Shift of the principal mode of Pan-Asian monsoon summer precipitation in terms of spatial pattern

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ABSTRACT

This paper documents that the principal mode of Pan-Asian monsoon summer precipitation experienced a prominent interdecadal shift around 1992/1993 in terms of spatial pattern and major driving factors. During 1979–1992 (Period 1, P1), Pan-Asian monsoon summer precipitation anomalies mainly display a meridional dipole pattern from north to south, whereas in the period 1993–2016 (Period 2, P2), it shows a meridional tripole pattern instead. The summer precipitation in P1 is primarily associated with a combination of the developing phase (central-eastern Pacific type) and decaying phase (eastern Pacific type) of El Niño–Southern Oscillation (ENSO); while in P2, it is mainly associated with the decaying phase of central-eastern-Pacific-type ENSO.

1. Introduction

The Pan-Asian monsoon includes several important sub-monsoon systems, such as the South Asian summer monsoon, East Asian summer monsoon, Southeast Asian monsoon, and the western North Pacific summer monsoon, which connect the Northern Hemisphere and Southern Hemisphere (Gao and Wang 2012). These sub-monsoon systems are intimately related with each other. In previous work, Gao and Wang (2012) defined the Pan-Asian monsoon region to investigate the principal modes of the summer precipitation and its associated air–sea features (Gao, Wang, and Chen 2015; Gao, Wang, and Jiang 2015).

However, many monsoon systems experienced an interdecadal change in the 1990s (Kwon et al. 2005; Yim, Jhun, and Yeh 2008; Wu et al. 2010; Chen, Wen, and Wang 2016). Wu et al. (2010) found that southern China summer rainfall experienced an interdecadal change around 1992/1993, with less rainfall in the preceding period and more rainfall in the latter period, associated with the tropical Indian Ocean SST and Tibetan Plateau snow cover. The El Niño–Southern Oscillation (ENSO), having the most significant variation in the tropics, plays an important role in modulating the summer monsoon rainfall intensity and distribution (Huang and Wu 1989; Chen 2002; Mishra et al. 2012; Fu 2015).

Kwon et al. (2005) pointed out that East Asia–western North Pacific (WNP) summer monsoon precipitation also experienced a decadal change in the mid-1990s, associated with a combination of the developing and decaying phases of eastern-Pacific-type ENSO in the preceding period, and with the developing phase of central-Pacific-type ENSO in the latter period (Yim, Jhun, and Yeh 2008). The Pacific–Japan pattern, as one of the important factors influencing the WNP summer monsoon climate, experienced a similar decadal change in the mid-1990s, corresponding to the ENSO decaying phase in the preceding period and ENSO developing phase in the latter period. The WNP subtropical high (WPSh), with mainly zonal change in geopotential height over the western Pacific, is also an impact factor of the Asian monsoon system, and
can be affected by ENSO (Lu and Dong 2001; Wu, Zhou, and Li 2009; Xie et al. 2009; Paek et al. 2016).

However, previous studies have mainly focused on the WNP region in the Northern Hemisphere, with less attention paid to southwestern regions in the tropical Indian Ocean and Maritime Continent. The aim of the present study is to examine whether the principal mode of Pan-Asian monsoon summer precipitation has experienced interdecadal change; and if so, to identify the factors responsible for the change in the pattern of rainfall anomalies.

2. Data and methods

The observational datasets used in the present study include the Climate Prediction Center Merged Analysis of Precipitation data-set (Xie and Arkin 1997), with a horizontal resolution of 2.5° latitude/longitude, for the period 1979–2016; the National Centers for Environmental Prediction/National Center for Atmospheric Research monthly reanalysis data-set (Kalnay et al. 1996), with a horizontal resolution of 2.5° latitude/longitude, for the period 1978–2016; and the National Oceanic and Atmospheric Administration monthly Extended Reconstructed Sea Surface Temperature data-set, version 3b (Smith et al. 2008), with a horizontal resolution of 2° latitude/longitude, for the period 1978–2016.

In this study, summer is defined as the seasonal mean from May to July (MJJ); the preceding spring is defined as the seasonal mean from March to April; and the preceding winter is defined as the seasonal mean from December to February. All datasets are detrended before further analysis.

3. Results

According to the study of Gao and Wang (2016), during the period 1979–2016, the spatial pattern of the first empirical
Figure 2. (a1–a3) Correlation coefficients of PC1 with the previous winter and spring, and the simultaneous summer SST, for the period 1979–1992. (b1–b3) As in (a1–a3), but for the period 1993–2016. (c1–c2) As in (a1–a3), but for the PI correlations. (d1–d3) As in (c1–c3), but for the period 1993–2016.

Note: Gridded regions indicate the correlations are significant at the 95% confidence level.
orthogonal function (EOF1) mode of summer precipitation in the Pan-Asian monsoon region mainly shows a meridional tripole pattern from north to south, with more (less) rainfall over the South China Sea (SCS)—Philippine Sea, and less (more) rainfall over the middle–lower reaches of the Yangtze River Valley—East China Sea and the tropical eastern Indian Ocean—western Maritime Continent (figure not shown). In addition, the principal component of EOF1 (PC1) experiences a notable change around 1992/1993, with smaller variations in the period 1979—1992 (Period 1, P1) and larger variations in the period 1993—2016 (Period 2, P2), which indicates that the tripole precipitation pattern is more significant in P2. According to this tripole precipitation distribution, a tripole precipitation index is defined by choosing three maximum rainfall centers as PI-tripole = A1 — A2 + A3, where A1 (27°—35°N, 105°—135°E), A2 (10°—25°N, 105°—140°E), and A3 (10°S—10°N, 75°—115°E) are the regional mean MJJ precipitation of these three rainfall centers (shown in Figure 1, blue and red rectangular boxes). The correlation pattern between the PI-tripole and summer precipitation in the Pan-Asian monsoon region is consistent with the EOF1 mode, and the correlation coefficient between the PI-tripole and PC1 is 0.87, which is statistically significant at the 99% confidence level. These tripole precipitation anomalies are associated with the ENSO signal, tropical Indian Ocean and Maritime Continent SSTs in the preceding winter and spring, and tropical Indian Ocean and Maritime Continent SSTs in the simultaneous summer (figure not shown). Thus, we calculate the sliding correlation coefficients of PI-tripole and PC1 with these three key SST indices (defined as the regional mean) during the preceding winter to summer with a sliding window of 11 years (figure not shown). The results show that the correlation coefficients of PI-tripole and PC1 with these three key SST indices from the previous winter to summer generally exhibit a prominent interdecadal change, indicating less correlation in P1 and significant correlation in P2 (the correlation coefficients are significant at the 95% confidence level). Therefore, we divide the studied periods of Pan-Asian monsoon precipitation into 1979—1992 and 1993—2016, respectively.

Table 1. Correlation coefficients of the PI and PC1 with ENSO indices during the previous winter, spring, and simultaneous summer, the IO index and the MC index during the simultaneous summer (indices are calculated by the SST regional mean, given in Table 2) for the periods 1979—1992 and 1993—2016.

|            | ENSO | IO  | MC (eastern) |
|------------|------|-----|--------------|
| 1979—1992  |      |     |              |
| DJF        | 0.65** | 0.65* | 0.75**       |
| MA         | 0.64*  | 0.77** | 0.69**       |
| MJJ        | 0.63*  | 0.69** | 0.59*        |
| 1993—2016  |      |     |              |
| DJF        | 0.75** | 0.76** | –            |
| MA         | 0.81** | 0.74** | –            |
| MJJ        | 0.69** | 0.57** | 0.71**       |

Notes: IO, Indian Ocean; MC, Maritime Continent; PI, precipitation index; DJF, December—February; MA, March—April; MJJ, May—July.

*95% confidence level; **99% confidence level.
Figure 3 displays the correlation coefficients of PI and PC1 with the summer 850 hPa geopotential height field. In P1, the Pan-Asian monsoon summer precipitation is positively correlated with tropical Indian Ocean, western Maritime Continent, and central-eastern Pacific SSTs in the preceding winter and spring. In summer, it is only positively correlated with tropical Indian Ocean and western Maritime Continent SSTs. Hence, in P1, the summer precipitation is related to a combination of the developing phase (central-eastern Pacific type) and decaying phase (eastern Pacific type) of ENSO, which is consistent with the results of Yim, Jhun, and Yeh (2008); whereas, in P2, it is related to the decaying phase of central-eastern-Pacific-type ENSO. Table 1 shows that the relationship of the dominant mode of Pan-Asian monsoon summer precipitation with ENSO and tropical Indian SST is more prominent in the latter period. Besides, the precipitation is negatively correlated with eastern Maritime Continent SST in P1 and positively correlated with western Maritime Continent SST in P2.

Table 2. Ranges of the ENSO indices during the previous winter, spring, and simultaneous summer, the IO index and the MC index during the simultaneous summer (green rectangular regions in Figure 2).

|          | ENSO          | IO           | MC (eastern) |
|----------|---------------|--------------|--------------|
| 1979–1992| DJF | MA  | MJJ | DJF | MA  | MJJ | MJJ |
| PI       | 150°–90°W   | 150°–90°W   | 100°–80°W   | 50°–100°E | 120°–150°E |
| PC1      | 150°–90°W   | 180°–90°W   | 10°S–10°N   | Same as PI | Same as PI |
|          | 10°S–5°N   | 10°S–10°N   | 10°S–10°N   | 5°S–10°N |

|          | ENSO          | IO           | MC (western) |
|----------|---------------|--------------|--------------|
| 1993–2016| DJF | MA  | MJJ | MJJ | MJJ | MJJ |
| PI       | 180°–90°W   | 180°–90°W   | 50°–120°E | 90°–120°E |
| PC1      | Same as PI   | Same as PI   | 10°S–10°N   | 10°S–10°N |
|          | Same as PI   | Same as PI   | 10°S–10°N   |

Notes: IO, Indian Ocean; MC, Maritime Continent; PI, precipitation index; DJF, December–February; MA, March–April; MJJ, May–July.

In P2, the SST fields associated with the PI and PC1 are consistent (Figure 2(d1)–(d3) and 2(b1)–(b3)), which indicates that the Pan-Asian monsoon summer precipitation is positively correlated with tropical Indian Ocean, western Maritime Continent, and central-eastern Pacific SSTs in the preceding winter and spring. In summer, it is only positively correlated with tropical Indian Ocean and western Maritime Continent SSTs. Hence, in P1, the summer precipitation is related to a combination of the developing phase (central-eastern Pacific type) and decaying phase (eastern Pacific type) of ENSO, which is consistent with the results of Yim, Jhun, and Yeh (2008); whereas, in P2, it is related to the decaying phase of central-eastern-Pacific-type ENSO. Table 1 shows that the relationship of the dominant mode of Pan-Asian monsoon summer precipitation with ENSO and tropical Indian SST is more prominent in the latter period. Besides, the precipitation is negatively correlated with eastern Maritime Continent SST in P1 and positively correlated with western Maritime Continent SST in P2.

Figure 3. (a, b) Correlation coefficients of PC1 with simultaneous summer 850 hPa geopotential height for the periods 1979–1992 and 1993–2016, respectively. (c, d) As in (a, b), but for PI correlations. Note: Gridded regions indicate the correlations are significant at the 95% confidence level.

In P2, the SST fields associated with the PI and PC1 are consistent (Figure 2(d1)–(d3) and 2(b1)–(b3)), which indicates that the Pan-Asian monsoon summer precipitation is positively correlated with tropical Indian Ocean, western Maritime Continent, and central-eastern Pacific SSTs in the preceding winter and spring. In summer, it is only positively correlated with tropical Indian Ocean and western Maritime Continent SSTs. Hence, in P1, the summer precipitation is related to a combination of the developing phase (central-eastern Pacific type) and decaying phase (eastern Pacific type) of ENSO, which is consistent with the results of Yim, Jhun, and Yeh (2008); whereas, in P2, it is related to the decaying phase of central-eastern-Pacific-type ENSO. Table 1 shows that the relationship of the dominant mode of Pan-Asian monsoon summer precipitation with ENSO and tropical Indian SST is more prominent in the latter period. Besides, the precipitation is negatively correlated with eastern Maritime Continent SST in P1 and positively correlated with western Maritime Continent SST in P2.
and less rainfall, so that the northern Indian Ocean warming cannot force anomalous rainfall in the Pan-Asian monsoon region, which is coherent with the result of Wu, Zhou, and Li (2009). Similar to P1, the anomalous warming over the northern Indian Ocean (Arabian Sea and Bay of Bengal) in P2 also corresponds to the local anomalous descending motion (Figure 9 in Gao and Wang 2016), which cannot modulate the Pan-Asian monsoon summer precipitation.

Figure 4 shows the 850 hPa wind fields associated with the PI and PC1 during P1 and P2. In P1 (Figure 4(a) and (c)), summer precipitation is modulated by ENSO. The anomalous westerlies occur over the equatorial central-western Pacific and anomalous easterlies appear over the tropical Indian Ocean. This indicates that the ascending branch of the Walker circulation is over the tropical eastern Pacific, while the descending branch is over the Maritime Continent. In addition, the tropical Indian Ocean is associated with an anomalous anticyclone, resulting in less rainfall. Meanwhile, the cross-equatorial Somali jet is anomalously weaker than normal; thus, the anomalous easterlies over the tropical Indian Ocean overlaying the westerlies during normal years weaken the westerlies and decrease cold water transport from the western Indian Ocean to the northern Indian Ocean, which decreases evaporation locally. For these reasons, a tropical Indian Ocean warming is induced. In P2 (Figure 4(b) and (d)), owing to the stronger relationship between the summer precipitation and WPSH, the tropical Indian Ocean SST can thus increase via the WPSH to weaken the westerlies over the northern Indian Ocean. Hence, through the air–sea interaction, the tropical Indian Ocean SST can build a linkage with the Pan-Asian monsoon summer precipitation (Gao and Wang 2016).

In addition, in both periods, the anomalous anticyclonic circulation over the Indochina Peninsula—tropical western Pacific region induces subsidence there, which makes less rainfall. However, the middle–lower reaches of the Yangtze River Valley–South Japan receives more moisture along the north of the WPSH, favoring more rainfall.

4. Conclusion and discussion
Pan-Asian monsoon summer precipitation experienced a remarkable interdecadal shift around 1992/1993. In P1, the summer precipitation anomalies display a dipole pattern from north to south, indicating the rainfall over the middle–lower reaches of the Yangtze River Valley–South Japan and the Malay Peninsula is opposite to that over the Indochina Peninsula–Philippine Sea and the equatorial eastern Indian Ocean. However, in P2, it shows a meridional tripole pattern from north to south, with the rainfall over the SCS–Philippine Sea opposite to both sides. The differences of summer precipitation between these two periods are found to be located over the tropical Indian Ocean.

In P1, the summer precipitation is mainly associated with a combination of the developing phase (central-eastern Pacific type) and decaying phase (eastern Pacific type) of ENSO; while in P2, it is primarily associated with the decaying phase of central-eastern-Pacific-type ENSO, which is modulated by the ENSO signal in the preceding winter and spring, and the Maritime Continent SST in the simultaneous summertime (Gao and Wang 2016). In comparison with P1, the relationship between summer precipitation anomalies and ENSO in P2 is more significant (Gao and Wang 2016). In future work, more research into the dynamic and physical mechanisms underlying the strengthened relationship between Pan-Asian monsoon summer precipitation and ENSO are needed. In addition, it is worth noting that the present study is based on observational analysis only; model examinations are also necessary to verify the findings.
Disclosure statement

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