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# The strengthening East Asia summer monsoon since the early 1990s

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Previous studies have documented a weakening tendency of the East Asian summer monsoon (EASM) since the end of the 1970s. In this study, we report that the EASM has been recovering since the early 1990s, although its strength is still less than in previous decades (averaged over the period 1965–1980). Following the recovery of the EASM, there has been a tendency in the last decade toward northward-moving rainbands and excessive rainfall in the Huaihe River valley (110°–120°E, 30°–35°N). There is evidence suggesting that the strengthening EASM since the early 1990s is linked to interdecadal change of land-sea thermal contrast.

**East Asia summer monsoon, precipitation, interdecadal change, land-sea thermal contrast**

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East Asia is dominated by a typical monsoon climate. The East Asian summer monsoon (EASM) showed considerable variability over a wide range of time scales during the 20th century [1]. Great effort has been devoted to understanding the interdecadal variability of EASM, due in part to its weakening since the late 1970s. This weakening was manifested as tendencies toward increasing drought in North China and excessive rainfall in South China, along the Yangtze River valley [2–4]. While there is still no consensus on the mechanisms of EASM weakening, there is increasing evidence that tropical ocean warming is one driving factor [5–8].

In addition to the impetus toward understanding this weakening, there is great concern within the climate research community about monsoon recovery in the near future. Observational analysis has depicted severe flooding events in the summers of 2000, 2003, 2005 and 2007 in the Huaihe River valley (110°–120°E, 30°–35°N) [9,10]. The monsoon rain belt tends to move northward in eastern China, from 30° to 35°N, accompanying the subtropics widening [11]. The shift of the Pacific Decadal Oscillation (PDO) from its positive to negative phase induces warming over Lake Baikal and a weakened subtropical westerly jet, through air-sea interactions over the Pacific. This has increased summer rainfall in the Huang-Huai River valley (32°–36°N, 110°–121°E), but decreased it in the Yangtze River valley (28°–31°N, 110°–121°E) during 2000–2008, compared to 1979–1999 [12]. All this evidence indicates that the East Asian climate may have experienced an interdecadal-scale regime shift during the latest decade. Whether the EASM is recovering is unknown. This is the issue addressed in this study. Based on rain gauge observations and reanalysis data, we present evidence that the EASM strengthened during 1991–2011, compared to the prior decade 1981–1990. Following this strengthening of the EASM since the early 1990s, the Eastern Chinese region between 30° and 35°N received greater summer rainfall. This EASM recovery was dominated by an interdecadal change of land-

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sea thermal contrast.

## 1 Data and monsoon index

Monthly rain-gauge data from 160 stations in China during 1951–2011 was used to measure monsoonal precipitation change. These data have been widely used in monsoon studies [13]. SST data at 2°×2° from the National Oceanic and Atmospheric Administration (NOAA) [14] and monthly land surface air temperatures at 2.5°×2.5° [15] are used to analyze land-sea thermal contrast. To reveal monsoon circulation change, National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data [16] are used, which are from the period 1951–2011. We also used the European Centre for Medium-Range Weather Forecasts 40-year reanalysis (ERA-40) [17], for 1958 to 2002. Although the EASM weakening of the 1970s derived from NCEP/NCAR reanalysis data is greater than that of ERA-40 [18,19], the two reanalyzed datasets are highly consistent in measuring recent monsoon changes. For brevity, therefore, we only show the NCEP/NCAR results.

There are various definitions of the EASM index [20]. The meridional wind is crucial to the EASM. Following previous studies [21,22], this index is defined as the JJA (June-July-August) mean meridional wind at 850 hPa, averaged over the region of 20°–30°N, 110°–130°E. The EASM index based on meridional wind has been widely used in climate change studies [5,21–24].

## 2 Results

### 2.1 Interdecadal change of East Asian summer monsoon

The evolution of the EASM index is shown in Figure 1(a). A distinctive interdecadal variation is seen. The epoch 1951–1989 witnessed a decreasing trend, whereas 1989–2011 saw an increasing trend. To examine the interdecadal transition point of the EASM, we use a 10-year running *t*-test method (Figure 1(b)). In the past 61 years, the EASM has experienced three interdecadal-scale regime shifts. The first occurred in 1965, the second in 1980, and the most recent in 1990. The first two shifts have been documented by previous studies. These studies found that the EASM began to decline on an interdecadal timescale in the mid 1960s [25,26], followed by a recovery through the early 1970s, and another weakening in the late 1970s [1,4,5,7,27]. Here, we augment these studies by presenting evidence that the EASM has been recovering since the early 1990s (Figure 1(b)).

To further confirm the EASM recovery, a 7-year smoothed summer (JJA) 850 hPa meridional wind, averaged over 115°–120°E, is shown in Figure 2. The decades prior to the

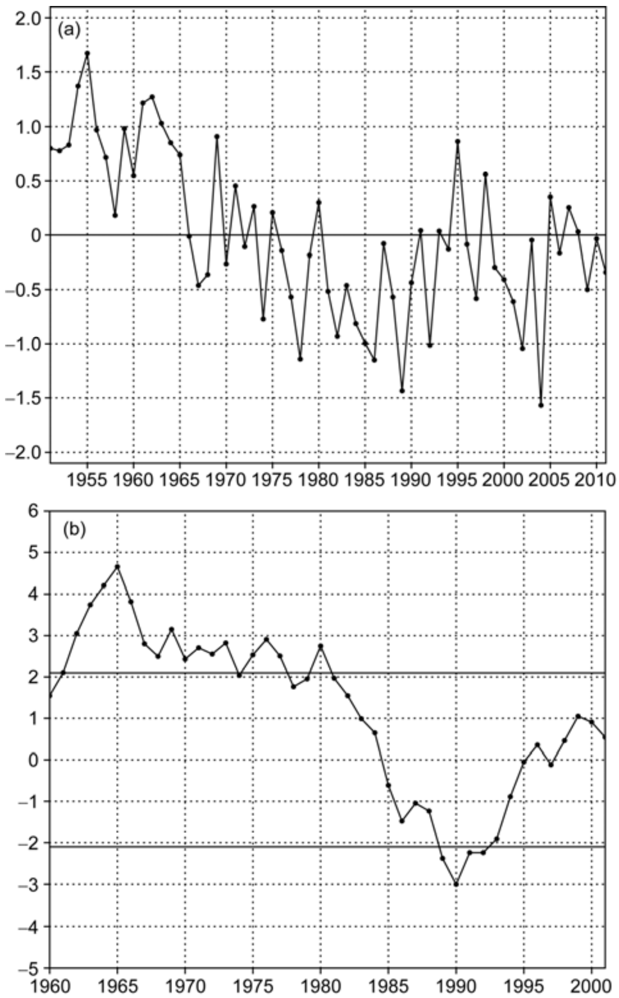


**Figure 1** (a) Normalized time series of EASM index in JJA from 1951 to 2011; (b) corresponding 10-year running *t*-test series, and two lines at 95% confidence level.

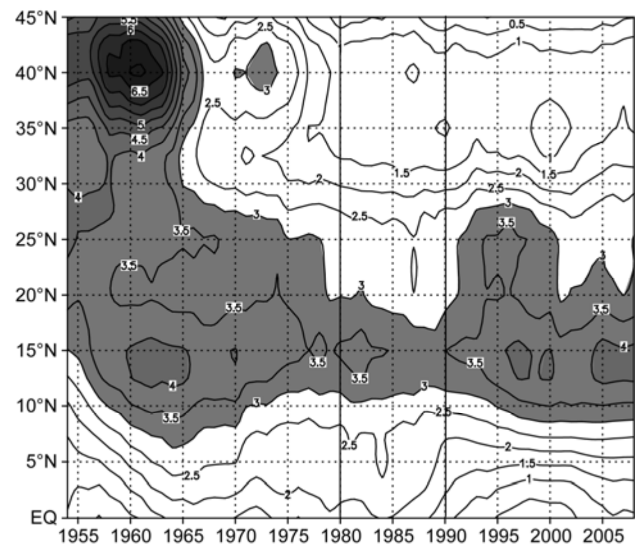


**Figure 2** Latitude-time cross-section of 7-year smoothed summer-mean 850 hPa meridional velocity, averaged over 115°–120°E from 1951 to 2011 (m/s). Shaded area is meridional velocity greater than 3 m/s. Thick vertical lines indicate transition points.

early 1980s saw a stronger-than-normal EASM, but the period 1981–1990 witnessed a weaker-than-normal monsoon, as reported previously [1,27–31]. Our focus here is on the recent change of the EASM. A meridional wind stronger than 3 m/s is a reasonable indicator of EASM changes. Figure 2 shows that such a meridional wind dominated between 30° and 40°N during 1954–1980. However, during 1981–1990, a southward withdrawal of the 3 m/s meridional wind is seen, such that the region between 10° and 20°N was dominated by these winds. A recovery appeared during the period 1991–2008, and the region within 10°–26°N was dominated by the strong meridional winds. This indicates that the EASM has been recovering during the decades of 1991–2011.

To reveal the surface circulation patterns of EASM recovery, Figure 3 shows 850 hPa wind differences of 1991–2011 relative to 1981–1990. An anomalous anticyclonic circulation dominates the region south of Lake Baikal. The western Pacific is also dominated by a robust anticyclone. Along the western edge of this anticyclone, East China is covered by anomalous southwesterly winds, indicating an enhanced summer monsoon circulation. Thus, the EASM circulation during 1991–2011 was stronger than that of 1981–1990.

The western Pacific subtropical high (WPSH), which is usually measured by geopotential height at 500 hPa, is an important component of the EASM. Accompanying the EASM enhancement since the early 1990s, the WPSH also exhibits significant change. As shown in Figure 4, there are anomalous positive heights to the south of 30°N in the western Pacific, with their center to the east of 140°E. This anomaly pattern indicates an eastward retreat of WPSH relative to its climate mean state, which is shown by shading in the figure. The geopotential height anomaly indicates a northward translation of the WPSH ridge line. These features contrast greatly with the WPSH westward extension associated with the monsoon weakening of the late 1970s [30]. The WPSH changes also indicate that EASM has been strengthening since the early 1990s.

## 2.2 Interdecadal variation of summer precipitation over eastern China

Following the recovery of EASM circulation in the early 1990s, monsoon rainfall also changed significantly. Figure 5 shows 7-year smoothed summer (JJA) precipitation anomalies, averaged over 110°–120°E. The period 1954–1980 had excessive rainfall between 32.5° and 37.5°N but deficient rainfall further south (27.5°–32.5°N), whereas precipitation

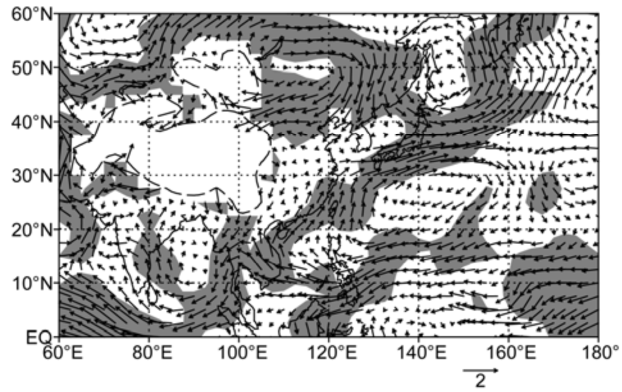


**Figure 3** Changes (1991–2011 mean minus 1981–1990 mean) in JJA 850 hPa winds (m/s). Shaded areas are statistically significant at the 95% confidence level according to Student's *t*-test. Thick dashed lines outline terrain greater than 1500 m elevation.

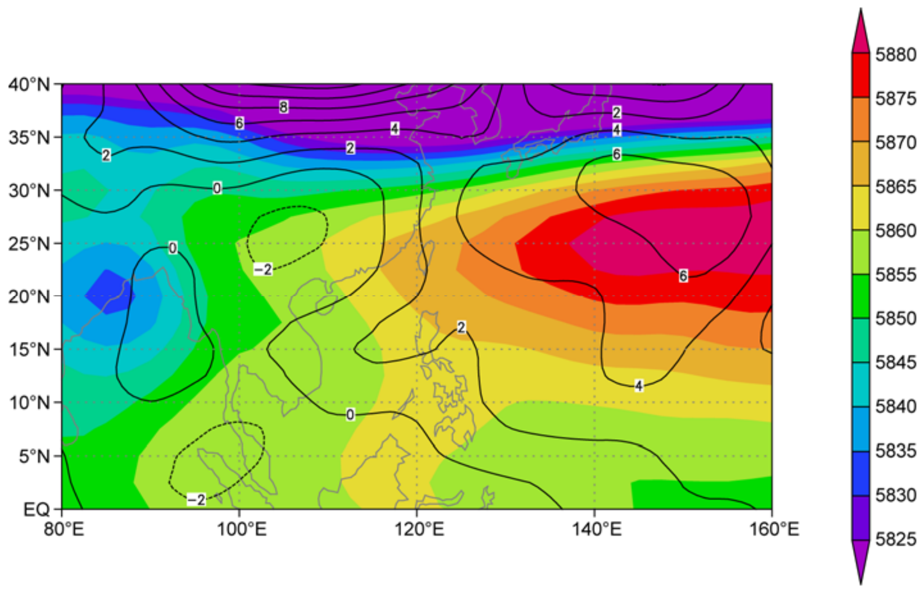


**Figure 4** Changes (1991–2011 mean minus 1980–1990 mean) in JJA 500 hPa geopotential height (gpm). Shading indicates climatic mean state of JJA 500 hPa geopotential height.

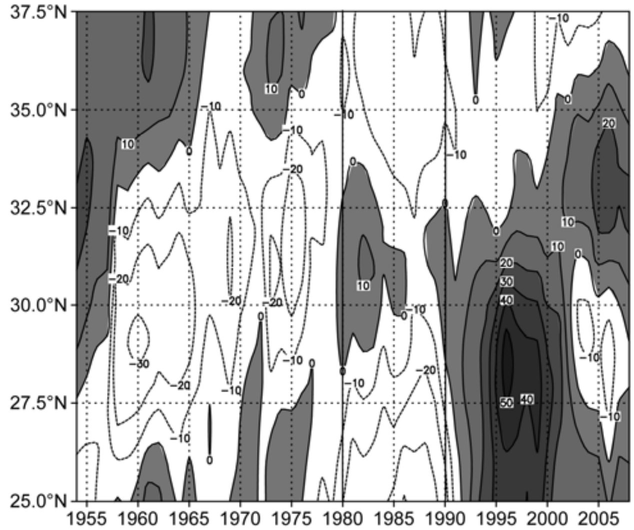


**Figure 5** Seven-year smoothed summer precipitation anomalies, averaged over 110°–120°E (mm). Shaded areas indicate regions of precipitation greater than zero. Thick vertical lines indicate transition points.

increased between 30° and 32.5°N over the period 1981–1990. The anomalous rainfall pattern during 1981–1990 has been commonly called "Southern China flood and Northern China drought" by previous studies [1,4,7,27]. Since the early 1990s, precipitation has tended to move northward.

To reveal the connection of monsoon circulation with rainfall change in the Huaihe River valley since the early 1990s, simultaneous correlations between the EASM index and rainfall at 160 stations in JJA during 1991–2011 are shown in Figure 6. There are significantly positive correlations in the valley (30°–35°N, 110°–120°E), indicating that increased valley rainfall is dominated by the intensification of EASM circulation. The pattern of rainfall anomalies is consistent with the WPSH change shown in Figure 4, which

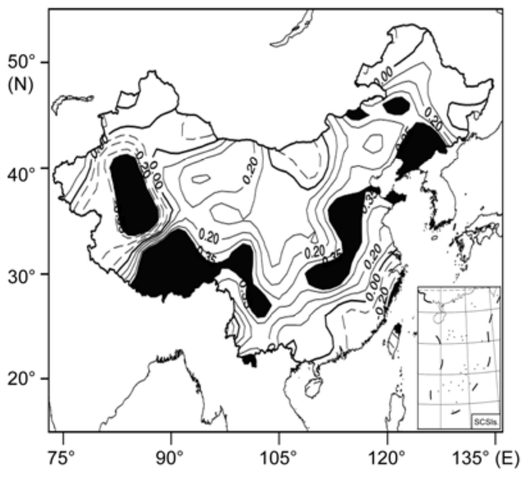


**Figure 6** Correlation coefficient between EASM index and rainfall at 160 stations in JJA, from 1991–2011. Shaded areas are statistically significant at 90% confidence level.

favors increased transport of water vapor to the valley [13]. In addition, the correlation pattern of Figure 6 is similar to the so-called "intermediate pattern" of summer rainfall in Eastern China, which is defined in the operational seasonal forecast and represents the center of the rain belt located in the Huaihe River valley [32]. Whether summer rainfall in eastern China is dominated by the intermediate rainfall pattern in coming years requires further study.

### 2.3 Possible mechanism responsible for interdecadal variation of East Asian summer monsoon

The monsoon is determined by land-sea thermal contrast [5,33], which can be expressed by low-level air temperature, sea-level pressure (SLP), and other factors [5]. Figure 7(a) shows SLP interdecadal changes (1991–2011 mean minus 1981–1990 mean). There are positive SLP anomalies over Inner Mongolia and the western Pacific, but negative anomalies over the Indochina peninsula.

The land-sea thermal contrast change between 1991–2011 and 1981–1990 is shown in Figure 7(b). The warming trend over land is far stronger than that over the ocean, generating an enhanced land-sea thermal contrast and resulting stronger monsoon circulation.

The increased land-sea thermal contrast across the East Asian continent and North Pacific comes primarily from the ocean components. Although the driving mechanism for the positive SLP anomalies over the Western Pacific needs further study, the PDO shift from its positive to negative phase may contribute [12].

## 3 Summary and discussion

The weakening of the EASM since the end of the 1970s has been of great concern to the climate research community, as indicated by previous studies. In this study, we show evidence that the EASM has been recovering since the early 1990s, although its strength is still less than in previous decades (averaged over the period 1965–1980). Accompanying the interdecadal EASM recovery, the monsoon rain belt in Eastern China has tended to move north, to between 30° and 35°N. The WPSH has shown a tendency toward eastward retreat and a northward shift in its ridge line, which favors increased transport of water vapor to the Huaihe River. The strengthening EASM since the early 1990s is linked to an interdecadal change of land-sea thermal contrast, which is dominated by positive SLP anomalies over the Western Pacific and a "warmer land-colder ocean". There is evidence indicating that the SLP change over the Western Pacific is associated with PDO phase transition [12], but the physical mechanism behind this statistical connection requires further study. Numerical experiments may aid in the understanding of this issue.

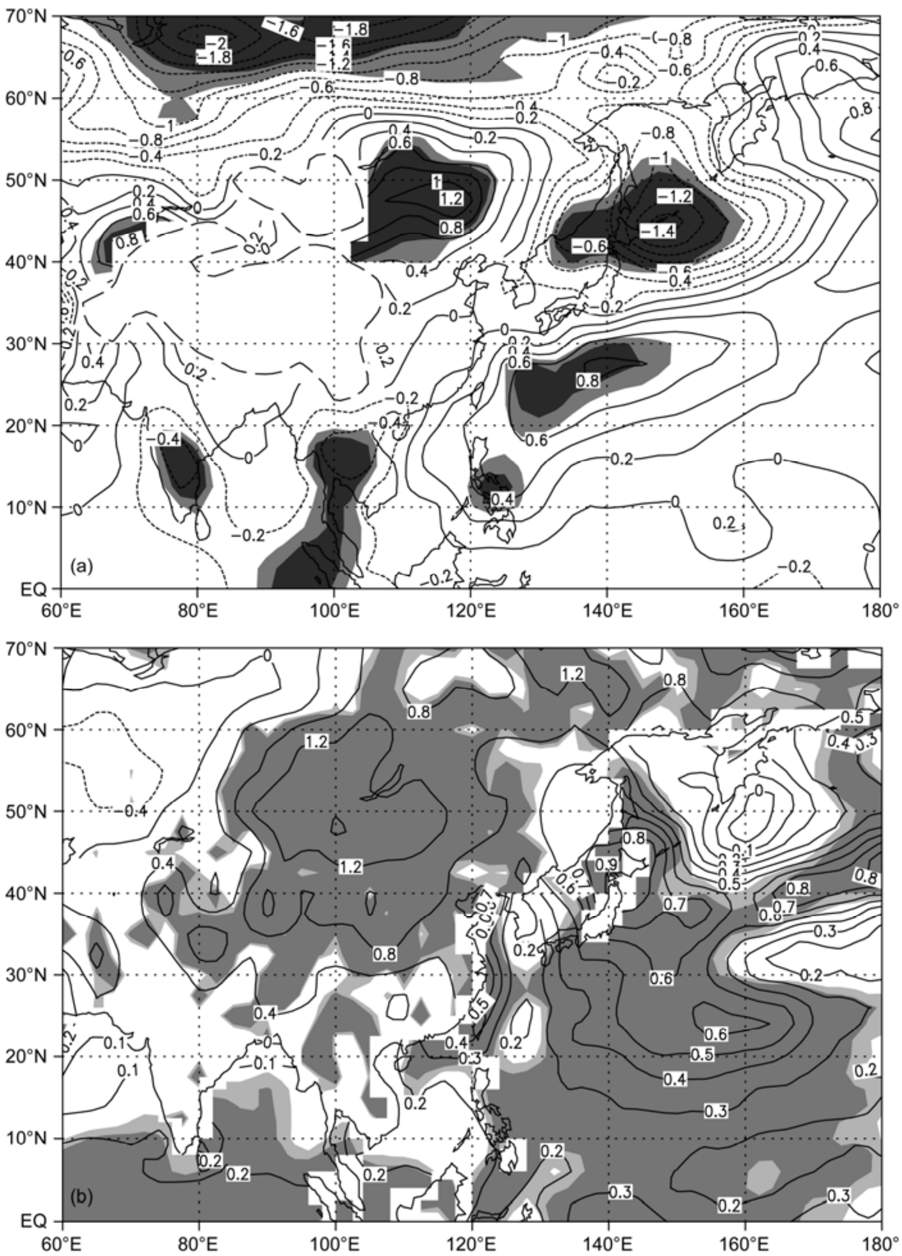


**Figure 7** Same as Figure 3, but for sea-level pressure (SLP) (hPa) (a); sea (land) surface temperature (°C) (b). Dark and lighter shadings identify statistical significance at 95% and 90% confidence levels from Student's *t*-test, respectively.

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