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**Article**

# Detecting and understanding the multi-decadal variability of the East Asian Summer Monsoon – Recent progress and state of affairs

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**Abstract**

East Asia is dominated by a typical monsoon climate. The East Asian summer monsoon (EASM) exhibits considerable variability on a wide range of time scales during the 20$^{th}$ century. A substantial portion is the multi-decadal variability. Over the recent decades, the EASM has been weakening from the end of the 1970s which results in a "southern China flood and northern China drought" rainfall pattern. Understanding the mechanisms responsible for the weakening tendency has been a challenge for climate research community. Examinations on the long-term change of the EASM during the 20$^{th}$ century find no significant trends, indicating the pronounced weakening tendency of the EASM in recent decades is unprecedented. After documenting the prominent features of the interdecadal climate transition, a review is presented in this paper on the proposed explanations to the observed changes. The proposed factors include the Indian Ocean and far western Pacific warming, the tropical central-eastern Pacific warming, the weakening sensible heat source over the Tibetan Plateau, and the aerosol forcing, as well as internal variability. While parts of the monsoon circulation changes can be explained in terms of the proposed mechanisms, it is still beyond the scope of our current knowledge to present a complete picture. Much remains to be learned about the mechanisms that produce such multi-decadal changes in the EASM, but it seems still unclear whether human activities and global warming are playing significant roles.

**Zusammenfassung**

Ostasien wird von einem typischen Monsunklima beherrscht. Der ostasiatische Sommermonsun (EASM) zeigt während des 20. Jahrhunderts eine erhebliche Variabilität über ein breites Spektrum von Zeitskalen hinweg. Ein größerer Teil davon ist multidekadische Variabilität. Seit dem Ende der 1970er Jahre hat sich der EASM abgeschwächt, was zu dem "Südchina-Flut - Nordchina-Dürre" Muster geführt hat. Das Verständnis für die Ursachen dieser Abschwächungstendenz stellt eine Herausforderung für die Klimatologie dar. Untersuchungen der langfristigen Änderungen des EASM während des gesamten 20. Jahrhunderts zeigen keine signifikanten Trends, was bedeutet, dass die Änderung in den letzten Jahrzehnten ohne Beispiel ist. Nach einer Dokumentation der wichtigsten Phänomene dieser interdekalen Klimaänderung bietet die vorliegende Arbeit einen Überblick über die möglichen Erklärungen für die beobachteten Änderungen. Diese beinhalten unter anderem eine Erwärmung des mittleren und östlichen Pazifiks, eine Abschwächung der Wärmequelle über dem tibetischen Plateau, einen Antrieb durch Aerosol wie auch interne Variabilitäten. Während Teile der Änderung der Monsunzirkulation hierdurch erklärt werden können, liegt eine vollständige Erklärung des Phänomens noch jenseits unseres derzeitigen Wissensstands. Es muss noch viel über die Mechanismen verstanden werden, die solche interdekalen Änderungen des EASM hervorrufen, wobei es noch unklar ist ob menschliche Aktivitäten und die globale Erwärmung eine signifikante Rolle spielen.

## 1 Introduction

The East Asian Summer Monsoon (EASM) is an important component of the Asian-Australian monsoon system. The distinctive topography and orography of East Asia produce unique features in the EASM. While the South Asian or Indian summer monsoon is purely a tropical monsoon system, the EASM is composed of both tropical and subtropical systems. The monsoon circulation system over East Asia has a high degree of independence and differs from that over South Asia, although some associations between them still occur at times (TAO and CHEN, 1987; DING, 1994; LAU et al., 2000). The monsoon activity is crucial to regional and local water resources: the summer monsoon rainfall accounts for 40–50 % (60–70 %) of the annual precipitation in South (North) China (GONG, 2007). Any process disturbing the normal seasonal advance or retreat of the monsoon rainbelt would lead to deficient or excessive precipitation, and hence influence the economy and so-

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ciety of this region. For example, anomalous monsoon activity in the summer of 1998 led to serious flooding along the Yangtze River valley and caused an economic loss of about 31 billion USD in China (HUANG et al., 2007).

Variations of the EASM during the 20$^{th}$ century have been an active topic in the climate research community in China. Great efforts have been devoted to understanding the long term variability (i.e. variability throughout the 20$^{th}$ century) and interdecadal variability (referring to the last 50 years) of the EASM, partly due to the interdecadal scale climate transition or regime shift that occurred around the late 1970s, which exhibited as a trend toward increasing drought in North China and excessive rainfall in South China along the Yangtze River valley (27°N–32°N, 100°E–120°E) (HU, 1997; XU, 2001). Associated with this regime shift, the linkage between the EASM and ENSO has been strengthened (WANG et al. 2008a). While the mechanisms responsible for this transition are still disputable, the extent to which the multi-decadal variability in the EASM can be attributed to global warming has been a focus in both the scientific community and society. A creditable explanation must rely heavily on the datasets. The trend of rainfall derived from data representing a limited length of time (e.g., 50 years) should be considered cautiously, since it is possible that the trend may indeed reflect a natural phase transition in the multi-decadal variability. Much progress in detecting and understanding multi-decadal variability of the EASM during the 20$^{th}$ century has been made in recent years. The main motivation of this paper is to summarize and comment briefly on achievements in this field. Note that we only focus on the multi-decadal variability of the EASM during the 20$^{th}$ century, a period with relatively reliable observations. Historical studies of the pre-20$^{th}$ century variability are not included in this review.

The rest of the paper is organized as follows. In section 2, we review the long-term change of monsoon rainfall on an observational basis. In section 3, we describe the basic characteristics of the EASM, including the seasonal evolution of precipitation and circulation over East Asia, the definition of the EASM and its evolution during the 20$^{th}$ century. In section 4, after describing the phenomenon of multi-decadal variability, we summarize the proposed mechanisms responsible for the weakening tendency/multi-decadal transition of the EASM starting in the late 1970s. Future changes of the EASM are discussed in section 5. Some concluding remarks are given in section 6.

## 2 Observational basis

The amount of precipitation is the most direct measure of monsoon activity. Quality-controlled operational instrumental measurements of precipitation only began in 1950 in China, and the most commonly used precipitation dataset in the study of the EASM is from the China Meteorological Administration. This reliable dataset consists of the monthly precipitation at 160 stations covering the period from 1951 to the present (e.g., HU et al., 2003; ZHOU and YU, 2005). The spatial coverage for longer time precipitation observations in China is limited. By blending instrumental measurements and historical documentary records of various sources, WANG et al. (2000) developed a precipitation dataset extended back to 1880. It consists of 35 stations distributing evenly in eastern China between 25°N and 45°N, and 105°E and 125°E (see Table 7.20 of WANG and LI (2007) for the list of 35 stations). Prior to 1951, because about 31.0 % (77.4 %) of stations were missing in the instrumental measurements for the period 1900–1950 (1880–1899), documentary and category data were used to fill the gaps (WANG et al., 2000). This dataset was recently expanded to 71 stations (WANG et al., 2009, hereafter referred to as the Wang dataset). As shown in Table 1, the number of stations with instrumental measurements changes with time. Uncertainties in the dataset come from inhomogeneities related to changes of instruments and observation methods, changes in the observational environment, and transformation methods for using documentary evidence. Although there are uncertainties in the dataset, it provides a useful estimate for the changes in precipitation over eastern China starting from the early stage of the 20$^{th}$ century. WEN et al. (2006) compared the annual mean precipitation anomalies over eastern China derived from the Wang and Climatic Research Unit datasets (WANG et al., 2002; GE et al., 2007; MITCHELL and JONES, 2005) and found a high consistency. The correlation coefficient between the two datasets during the 20$^{th}$ century is 0.88, which is statistically significant at the 1 % level. The major droughts in the 1920s and the 1940s described in the Chinese literature and journals were identified well in the both datasets. The annual mean precipitation over China exhibits decadal oscillations, and no long-term trend is found during the 20$^{th}$ century (WANG et al., 2002; GE et al., 2007). There also exists no long-term trend in the time series of precipitation averaged over eastern China (east of 105°E). However, there is a slight increase in the annual mean precipitation averaged over China for the period 1951–2001, with 1998 being the wettest year (REN et al., 2005).

The above analyses focused on the precipitation averaged over all of continental China. It should be noted that the EASM has complex space and time structures that encompass the tropics, subtropics, and midlatitudes; it is difficult to describe the complex rainfall structure simply with a regional average of precipitation (WANG et al., 2008c). The precipitation variability between North China and the Yangtze River valley often has an opposite phase, e.g. while North China has deficient precipitation, the Yangtze River valley usually has excessive precipitation, and vice versa (WANG, S.W. et al., 2005).

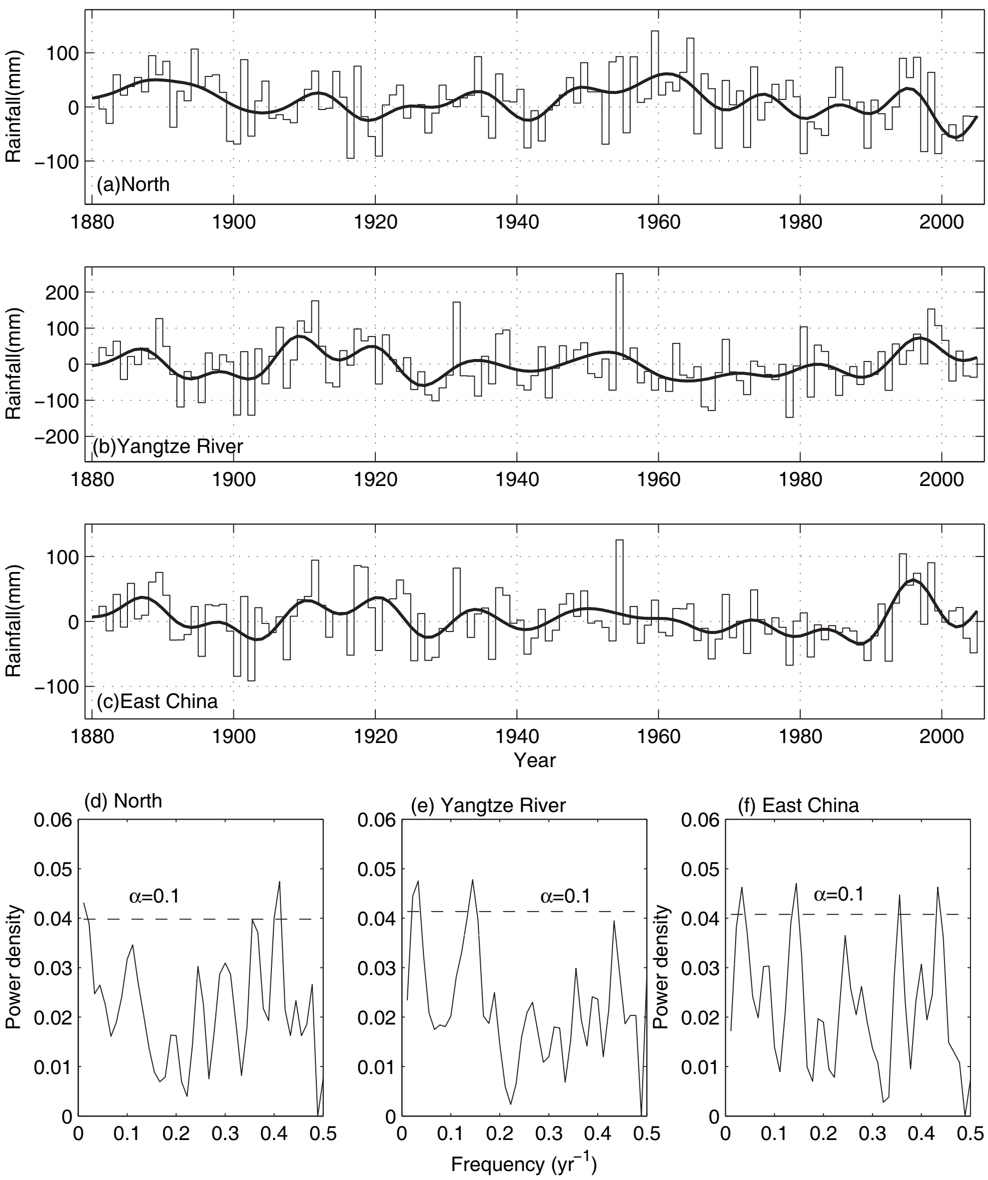


**Figure 1:** Time series of mean summer precipitation anomalies over (a) the northern China (between 35°–45°N, east of 100°E), (b) the Yangtze River valley (between 25°–35°N, east of 100°E), (c) the eastern China (east of 100°E), and corresponding power spectral analyses (d, e, f). The smoothed lines in figures a–c are low-frequency variations from 10-year filters. All anomalies are with respect to the reference period of 1971–2000. The analysis is based on the data for 71 stations located in eastern China. (Redrawn after GONG, 2007).

**Table 1:** Number of stations at which instrumental measurements are available (after WANG et al., 2009).

| Year | 1881 | 1891 | 1901 | 1911 | 1921 | 1931 | 1941 | 1951 |
|---|---|---|---|---|---|---|---|---|
| Number of stations for temperature | 2 | 5 | 12 | 26 | 36 | 47 | 66 | 160 |
| Number of stations for precipitation | 4 | 13 | 18 | 32 | 45 | 54 | 67 | 160 |

What about the long-term changes of precipitation in North China and South China? GONG (2007) examined the 20$^{th}$ century variations of rainfall averaged over northern China, the Yangtze River valley, and all of eastern China (WANG and LI, 2007). The results are redrawn in Figure 1, along with a statistical analysis of the trends in regional precipitation time series for the different time periods listed in Table 2. While remarkable interannual and decadal variations are evident in both time series, no significant long-term trend across all of the 20$^{th}$ century was found, signifying no increase in the EASM rainfall in response to the warming of the 20$^{th}$

century. In addition, WANG et al. (2006) analyzed the precipitation data for Seoul, in South Korea, recorded since 1778. They calculated the trends for 1778–2004, 1900–2004, and 1950–2004 and found that a real trend has occurred only in the recent 55 years. Given the concurrent change of summer rainfall between Seoul and the Yangtze River valley in the present climate (WANG et al., 2006), the consistency of WANG et al. (2006) with GONG (2007) in the insignificant long-term trend over the $20^{\text{th}}$ century is reasonable. Note that the spectral analysis reveals significant decadal scale oscillations of the time series averaged in the Yangtze River and East China (Figure 1d–f).

# 3 Basic Characteristics of the EASM

## a) Seasonal evolution of precipitation and circulation over East Asia

The long-time change of the EASM can be measured by either precipitation or circulation indices. A basic description of the EASM is helpful in understanding the monsoon index definition. The EASM rainfall structure and circulation system are shown in Figure 2 as a combination of wind vectors at 850 hPa, geopotential height at 500 hPa (hereafter Z500), and precipitation rate. The circulation data are from ERA40 (UPPALA et al., 2005), while the precipitation data are from CMAP (XIE and ARKIN, 1996). The Z500 is representative of the western Pacific subtropical high (hereafter WPSH), which dominates the seasonal migration of the monsoon rain band. The ridge line of the WPSH, defined as $u = 0$ and $\frac{\partial u}{\partial y} > 0$, is also shown. The northern edge of the 3 mm/day precipitation rate is a simple but useful indicator of the seasonal monsoon rainband migration. One prominent feature of the EASM is the precipitation concentration in an east-west-elongated rainbelt, which affects China, Japan, Korea, and the surrounding seas. The seasonal transition of the monsoon rain band is closely related to the seasonal change of large-scale circulations. The seasonal march of the EASM displays a stepwise northward and northeastward advance. During the period from early May to mid May, the ridge line of the WPSH is located along 15°N, and southern China experiences a pre-monsoon rainy season (Fig. 2a). Then, the WPSH exhibits two northward jumps in June and July with the ridge line located at 20°N and 25°N, respectively (Fig. 2b–c). Corresponding to the northward jumps of WPSH, the monsoon rain band extends abruptly from the Indochina Peninsula – the South China Sea – from the Philippines to the Yangtze River valley in early to mid June (Fig. 2b), and the Meiyu (or Baiu in Japan and Changma in Korea) begins. The monsoon penetrates into northern China (34°–41°N) in mid July (Fig. 2c), and the monsoon rainy season there lasts for one month and ends in early-middle August. The ridge line of the WPSH is located along 28°N in August (Fig. 2d). The retreat of the monsoon is faster than its advance, viz. from the end of August to early September, the monsoon rainbelt retreats rapidly back to South China (TAO and CHEN, 1987; DING and CHAN, 2005). The complex seasonal migrations of monsoon rainfall and circulation make it difficult to measure the monsoon intensity with a simple index.

## b) Definition of the EASM and its evolution during the 20th century

Methods for defining the strength of the EASM have been controversial. Unlike the Indian summer monsoon, which can be defined in terms of simple scalar indices partly due to its homogeneity in rainfall distribution, it is more complicated to define an index for the EASM (WANG and FAN, 1999; WU et al., 2008). WANG et al. (2008c) discuss the meanings of 25 existing EASM indices and classify these indices into five categories: the east-west thermal contrast, north-south thermal contrast, the shear vorticity of zonal winds, the southwesterly monsoon, and the South China Sea monsoon. The relationships of these indices with El Nino have been documented in detail in WANG et al. (2008c). Although the existing indices highlight different aspects of the EASM, they agree well in the traditional Chinese meaning of a strong EASM, viz. an abnormal northward extension of the southerlies into North China. The associated precipitation anomaly appears as excessive rainfall in North China along with a deficient Meiyu in the Yangtze River valley. WANG et al. (2008c) argue that since the traditional definition is inconsistent with the meaning used in other monsoon regions, where abundant rainfall within the main rain-bearing monsoon system is regarded as a strong monsoon, thus a new index reversing the traditional Chinese meaning is recommended. To facilitate our review of the previously published literatures, we here employ the conventional concept of a strong summer monsoon. This choice may be not perfect, as discussed by WANG et al. (2008c), but the results of multidecadal variability presented subsequently in this paper do not depend on this choice.

Precipitation is the most direct but not the most reliable measure of the monsoon, partly due to its sparse spatial coverage. The short data length also makes it difficult to quantify long-term changes of the monsoon with precipitation. The better quality and larger sample size of sea level pressure (SLP) datasets provide another opportunity for measuring the long-term change of monsoon intensity. Since the EASM is driven by the land-sea thermal contrast, GUO (1983) defined an EASM index as the summation of the SLP gradient between the land (110°E) and the sea (160°E) from 10°N to 50°N (hereafter the Guo index). This is the most widely used index in EASM studies (e.g., WANG and LI, 2007; ZHOU et al., 2008a). The Guo index derived from NCEP/NCAR reanalysis (KALNAY et al., 1996) is shown in Figure 3,

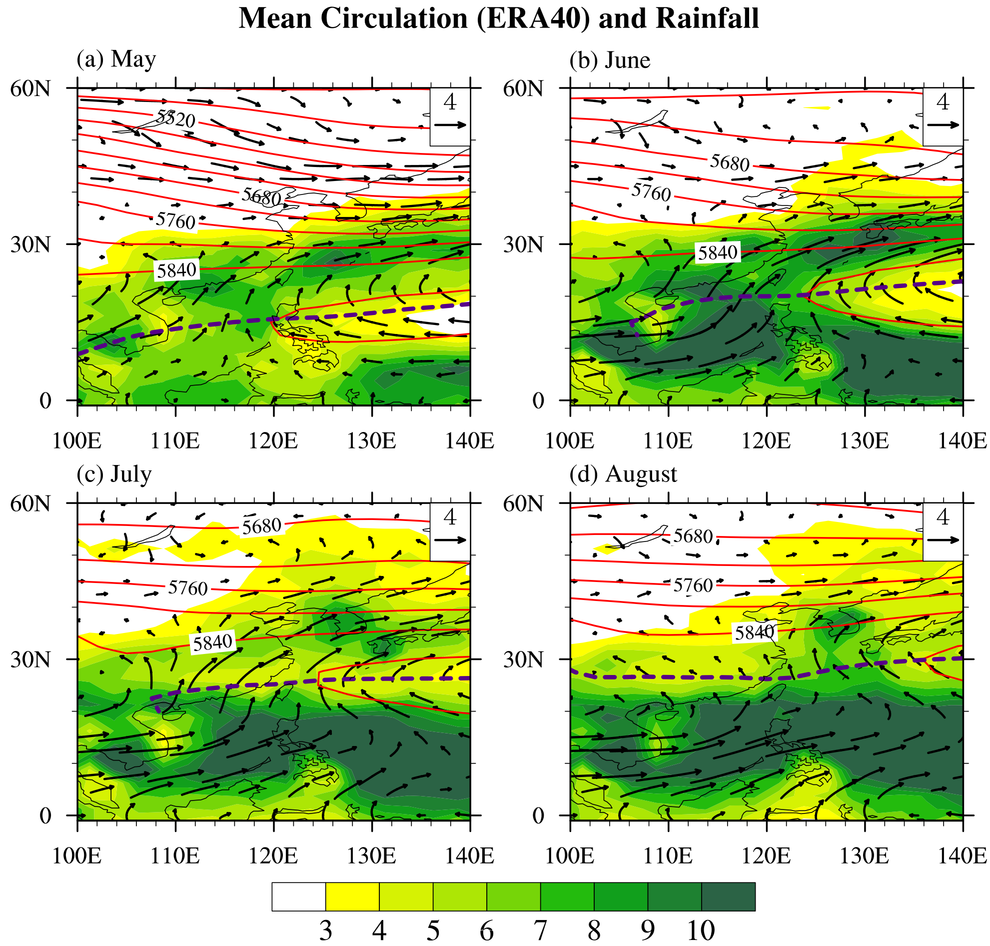


**Figure 2:** Climatological mean 850 hPa winds (arrows in units of m/s), 500 hPa geopotential height (contours in units of gpm), and precipitation rate (color shading in units of mm/day) for (a) May, (b) June, (c) July, and (d) August. The ridge line of WPSH is denoted as a dashed blue line. The circulation data used are derived from ERA40. The precipitation data used are derived from CMAP. All of the figures are for the average of 1979–2002.

**Table 2:** Linear trends in regional precipitation for different time periods (Units: mm/10yr). *significant at the 5 % level.

| | North China | Yangtze River | East China |
|---|---|---|---|
| 1880-2005 | -1.9 | -0.8 | -0.9 |
| 1920-2005 | -2.0 | +2.7 | +0.0 |
| 1951-2005 | -11.4* | +7.1 | +1.5 |
| 1951-1979 | -8.7 | -22.5 | -10.5 |
| 1980-2005 | -0.4 | +13.8 | 16.3 |

along with a graphical illustration of the rainfall conditions during years of a strong/weak monsoon based on the Guo index. A threshold of one standard deviation is used to derive strong or weak monsoon years. We chose 10 typical strong monsoon years (1953, 1954, 1957, 1958, 1959, 1960, 1961, 1962, 1963, 1964) and five typical weak monsoon years (1980, 1986, 1991, 1996, 1997) during the period 1951–2000. The composite rainfall anomalies relative to the climatology of 1951-2000 are shown in Figure 3b–c. The summer precipitation composites for years with a high/low Guo index are consistent with the conventional definition of the EASM, viz. a stronger EASM is characterized by excessive rainfall in North China but deficient rainfall in South China along the Yangtze River valley.

To reveal the evolution of the EASM during the 20$^{th}$ century, the Guo index was expanded to cover the long time period of 1873–2000 (GUO et al., 2004). Based on the definition of GUO (1983) but using the newly developed Hadley Centre SLP dataset version 2 (ALLAN and

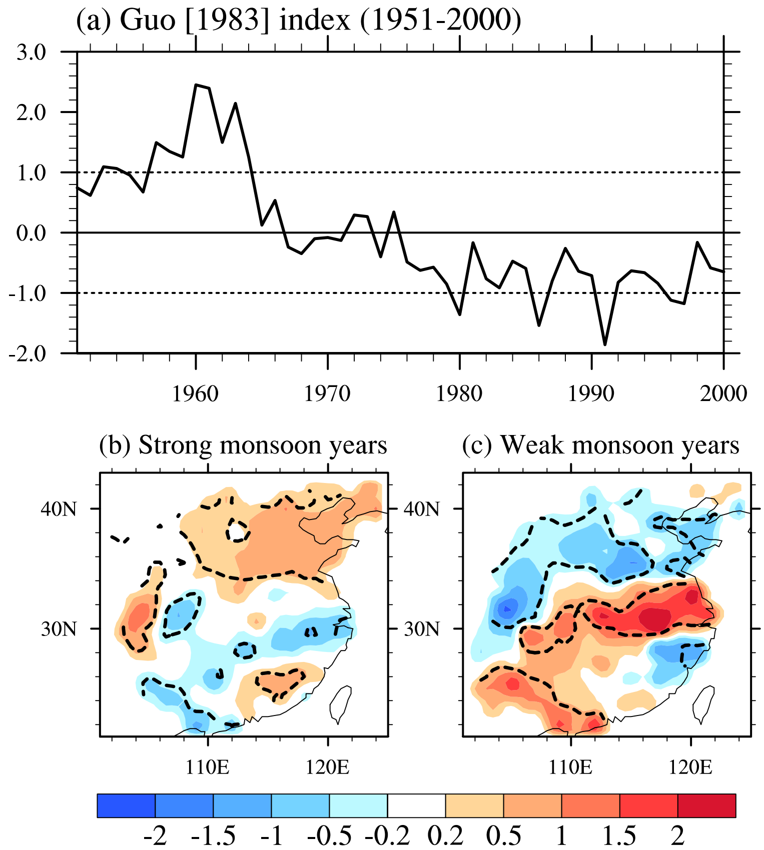


**Figure 3:** (a) Normalized JJA EASM index derived from NCEP/NCAR reanalysis based on Guo (1983). The composite JJA rainfall anomalies are associated with (b) strong and (c) weak EASM indices shown in Figure a. The rainfall anomalies are based on 160 stations data provided by the China Meteorological Administration (in units of mm/day). The black dotted line in Figure b–c denotes a statistically significant test at the 5 % level based on a student-t test.

Ansell, 2006), the index covering a longer period of 1850–2004 was given in IPCC AR4 (Trenberth et al., 2007). As shown in Figure 4a, the long-term variation of the EASM features a weak early state from 1885–1905. There is a broad maximum from the 1920s through the 1930s and from the 1950s to the 1970s, and a decreasing trend from the late 1970s to the present. Although there exists a slight weakening trend from the 1920s to the present, it is not reflected in the longer record extending back to the 1850s. So there is no significant long-term trend in the observed EASM index during the whole 20$^{th}$ century, which is consistent with the long-term precipitation record in northern and southern China shown in Figure 1. A further examination of the secular trends of Figure 1 found that since the 1920s, summer precipitation has been slightly decreasing in North China (–2.0mm/10yr), but increasing along the Yangtze River valley (2.7 mm/10yr) (see Table 2), which is consistent with the conventionally accepted concept that a weaker monsoon is accompanied by a wetter-south-and-drier-north rainfall pattern.

In addition, there are evident decadal changes in the last couple of decades, particularly since the late 1970s. This is evident in both the Guo index (Figure 4a) and rain-gauge observations (Figure 4b). Associated with the weakening tendency of the EASM in the past 50 years, the trend of JJA precipitation exhibits a typical "South-Flood-North-Drought" pattern in eastern China (Figure 4b). An analysis of the trend of Figure 1 also reveals that the precipitation in North China has been decreasing (–0.4 mm/10yr during 1980-2005, –11.4 mm/10yr during 1951–2005) while in South China along the Yangtze River has been increasing (+13.8mm/10yr during 1980–2005, +7.1 mm/10yr during 1951–2005) (Table 2), which agrees with the concurrent weakening of monsoon circulation shown in Figure 4a. The underlying mechanisms are discussed in the following section.

## 4 Interdecadal transition of the EASM

### a) Description of the phenomenon

The monsoon index presented above indicates many significant inter-decadal oscillations during the 20$^{th}$ century. The most recent reduction of the EASM strength started at the end of 1970s. Following this weakening tendency, the northward penetration of the southerlies

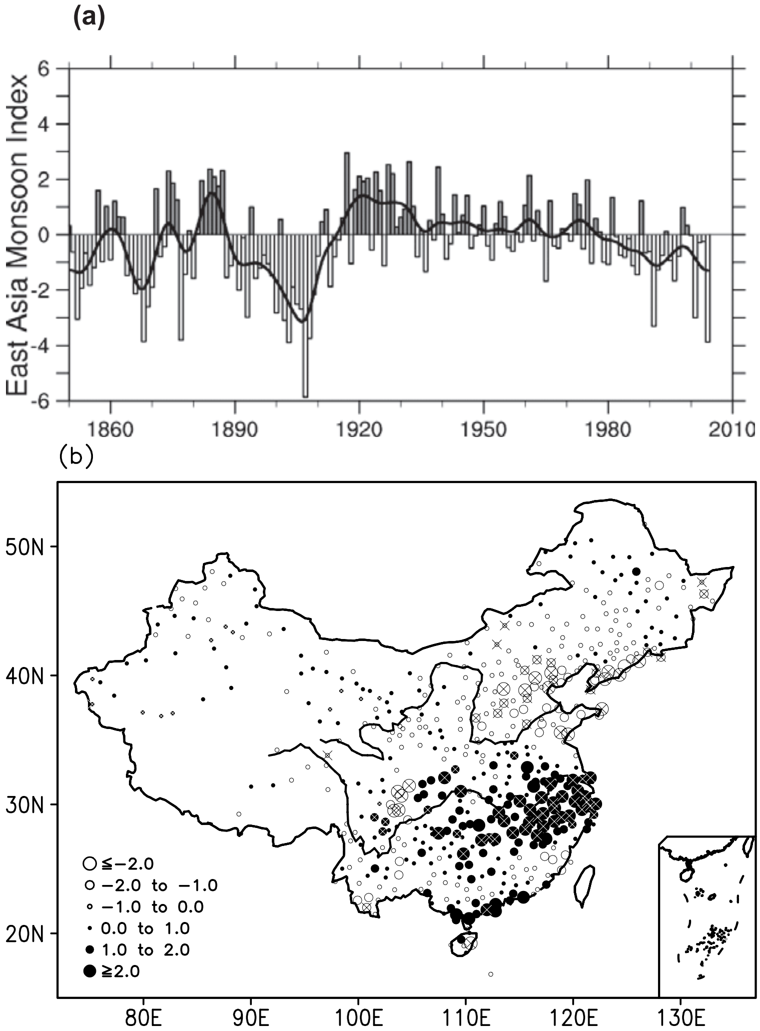


**Figure 4:** a) East Asian summer monsoon index derived from MSLP gradients between the land and ocean in the East Asia region. The definition of the index is based on GUO et al. (1983) but was recalculated based on the HadSLP2 (ALLAN and ANSELL, 2006) dataset. The smoothed black curve shows the decadal variations (after TRENBERTH et al., 2007, Figure 3.35 of IPCC AR4). (b) Trends of JJA mean precipitation during 1958–2003 based on rain-gauge data provided by the China Meteorological Administration (mm/day/50yrs). A cross denotes that the trend is statistically significant at the 5 % level.

over East Asia has declined, and a significant precipitation trend is recognized (Figure 4b). We focus on this interdecadal scale transition in the following discussions. Other interdecadal scale transitions will not be discussed due to the limitation of reliable data length. Recent studies demonstrate that the 1970s interdecadal climate transition is a local manifestation of the Northern Hemispheric climate transition that occurred in the late 1970s (TRENBERTH and HURRELL, 1994; WANG and DING, 2006; ZHOU et al., 2008b, c) rather than a regional phenomenon (YU et al., 2004; YU and ZHOU, 2007; ZHOU and ZHANG, 2009). Over Asia, some prominent features of the interdecadal climate transition include:

1) The precipitation anomaly is dominated by a "Southern China flood and northern China drought" pattern (HU, 1997; WANG, 2001; ZHAI et al., 2005). In addition to the rainfall amount change, the frequency of precipitation and of extreme precipitation and the intensity of torrential rain have significantly increased along the Yangtze River valley and clearly decreased in North China (LI et al., 2008a).

2) The summer monsoon precipitation has increased in a southwest-northeast oriented belt from the middle-to-lower Yangtze River valley across the East China Sea and South Korea to northern Japan (Meiyu/Baiu rainbelt); meanwhile, rainfall has decreased to the north and south of the enhanced Meiyu/Baiu rainbelt, appearing as a "sandwich" shape (WANG et al., 2006);

3) A decadal scale westward extension and intensification of the western Pacific subtropical high is observed (HU, 1997; GONG and HO, 2002);

4) The South Asian High, which is a persistent subtropical anticyclone controlling the free atmosphere over Asia during the boreal summer (TAO and CHEN, 1987), has experienced an expansion in zonal coverage (ZHANG et al., 2000);

5) A strong tropospheric cooling trend over East Asia during July and August, which is most prominent in the upper troposphere around 300 hPa, is found (YU et al., 2004; ZHOU and ZHANG, 2009);

6) There is a potential change of the East Asian westerly jet. While an enhancement of the westerly south to the climatological axis of the jet is found during 1958-2001 (YU et al., 2004; YU and ZHOU, 2007), a global study of ERA40 and NCEP/NCAR reanalysis data by ARCHER and CALDEIRA (2008) points to a northward trend in the jet-stream position in 1979–2001. Another study about the variability of the westerly jet in the Tibetan Plateau region based on ERA-40 reanalysis data did not find a trend in the dates of the seasonal transition of the jet between the north and south sides of the plateau (Schiemann et al., 2009).

7) The "southern China flood and northern China drought" or a broader scale "sandwich-like" rainfall pattern also stands out in the late springtime, except for the meridional locations of the anomalous rainfall centers different from that in the summer (XIN et al., 2006);

8) The EASM precipitation change is part of a long-term change of global land monsoon precipitation, which shows a decreasing tendency in the past half-century (WANG and DING, 2006; ZHOU et al., 2008b, c).

## b) Suggested mechanisms

Based on the above proceedings, it is becoming clearer that the EASM weakening tendency is a large-scale rather than regional climate feature; however, the mechanisms responsible for this transition are not yet fully understood. Different physical explanations have been put forward. We summarize the suggested potential contributors below.

## 1) Tropical Ocean warming

The WPSH plays a major role in modulating the weather and climate over East Asia. The low-level jet along the northwestern edge of the WPSH transports a large amount of water vapor into East Asia (ZHOU and YU, 2005). Associated with the interdecadal scale climate transition, the WPSH has extended westward since the late 1970s, which reduces the water vapor to North China from the South China Sea and thus contributes to the observed rainfall changes there (CHANG et al., 2000; HU et al., 2003; ZHOU and HUANG, 2003; YANG and LAU, 2004). Since 1977, tropical SSTs (sea surface temperatures) have increased significantly in the Indian Ocean and far western Pacific (IWP) relative to the period 1950-1976 (DESER and PHILLIPS, 2006). A number of studies have investigated the influence of tropical convection in the Indian Ocean/Western Pacific (in particular the IWP region) on Central/South Asia and the Tibetan Plateau region (e.g., BARLOW et al., 2002, 2005, 2007; HOERLING and KUMAR, 2003; SCHIEMANN et al., 2007). The influence of the Indian and Pacific Oceans on the EASM inter-annual variability has also been discussed in many previous studies (e.g., LAU et al., 2006; LIU et al., 2008; WU and ZHOU, 2008; WU et al., 2009; XIE et al., 2009). Analysis has suggested that the decadal westward extension of the WPSH may be due to the changes of SST and convective activity over the tropical Indian Ocean and far western Pacific (HU, 1997; GONG and HO, 2002). Coordinated by the European Union Framework 6 project "understanding the dynamics of the coupled climate system" (DYNAMITE), five AGCMs were forced by identical idealized SST patterns representative of the IWP warming and cooling (ZHOU et al., 2009a). The results of numerical experiments suggest that the negative heating in the central and eastern tropical Pacific and increased convective heating in the equatorial Indian Ocean/maritime continent associated with IWP warming support westward extension of the WPSH. The model results suggest that the SST changes in the IWP influence the Walker circulation, with a subsequent reduction of convection in the tropical central and eastern Pacific, which then forces an ENSO/Gill-type response that modulates the WPSH. The monsoon diabatic heating mechanism proposed by RODWELL and HOSKINS (1996) plays a secondary reinforcing role in the westward extension of the WPSH (ZHOU et al., 2009a). The low-level equatorial flank of the WPSH is interpreted as a Kelvin response to monsoon condensational heating, while the intensified poleward flow along the western flank of WPSH fits with the Sverdrup vorticity balance. The IWP warming has led to an expansion of the South Asian High in the upper troposphere, as seen in the NCEP/NCAR reanalysis (ZHANG et al., 2000). Analysis of the output from a global SST-driven AGCM simulation also demonstrates the contribution of recent warming in the North Indian Ocean and around the South China Sea to the WPSH and hence to the monsoon rainfall change (ZENG et al., 2007).

Tropical ocean warming is not limited to the IWP domain. The period from the 1970s to the 1990s coincides with a rise in SST of about 0.8°C in the equatorial central-eastern Pacific (ZHANG et al., 1997). Examinations of the long-term change in global land monsoon rainfall using rain-gauge precipitation datasets compiled for the period 1948–2003 suggest an overall weakening of the global land monsoon precipitation, primarily due to weakening of the summer monsoon rainfall in the Northern Hemisphere (WANG and DING, 2006). The weakening tendency of the EASM is part of the global land monsoon rainfall change (ZHOU et al., 2008b). When forced by historical SST covering the same period, the ensemble simulation with the NCAR CAM2 model successfully reproduced the weakening tendency of global land monsoon precipitation (ZHOU et al., 2008c). This decreasing tendency was mainly caused by the warming trend over the central-eastern Pacific and the western tropical Indian Ocean (ZHOU et al., 2008c). However, the reproduced signal in East Asia monsoon rainfall is low, partly due to the neglect of air-sea feedback in the SST-specified simulation (WANG, B. et al., 2005).

Since precipitation simulation is the most rigorous test for climate models, analysis of atmospheric circulation changes is an essential prerequisite for understanding precipitation variations. LI et al. (2008b) analyzed the ensemble runs from 1950–2000 by two different AGCMs, namely NCAR CAM3 and GFDL AM2.1, forced separately by observed tropical SSTs and global SSTs. They found that the observed SST forcing, primarily from the tropics, including both the Pacific and the Indian Ocean, can induce most of the observed circulation changes associated with the weakening of the EASM since the 1970s. The simulated EASM circulation changes from runs forced separately with global and tropical SSTs are comparable, and the simulated EASM indices have similar variations that are correlated with the observed Pacific Decadal Oscillation index. These results, combined with previous studies (e.g., DESER et al., 2004; DESER and PHILLIPS, 2006), suggest that the recent warming over tropical oceans, especially those associated with the tropical interdecadal variability centered over the central and eastern Pacific, has played a major role in the weakening of the EASM during the recent decades. However, despite the reasonable simulations of the observed circulation changes, the two AGCMs failed to reproduce the relatively small-scale rainfall change patterns over East China, suggesting that a realistic simulation of the EASM rain-belt and its decadal change remains a challenge to current state-of-the-art global climate models.

## 2) Forcing of the Tibetan Plateau

An analysis of the surface air temperature averaged over 90 weather stations of Tibetan Plateau (TP) found a coherent warming trend, with an increase of about 1.8°C over the past 50 years (WANG et al., 2008b). Numerical experiments with the ECHAM4 model driven by a reduction in albedo representing a surface TP warming show that the atmospheric heating induced by the rising TP temperatures has enhanced the East Asian subtropical frontal rainfall (WANG et al., 2008b). However, the specified TP warming in the model has led to a strengthening of the low-level southwesterly monsoon flow, rather than a weakened southwesterly flow as found in the observation. Whether this controversial response is due to the mean state shift of the model deserves further study. Recently, DUAN and WU (2008) argued that although both the surface and the troposphere over the TP have a warming tendency, the sensible heat (thereafter SH) flux over the TP exhibits a significant decreasing trend. The largest trend occurs in spring, the season with the highest SH over the TP. The weakening SH is induced mainly by the decreased surface wind speed. Since sensible heating of the TP can intensify the EASM by inducing air pumping over the plateau (WU et al., 2007), the weakened heat source over the TP may partly contribute to the EASM weakening.

The long-term change of snowfall over the TP may also affect the EASM via sensible heating. The snow-monsoon relationship has been discussed in many previous studies (e.g., LIU and YANAI, 2002; WU and KIRTMAN, 2007; also see HUANG et al., 2007 for a review). ZHANG et al. (2004) found a close relationship between the interdecadal increase of snow depth over the TP during March-April and wetter summer rainfall over the Yangtze River valley. The sharp increase of springtime snow depth over the TP after the late 1970s has led to reduced surface sensible heating over the TP, as more solar energy is consumed to melt the increased snow cover. The weakened heating results in a more intense and westward extension of the WPSH, which in turn enhances the Meiyu fronts and thereby increases summer rainfall in the Yangtze River valley. ZHANG et al. (2004) suggested that the enhanced coupling between the SST warming in the northern Indian Ocean/maritime continent and the tropical convective maximum is responsible for the increased springtime snowfall over the TP.

## 3) Aerosol forcing

Some studies speculate that man-made absorbing aerosols in remote populated industrial regions may alter the regional atmospheric circulation and contribute to regional climate change (QIAN and GIORGI, 1999; XU, 2001). MENON et al. (2002) used an AGCM to investigate possible aerosol contributions to the climate changes over Asia. They found precipitation and temperature changes in the model that were comparable to those in observation if the aerosols included a large proportion of absorbing black carbon (BC). The specified aerosols heat the air and alter the regional atmospheric stability and vertical motions, thus affect the regional monsoon rainfall. However, the simulated cloud change is contrary to the observation. The result of MENON et al. (2002) was recently argued by LI et al. (2008b), who analyzed the output of CAM3 runs forced by the IPCC time-varying atmospheric forcings (primarily greenhouse gases plus the direct effect of aerosols, including BC). They found that the specified atmospheric forcings can increase the summer land-ocean temperature contrast and thus enhance (rather than weaken) the EASM circulation. A similar enhanced EASM response is also evident in another independent model experiment (LI et al., 2007). Hence, the current understanding of the regional climate effects of aerosols, including black carbon, is extremely controversial.

The above studies are based on stand-alone AGCMs. Many studies have demonstrated the importance of the air-sea coupling in modeling the EASM variability (e.g., WANG, B. et al., 2005; ZHOU et al., 2009b). MEEHL et al. (2008) analyzed a six-member ensemble of twentieth-century simulations with time-evolving global distributions of BC aerosols in a global coupled climate model to study the effects of BC aerosols on the Asian monsoon. Since there is disagreement in sign over southern China between the observed and the multiple-forcing modeled precipitation trends for the summer monsoon season, they suggest that the EASM changes may not be related to changes in aerosol forcing and perhaps be linked to the inherent decadal time-scale variability. A further analysis of single ensemble members suggests that the rainfall change over China appears to be associated with natural variability connected to surface temperature changes in the northwestern Pacific (MEEHL et al., 2008).

### 4) Internal variability

Internal variability has been suggested as one mechanism for the recent EASM weakening trend. Based on a reconstruction of the summer rainfall record for the last 500 years in China, WANG et al. (1981) found a dominant 80-year variability. ZHU and WANG (2002) found a distinct 80-year oscillation of summer rainfall over North China (near 35°–40°N and east of 110°E), the southern part of Northeast China (south of 42°N in Northeast China), the lower-middle Yangtze River valley (east of 110°E) and South China (south of 25°N and east of 110°E). Observational analyses reveal a weak monsoon index before the 1910s, a stronger monsoon index from 1910 to 1970, with the 1930s and 1940s having the maximum intensity, and a weakening monsoon since the late 1970s (GONG and HO, 2003; ZHAO et al., 2005). DING et al. (2007a, b) stated that the recent weakening tendency of the EASM may be one phase of the quasi-80-year oscillation.

## 5 Future change of the EASM

Coupled ocean-atmosphere models have been useful tools for climate projections. Multi-model ensemble scenario projections of future climate indicate an increased monsoon rainfall over eastern Asia due to enhanced moisture convergence under the warmer climate, despite a tendency towards weakening of the monsoonal flows themselves (CHRISTENSEN et al., 2007). Since long-term records of the EASM do not show any significant increase across the whole 20$^{th}$ century in response to global warming, there is a mismatch between the climate models, where significant warming brings significant increases in monsoon precipitation, and the real world, where actual observational data suggest that this is not the case. This mismatch does not support the idea of attributing the declined EASM to global warming. It should be noted that uncertainties in global model precipitation projections may be partly due to the low resolution (e.g., GAO et al., 2006, 2008).

Although many global climate models project an enhanced summer rainfall in the East Asian region, limitations of the current state-of-the-art coupled climate models in simulating spatial patterns of the present climate cast shadow on their capability for projecting credible geographic distributions of future climate change through IPCC scenario simulations. For example, JIANG et al. (2004) analyzed an ensemble of six coupled models and found a stronger EASM with increased rainfall in North China in the future warming climate. KRIPALANI et al. (2007) analyzed the coupled model simulations and projections under IPCC AR4 and only found a significant increase over Korea and Japan and the adjoining northern China region. ZHOU and YU (2006) examined variations of the surface air temperature (SAT) simulated by nineteen coupled climate models driven by historical natural and anthropogenic forcings under IPCC AR4. Most models perform well in simulating both the global and the Northern Hemispheric mean SAT evolutions. However, there are discrepancies between the simulated and observed regional features of the SAT trend over eastern Asia. Since the monsoon is dominated by the land-sea thermal contrast, a large spread is also evident in the precipitation responses among the CMIP3 models consistent with the deficiencies in the SAT simulations. The tremendous uncertainties among the models in precipitation simulations make it difficult to link the EASM precipitation variations to global warming (HU et al., 2003).

## 6 Concluding remarks

The potential changes of the EASM associated with global warming are of great scientific and societal importance, because monsoons determine essential features of the East Asian climate. Examinations of the EASM precipitation and circulation index covering the whole 20$^{th}$ century found no significant trend, indicating the pronounced rainfall deficit in North China associated with the weakening tendency of the EASM in recent decades may be unprecedented. Although the proposed mechanisms and model simulations shown above may explain some of the features of the recent EASM weakening tendency, now it is still difficult to present a complete explanation of the observed changes. The weakening of the summer monsoon over East Asia is a three-dimensional large-scale circulation change through the deep troposphere, including the upper troposphere temperature change (YU et al., 2004). The weakening of the EASM is part of an interdecadal climate transition existing throughout the year with robust signals in the spring and summer (YU and ZHOU, 2007). While the separately specified forcings to climate models do partly reproduce some observational features, it is still difficult to reasonably reproduce all of these large-scale changes. Hence, identifying the causes of the monsoon weakening remains elusive and requires further investigation.

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