal winter) and Asia (boreal summer). This suggests that a lead/lag relationship may exist between the Indian summer monsoon rainfall (ISMR) and the rainfall in Southeast Asia during the previous spring and early summer.

Tropical China is not exactly along this path of southeast-northwest migration of convection, but this migration appears to be part of a broader pattern of monsoon onset depicted in Fig. 2, which shows 14-year averages of monthly outgoing long-wave radiation (OLR) observed by satellites (discussed more fully in Section 2). OLR is considered to be a good proxy for measuring atmospheric convection, especially deep convection, in the tropics. It can be seen from the figure that, during April, strong atmospheric convection ($OLR \leq 240 \text{ Wm}^{-2}$; e.g., Murakami, 1980; Richards and Arkin, 1981) mainly occurs within the equatorial regions. (The low OLR values in the higher latitudes during April are a result of the cold Earth's surface and not associated with tropical convection.) From April to May, the convection extends northward to Southeast Asia and tropical China. From May to June, it extends, largely westward, to India and its vicinity. The OLR pattern for July is similar to that for June. Thus, Fig. 2 suggests a northward followed by a westward propagation of the onset of the Asian summer monsoon that crosses tropical China.

Fig. 2. Climatological mean patterns of OLR (Wm^{-2}) for April–July. Data are averaged between 1974 and 1988. Values $\leq 240 \text{ Wm}^{-2}$ are shaded.

We hypothesize here that the evolution of *total* rainfall follows a similar advance toward the north and west, helping to produce a correlation between ISMR and tropical Chinese rainfall (TCR) during the previous spring. More specifically, we hypothesize that the interannual variability in rainfall during the initial phase of the tropical Chinese monsoon will be correlated with the interannual variability in the ISMR. The annual cycle of convection motivates an additional hypothesis that the interannual variability in rainfall during the decay of the Chinese monsoon will also be correlated with the ISMR variability. To test these hypotheses, we compute correlations between an ISMR index and the monthly TCR to determine the significance of associations

Fig. 3. Distribution of stations producing the data analyzed in this study. Data were available from 1954 to 1988 for all 31 stations shown. Also shown are the boundaries of 4 subdomains (East, West, Central, and South) used for later analysis.

between the two regional monsoons at various stages of TCR evolution. Our aim is to develop a better understanding of regional features within the Asian monsoon.

2. Data

The monthly mean Chinese rainfall data used in this study were obtained from a 260-station climate network data set for the People's Republic of China (PRC) prepared for the United States Department of Energy and the Chinese Academy of Sciences joint research program on the greenhouse effect (Koomanoff *et al.*, 1988; Riches *et al.*, 1992). The data records cover a period from the late 19th or early 20th century, depending on the station, through 1988. Further description of the data set was given by Koomanoff *et al.* (1988) and Riches *et al.* (1992).

Because we examine tropical monsoon rainfall variability, we focus our analysis on a region south of 30°N. 31 stations in tropical China were chosen that collectively satisfy three criteria: (1) a relatively uniform distribution, (2) long data records, and (3) relatively low altitude (<2000 meters). The latter criterion is included to minimize effects of strong local influences on rainfall due to topography. All 31 stations' data cover the 35-year period between January 1954 and December 1988. The distribution of the stations is shown in Fig. 3. A time series of TCR has been constructed by averaging rainfall data for all the tropical Chinese stations shown. In addition, we have computed individual time series for each of the subdomains appearing in the figure. The physical motivation for the division of these subdomains is given in Section 3.2.

Variability in the ISMR is measured by a normalized monsoon rainfall index devised by Shukla and Paolino (1983) for 1913–1981. We have extended

the record to include 1982–1988 using index data kindly provided by Dr. C.F. Ropelewski of the U.S. National Meteorological Center (NMC). The index is proportional to the total Indian rainfall occurring from June through September, the typical period for the Indian monsoon. To study the relationships with the monthly TCR, a monthly record of the ISMR may be more desirable. However, the Indian monsoon tends to become fully developed much more rapidly than its Chinese counterpart (Liang *et al.*, 1990), so even monthly resolution may not be adequate for capturing the development stage of the monsoon. Thus, our study compares the year-to-year variability in monthly TCR with the corresponding variability in the ISMR averaged over the summer monsoon season.

The OLR data used in this study are from the "Tropical Strip Wind and Outgoing Longwave Radiation" dataset from the operational tropical objective analyses of the NMC. They consist of monthly mean values since June 1974, with data missing from March to December 1978. The data are set on a 72 × 72 Mercator longitude-latitude grid. The longitudinal spacing is 5°, while the latitudinal spacing varies from 5° at the equator to 3.5° at the northern and southern boundaries which are located at 48.1° of latitude. A more detailed description of the NMC analyses was given by Arkin (1982), Webster and Yang (1989), and Yang and Webster (1990).

3. Results

3.1 Entire domain TCR vs. ISMR

For each month of the 35-year record, we computed tropical Chinese rainfall as the arithmetic mean of the 31-stations' precipitation values. This gives a TCR index for each month. Figure 4 shows the correlation of interannual variability between the ISMR and each month's TCR. Also plotted on Fig. 4 are lines depicting the 95 % confidence level that a correlation is different from zero. This measure of significance was obtained by first computing the autocorrelation of interannual rainfall variability at lag 1 year for the monsoon season June–September. Under the assumption of a red spectrum for interannual variability, we then used the correlation coefficient which we obtained, 0.08, in Leith's (1973) formula for determining the interval between independent samples of a time series. For the 35-year time series, the procedure yielded an interval of 1.1 years between independent samples, or 31 independent observations (degrees of freedom), for which the 95 % confidence level is 0.36.

The most notable feature in Fig. 4 is the correlation between the ISMR and the May TCR, which is significant at the 99 % level (under the assumption of 31 degrees of freedom in the data). The correlation occurs as the TCR increases toward the maximum in its annual cycle (Fig. 1). The high correlation oc-

Fig. 4. Correlations of interannual variability between the ISMR and monthly mean tropical Chinese rainfall, where month 1 = January, etc. Dotted lines depict zero correlation and the 95 % confidence level for significant nonzero correlation.

curs during the initial stage of the tropical Chinese monsoon and is thus consistent with our hypothesis posed in the introduction. The possibility exists of course that the significant correlation for May in Fig. 4 occurs by chance. We have correlated 12 time series, one for each month, with the ISMR. Assuming each monthly time series is independent, the chance of random data giving 1 month out of 12 with a statistically significant correlation at the 99 % level is about 11 %, which is small, though not negligible.

To show the ISMR/May-TCR relationship more clearly, we present a scatter diagram for the two normalized time series (Fig. 5). It can be seen that more (less) than normal Indian monsoon rainfall always occurs when the May tropical Chinese rainfall is more (less) than its climatological mean by >1 standard deviation. The ISMR/May-TCR relationship is even better when the values of the normalized May TCR are positive. Indeed, among the 13 years of positive normalized May TCR, negative values of the normalized ISMR appear in only 1 year.

Maximum TCR occurs during the 3-month period from June to August (Fig. 1). During this period, there is no significant correlation of interannual variability between the TCR and the ISMR (Fig. 4). Not surprisingly, there is also no significant correlation between the ISMR and the seasonal TCR averaged over the months June–August and the months June–September. For the June–September average, our result is the same as found by Guo and Wang (1988). Evolution of the Chinese monsoon after its onset phase thus appears to proceed independently from the Indian monsoon. In addition, for tropical China, the May rainfall's interannual variability has no significant correlation with the rainfall averaged over June–August or June–September, so the interannual variability of the TCR during its most

Fig. 5. Scatter diagram of the normalized May tropical Chinese rainfall and June–September Indian rainfall for the 35-year period between 1954 and 1988.

intense period proceeds independently from its variability during the onset period.

Large correlation also occurs between the ISMR and the September TCR (Fig. 4), as the Chinese rainfall wanes, though the correlation falls just below the 95 % confidence level. Meehl's (1987) study of OLR, clouds, precipitation and sea level pressure indicates that the Asian monsoon exhibits a south-eastward retreat of monsoonal activity during the transition from summer to winter. Such behavior suggests that regions may be linked as the summer monsoon fades by a broad-area retreat of the monsoon, the reverse behavior hypothesized for the monsoon onset. The September correlation occurs as the monthly TCR diminishes from its summer maximum (Fig. 1) and is thus consistent with the possibility of monsoon retreat organized across the whole of southeastern Asia, though Fig. 4 indicates that the significance of this result should be treated with caution.

3.2 Subdomain TCR vs. ISMR

The correlations between the ISMR and the TCR shown above raises the question of whether or not similar correlations appear for regions of smaller size. Averaging over many stations can reduce the influence of localized processes on rainfall statistics. However, we find that when we compute correlations like those in Fig. 4 but for individual stations, the results are noisy and no significant correlation emerges like that in the figure. Thus, we divide the entire domain into 4 subdomains (Fig. 3). These subdomains were chosen by first computing the 35-year average rainfall at each station for every month of the year.

Fig. 6. Like Fig. 4, but for each subdomain of tropical China.

Stations were then grouped together according to the timing of the growth and decay periods of their annual cycles to produce the 4 regions. These subdomain sizes were supported by considering the correlation between one (anchor-point) station and all other stations, using a selected set of anchor-point stations. The size of the positive correlation region surrounding an anchor-point had a typical width of about 500 km, consistent with the adopted subdomains. The sizes of the overall domain and the subdomains shown in Fig. 3 are similar to those of Shen (1991), who constructed climate regions objectively by applying cluster analysis to Chinese rainfall data.

For each of the subdomains, we have calculated the correlation of interannual variability between the ISMR and the monthly rainfall averaged over the subdomain's stations, with the results appearing in Fig. 6. In the three largest subdomains (Central, East, and West), largest positive correlations between the ISMR and the TCR occur in May and September. For May, correlations are at the 99% level of significance for the East and West domains. These strong correlations between May TCR and the ISMR are consistent with an expectation of high positive correlation during the onset of monsoonal rainfall. A maximum correlation also occurs for May rainfall in the Central domain, though the correlation is just short of the 95% level of significance. The reason for the weaker correlation in the Central domain compared to the East and West domains is

not clear. In addition, no apparent relationship can be found between ISMR and the May rainfall in the South domain. This may be because of the small size of the domain and because of the orographic effects on Hainan Island, which dominate the characteristics of local rainfall.

Positive correlations for September occur as the monthly rainfall declines from its annual maximum. However, only one of these correlations is significant at the 95% level, so the September correlation observed for rainfall over tropical China as a whole (Fig. 4) appears, but not strongly, for the subdomains. Differences among the subdomains in the evolution of rainfall after June suggest weaker physical links between each of these regions and the rest of the monsoon system as the monsoon declines, a result corroborated by the appearance of only one significant, positive correlation between the ISMR and the subdomains as monthly rainfall declines.

None of the subdomains show a significant correlation with the Indian monsoon during the months June–August, repeating the result obtained for the tropical Chinese domain as a whole. There is a suggestion of negative correlation between the subdomains and the ISMR during November, though we have no physical explanation for the correlation, if it is real. Finally, the results suggest that the best May correlation is on the largest (several hundred kilometer) scales, and that the relationship between tropical Chinese rainfall and the Indian monsoon becomes weaker or non-existent on smaller scales.

3.3 OLR field

As stated before, the strong positive correlation between the ISMR and the May TCR may occur by chance. To minimize this possibility, we analyzed an independent data set, the NMC OLR, which overlaps the Chinese rainfall data set for the years 1974–1988. From the normalized May TCR, we selected all years for which the observed rainfall varied by more than one half standard deviation from its climatological mean state. By this criterion, the strong May TCR years included 1975, 1981, and 1984; weak May TCR years included 1979, 1982, 1985, and 1986. The composite patterns of OLR anomaly are shown in Fig. 7 for strong and weak May TCR, respectively. In the figure, the patterns are shown for tropical China and its vicinity for May, and for India and its vicinity for June–September. It can be seen from Fig. 7a that, when convection is stronger (negative OLR anomaly) over tropical China during May, the atmosphere is more convective over India during the following June–September. The opposite conclusion can be drawn from Fig. 7b. Applying the same analysis to each strong or weak May TCR year gives patterns similar to those shown in Fig. 7.

Using the same strong or weak May TCR years as above, we also compared composite OLR anomaly

Fig. 7. Composite patterns of OLR anomaly (Wm^{-2}) for (a) strong May TCR and (b) weak May TCR. Note that data are shown for both May (right-hand side) and June–September (JJAS; left-hand side) in each panel. Negative values are shaded.

patterns for May India vs. May China, and for June–September India vs. June–September China (not shown). In neither case did a clear correspondence between anomaly patterns emerge as in Fig. 7. Thus, the OLR anomaly patterns support our precipitation results: the most significant correlation between the ISMR and TCR occurs on relatively large scales during the strengthening phase (May) of the TCR.

4. Summary and discussion

We have analyzed the interannual relationship between the tropical Chinese rainfall (TCR) and the Indian summer monsoon rainfall (ISMR) for the 35-year period from 1954 to 1988. The May TCR has the largest positive correlation with the ISMR; it is significantly different from zero at the 99 % level. This relationship has been confirmed independently by OLR patterns. The second largest correlation maximum occurs in September though it falls just below the 95 % confidence level. No significant correlation has been found between the ISMR and the Chinese rainfall during the most active TCR phase (June–August).

The significant interannual correlation between the ISMR and the May TCR indicates that the May TCR can be used as a predictor for the interannual variability in the ISMR. Of course, even though the May correlation is significantly different

from zero at better than the 99 % level, the correlation between the ISMR and May TCR is 0.46, so only about 21 % of the ISMR's interannual variability can be explained by the May TCR. Thus, the May TCR is not, of course, the only predictor for the Indian monsoon. The correlation between the ISMR and May TCR certainly does not mean that interannual variability in the Indian monsoon has its source in Chinese weather. Rather, we interpret the correlation as implying a common initiator for the Asian monsoon in both regions that affects China earlier than India. Thus, the lead/lag interannual relationship between the ISMR and the May TCR is considered to be a result of the annual migration of the Asian summer monsoon rainfall, as shown for example by Fig. 2.

This study has provided information about the relationships between tropical Chinese rainfall and Indian monsoon rainfall, which is useful for understanding the regional features of the Asian monsoon system. However, the mechanisms responsible for the association between the two regional monsoons have not been revealed thoroughly. In addition, strongest May correlations between TCR and ISMR occur in subdomains of tropical China with spatial scales of several hundred kilometers. The empirical derivation of these domains suggests that they are physically homogeneous precipitation regions, but it does not reveal the mechanisms generating these regions. To have a better understanding of all mechanisms involved in the TCR-ISMR relationship, it will be necessary to study the physics of the evolution of the Asian monsoon *circulation*. Experiments with high-resolution climate models possess a great potential to achieve this goal.

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中国熱帯地方の降水量とインドモンスーンの降水量との関係について

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中国熱帯地方における月別降水量 (TCR) と、インドにおける 6-9 月合計の夏季モンスーン降水量 (ISMR) との関係、1954-1988 年の間の 35 年間について調査した。両者の間のもっとも強い正相関関係は、5 月と 9 月に認められ、5 月においては、99% の有意水準を越えていた。熱帯中国において降水がもっとも多い、6-8 月の各月の TCR は、ISMR と無相関であった。同様の関係は、赤外長波放射量 (OLR) の偏差合成図においても、また熱帯中国を 4 つの地域に分けた地域別降水量においても、認められた。

5 月の TCR と ISMR との密接な関係は、5 月の TCR が ISMR の前兆現象となることを示唆しており、それはアジアモンスーンの平均的な開始時期が、気候学的な OLR 分布において、東から西へと進行していくことと調和的である。