ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 32, FEBRUARY 2015, 206–229

Recent Advances in Monsoon Studies in China

XUE Feng*, ZENG Qingcun, HUANG Ronghui, LI Chongyin, LU Riyu, and ZHOU Tianjun

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

(Received 2 June 2014; revised 3 August 2014; accepted 23 August 2014)

ABSTRACT

This review provides a synopsis of the major progress that has been made in monsoon studies in China and to further bridge the gap between the Chinese and international meteorological community. It consists of seven major sections. After the introduction, the second section begins with the global monsoon systems and their seasonal variation, based on some new methods proposed in recent years. Besides, some major intraseasonal features of East Asian monsoon, including the onset of South China Sea summer monsoon are discussed. In the third section, we review the interactions between ENSO and the East Asian monsoon, focusing in particular on the results of Chinese meteorologists that indicate the influence of ENSO on the East Asian summer monsoon (EASM) is obviously different from that on the tropical monsoon. Besides the tropical Pacific, other ocean basins, such as the Indian Ocean and the Atlantic Ocean, are also important to the East Asian monsoon, and this topic is discussed in the fourth section. In the fifth section, we address the role of land surface processes in East Asian monsoon. For example, we describe work that has shown more snow cover in spring on the Tibetan Plateau is followed by a weakened EASM and more summer rainfall in the Yangtze River valleys. The sixth section focuses on the influence of atmospheric circulation in the Southern Hemisphere (SH) on EASM, demonstrating how the signal from the SH is likely to provide new clues for the seasonal forecasting of summer rainfall in China. Finally, in the seventh section, we concentrate on the interdecadal variations of EASM. In particular, we look at a significant interdecadal variation that occurred at the end of the 1970s, and how our understanding of this feature could affect forecasting ability.

Key words: East Asian monsoon, global monsoon system, ENSO, interannual variability, interdecadal variability

Citation: Xue, F., Q. C. Zeng, R. H. Huang, C. Y. Li, R. Y. Lu, and T. J. Zhou, 2015: Recent advances in monsoon studies in China. *Adv. Atmos. Sci.*, **32**(2), 206–229, doi: 10.1007/s00376-014-0015-8.

1. Introduction

China is located in the East Asian monsoon region. Climate anomalies in China, especially in the eastern part of the country, are significantly affected by the East Asian monsoon. China's socio-economic dynamics are severely affected by climate disasters, such as droughts, floods and cold surges, due to the large variability of the East Asian monsoon. It is estimated that the damages and losses (e.g. the property) caused by such disasters amounts to 3%–6% of the total gross domestic product of China. The advance and retreat of this monsoon, especially the summer monsoon, plays a role in the weather and climate of China. Because it affects agricultural production, the monsoon has been noted since the time of the ancient Chinese. Based on textual research, Zeng (2005) proved that the world's first literature on the monsoon was recorded in the "Grand Stories" written by the great historian SIMA Qian (145 BC–87 BC). King SHUN's poem "Southerly Wind" was written for singing around the 22nd to 23rd centuries BC. The poem very concisely yet poignantly describes the major features of the East Asian summer monsoon (EASM) and its socio-economic impacts. The poem tells us that the warm southerly comes in summertime, characterized by hot weather and rich rainfall, thus providing a good harvest and keeping the people from suffering hunger and coldness. The ancient Chinese also knew well the abrupt changes of the summer monsoon, as described in a poem written by SU Dongpo (1037 AD–1101 AD) during the Song dynasty. The poem relates that the Mei-yu terminates suddenly in late July, when the southeast wind prevails in the Yangtze River basin. There are more references proving that the ancient Chinese recognized that the seasonal variations in East Asia, characterized by wind direction and rainfall, are stepwise and abrupt. Knowledge of the monsoon provided guidance for agricultural production and for the development of the ancient Chinese civilization.

Descriptions of the weather, climate and the seasonal variations of East Asian monsoon based on modern meteorology originated from the classical works of Zhu (1934) and Tu and Huang (1944). By using limited observational data, Zhu (1934) found that Mei-yu in the Yangtze River basin is caused by the confluence between the summer monsoon from the south and the cold air mass from the north. When the southeast wind prevails after late July, however, there is less rainfall due to the lack of ascending airflow. According to

* Corresponding author: XUE Feng
Email: fxue@lasg.iap.ac.cn

the hot and moist feature of EASM, Tu and Huang (1944) took the 20°C isoline of wet-bulb potential temperature as the northern boundary of the summer monsoon. They found that there are two abrupt changes during the advance and retreat of EASM.

With the availability of upper atmosphere data after the 1950s, Chinese meteorologists began to explore the relationship of EASM with the variations in the upper atmospheric circulation in East Asia. Tao et al. (1958) noted that the onset of Mei-yu is associated with the northward displacement of the jet stream over East Asia. When the jet stream disappears and the easterly winds begin to appear, the Mei-yu period terminates. Huang and Yu (1962) and Huang and Tang (1962) found that the variability of the western Pacific subtropical high (WPSH) plays a role in summer rainfall in China. The northward jump of the WPSH during mid-June and mid-July, for instance, corresponds to the onset and termination of Mei-yu over the Yangtze River valleys, respectively. Tao and Chu (1964) further revealed that the east–west movement of the WPSH is closely related to that of the South Asian high (the Tibetan high) in the upper troposphere. These studies on EASM were later summarized by Tao and Chen (1987) and Ding (1994). These classical works have laid out a firm basis for monsoon research and have developed the capability to forecast monsoon activities in China.

Building upon the above classical works, monsoon research in China has advanced remarkably in recent decades. This is largely due to the availability of observational data as well as advances in computing power and climate models. Research in this area now covers all aspects of the monsoon, including observational studies, climate modeling and prediction. Due to the advent of the internet and widespread international communication, part of this work is already known to the world's meteorological community and has also been introduced in a number of summaries and books. In recent years, many Chinese meteorologists have published papers in international journals. However, some very important results have been published in Chinese (mostly with an English abstract). Based on the above considerations, we focus in this review on these studies published in Chinese journals, although those published in international journals are also mentioned.

Several important aspects are highlighted in this article, focusing on seasonal and interannual to interdecadal timescales. In section 2, we begin with an introduction of the global monsoon systems, together with the South China Sea (SCS) summer monsoon and intraseasonal variation of the East Asian monsoon. This is followed by a review of the interannual variability of EASM, as this variability is important to summer rainfall prediction in China. Sections 3 and 4 focus on the influence of the tropical oceans on EASM, including ENSO, the Indian Ocean and the Atlantic Ocean. Section 5 reviews the influence of land surface processes, including snow cover and soil moisture. Section 6 discusses the interactions of the atmospheric circulations in both hemispheres and their influence on EASM. Finally, the interdecadal variability of the East Asian monsoon and its influence on interannual variability is presented in section 8.

2. Seasonal and intraseasonal variation of the global monsoon system and East Asian monsoon

2.1. *The global monsoon system and its seasonal variation*

Classically, monsoon is a climate concept characterized by a large seasonal variation of wind and rainfall. In particular, wind direction exhibits a very large variation during the annual cycle. In the East Asian monsoon region, for instance, the northerly wind prevails in winter while the southerly wind prevails in summer, resulting in a cold and dry winter and a hot and humid summer. For this reason, Zeng et al. (1994) proposed the seasonality of horizontal wind for a quantitative description of monsoon. The seasonality can be expressed by the wind difference between winter and summer divided by the annual mean or the sum of winter and summer. Since the wind direction in winter tends to be opposite to that in summer, it can be expected that seasonality is large in monsoon regions.

The distribution of seasonality allows the monsoon region to be accurately described (Zeng and Zhang, 1998; Xue and Zeng, 1999). In the lower troposphere (Fig. 1a), there are three maxima in both hemispheres. In the tropics, a large seasonality coincides with the tropical monsoon region. The maximum is found in the Asian–Australian monsoon region, with the centers in the western Pacific warm pool (WPWP) region and the tropical Indian Ocean. In the subtropics, especially in the subtropical Pacific, there are also maxima of seasonality, with the value less than that in the tropics, which is closely related to the seasonal migration of the subtropical high. In high latitudes, the maxima of seasonality correspond to the seasonal variation of storm tracks of the westerly. Broadly speaking, the above three regions with large seasonality represent the three evident monsoon regions in the lower troposphere, i.e., the tropical monsoon region, the subtropical monsoon region and temperate-frigid monsoon region.

Seasonality exhibits a clear baroclinic structure in the vertical direction. In particular, the subtropical monsoon region tends to approach the tropical one with height; and as a result, the two monsoon regions merge into a whole in the upper troposphere (Fig. 1b). This is called the planetary monsoon due to its large scale. In the stratosphere, seasonality is much larger than that in the troposphere due to the opposite circulation between winter and summer. There is a well-defined belt between the tropics and subtropics in each hemisphere, and the northern belt is much stronger than the southern one (Fig. 1c). It is also noted that there exists a night jet in winter over high latitudes that collapses after late spring, such that the maximum belt in the upper stratosphere tends to be located more poleward than that in the middle stratosphere.

In summary, the defined seasonality can describe the classical monsoon region as well as other monsoon regions with large seasonal variations. All these monsoon regions

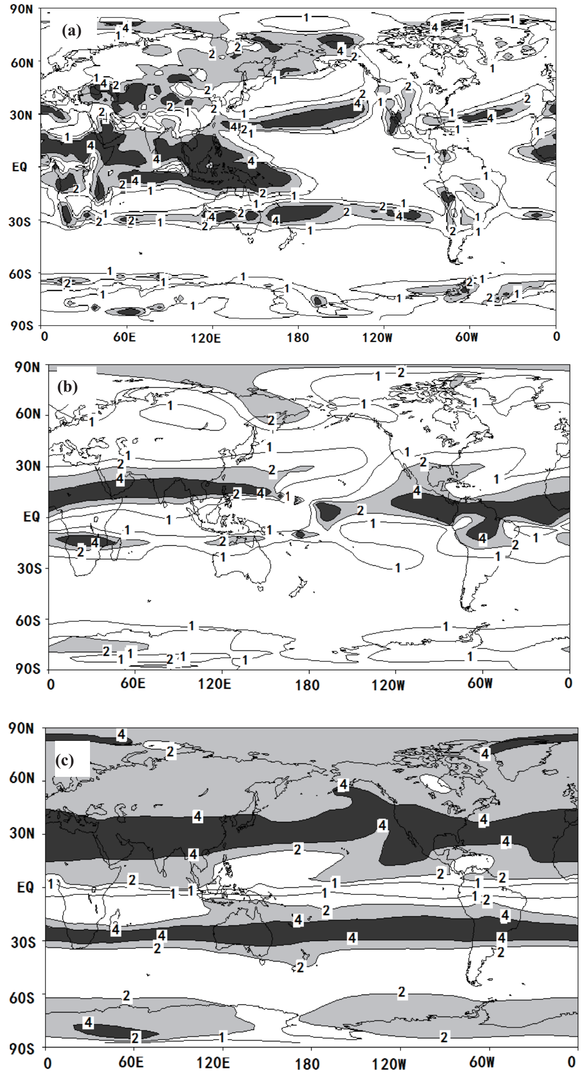

Fig. 1. Distribution of seasonality (dimensionless): (a) 850 hPa; (b) 200 hPa; (c) 50 hPa. Regions larger than 2 or 4 are lightly and heavily shaded, respectively. [Reprinted from Xue and Zeng (1999)]

with large seasonality can be referred to as the global monsoon system, which includes the tropical, subtropical and temperate-frigid monsoon in the lower troposphere, the planetary monsoon in the upper troposphere, and the stratospheric monsoon.

In order to further reveal the seasonal variation of the global monsoon system, Zeng and Zhang (1992) utilized a spatial correlation in one region to describe the seasons of the atmospheric circulation. Based on the correlation coefficient with the winter or summer, it is easy to determine the starting time and duration of each season. The case study by Zhang and Zeng (1998) proved that this method is generally effective. Later, Xue et al. (2002) improved the division of the season to match with the usual division of the seasons. Using the pentad mean data, they identified the global distribution of the starting time of winter and summer circulation in the lower troposphere (Fig. 2a). The Asian winter monsoon initiates from the westerlies in high latitudes of Eurasia at the end of September, followed by development in the south of India and adjacent oceans in the middle October. The winter circulation in East Asia establishes from the end of October to middle November. After that, the SCS, the tropical western Pacific and Indian Ocean gradually change into the winter circulation pattern eastward and southward. Finally, the winter circulation in the tropical middle Pacific south to the Aleutian Islands and in the North Atlantic sets up in the second half of December.

The Asian summer monsoon circulation initiates from the winter circulation in the Southern Hemisphere (SH). In the SH subtropics, an earlier establishment of winter circulation (boreal summer) is found in the regions of the Mascarene and Australian highs, which can influence Asian summer monsoon through the cross-equatorial flows (CEFs) in East Africa and near Indonesia (Fig. 2b). In addition, in agreement with the onset date of SCS summer monsoon (SCSSM), summer circulation in the SCS begins in the second half of May. Over the regions extending from India, eastern China to Japan, summer circulation begins in the first half of June, in good agreement with the summer monsoon rain belt. Globally, the boreal or austral winter circulation initiates in high latitudes of Eurasia and Antarctica, both of which are the coldest regions on Earth. Therefore, the seasonal variation of the atmospheric circulation in the lower troposphere initiates from the coldest region in the winter hemisphere.

As the global monsoon system, the establishment of winter and summer circulation also exhibits a clear 3D structure (Fig. 3). In the Northern Hemisphere (NH), the winter cir-

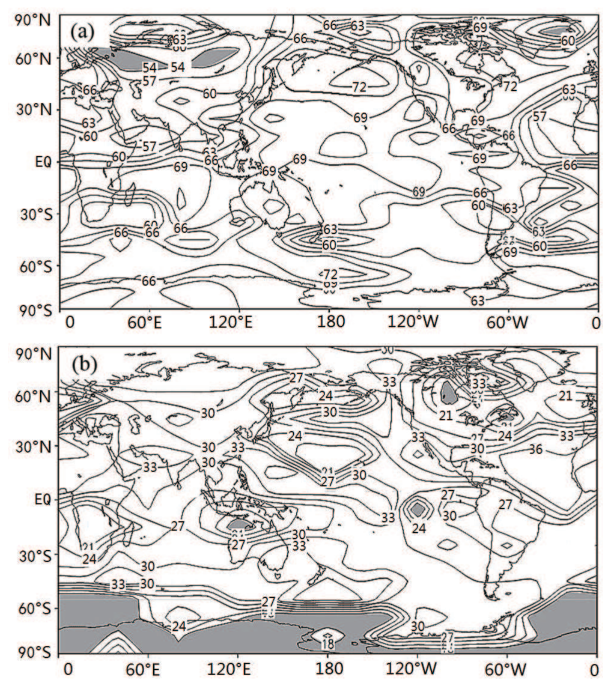

Fig. 2. Distribution of the start time of the 850 hPa wind field (Julian pentad): (a) northern winter; (b) northern summer. Regions earlier than pentad 18 or 54 are shaded. [Reprinted from Xue et al. (2002)]

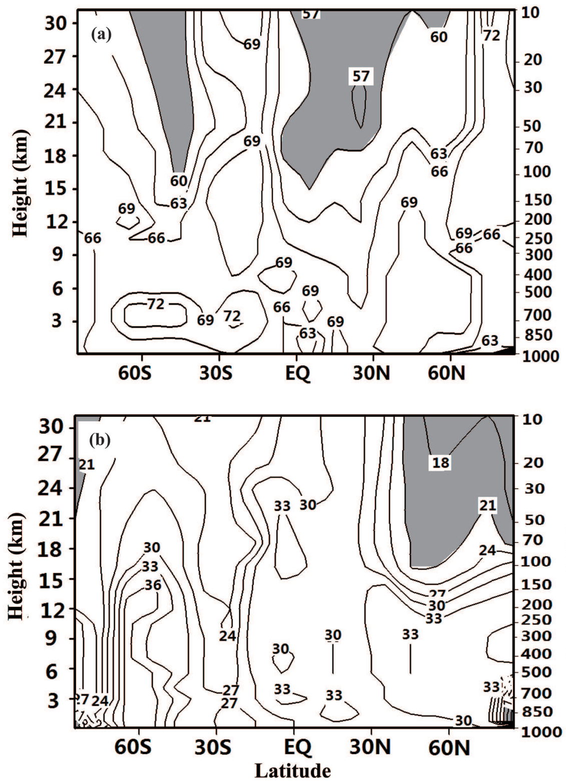

Fig. 3. Latitude–height cross section of the start time (Julian pentad): (a) northern winter; (b) northern summer. Regions earlier than pentad 21 or 60 are shaded. [Reprinted from Xue et al. (2002)]

culation initiates from the mid-high stratosphere between the tropics and subtropics at the end of October, and then propagates downward. In the SH, the winter circulation initiates from the stratospheric subtropics at the end of April and propagates downward. Similar to the winter circulation, an earlier establishment of the summer circulation is also found in the stratosphere. In general, it takes about two months for the establishment of the winter or summer circulation. The seasonal variation originates from the stratosphere possibly due to the fact that the stratospheric circulation is very sensitive to the solar radiation absorbed by the ozone layer; the winter or summer circulation is then established in the polar regions of the lower troposphere. Afterwards, it develops independently downwards and upwards, finally resulting in the establishment of the whole circulation system.

2.2. *SCSSM*

The onset of SCSSM is a key indicator characterizing the abrupt transition from the dry season to the rainy season and subsequent seasonal change in the Asian monsoon region. Unlike the Indian summer monsoon, the onset of SCSSM is achieved during a relatively short period (Tao and Chen, 1987; Ding et al., 2004). It plays a role in connecting EASM with Indian summer monsoon due to the geographical position. Due to the importance of SCSSM to Asian monsoon, an international experiment about SCSSM called the SCS Monsoon Experiment (SCSMEX) was conducted in 1998; scientists from many countries, including Chinese scientists, participated in this experiment (Ding et al., 2004).

Based on the observational data from SCSMEX and NCEP reanalysis data, Li and Qu (2000) and He et al. (2000) revealed the large-scale features related to the onset of SCSSM. These features can be summarized as follows: the development of the Somali jet and cross-equatorial flow in the eastern Indian Ocean; the rapid intensification of the heat source in the Indochina Peninsula, South China, the Tibetan Plateau and adjacent regions; the development and northwestward movement of the South Asian high at 200 hPa; the acceleration of the westerly in the eastern Indian ocean; and the split of the subtropical high and the formation of the monsoon depression in the Bay of Bengal. Associated with the above changes, the subtropical high retreats eastward, and rainfall and southwest wind prevails in the SCS, signaling the onset of SCSSM. Besides the regional characteristics, the onset of the SCSSM is also connected with the seasonal transition of the global atmospheric circulation from boreal winter to summer.

The onset of SCSSM is directly represented by the abruptness of the wind field. After the onset, the northeast wind is substituted by the southwest wind in the SCS. In order to study the abruptness more objectively, Zeng et al. (2005) proposed a new method called the normalized finite temporal variation method, which can be obtained from the time series of a functional of the wind field. It is shown that the critical day of abruptness in one region can be determined objectively by this method (Zhang et al., 2005). This day is referred to as the presage day, which is just 2–4 days earlier than the onset day of monsoon defined by the conventional method. As a typical example, Fig. 4a shows the daily normalized finite temporal variation with height in the SCS. During the onset stage, a rapid adjustment is found below 400 hPa, with a maximum between 850 and 700 hPa. Above 700 hPa, the adjustment tends to be longer with smaller amplitudes. The maximum occurs on 16 May and continues until 28 May. After that, the major adjustment is related to the establishment of summer monsoon in South and East Asia. In particular, a significant adjustment occurs in the lower stratosphere and upper troposphere between 20 April and 1 May, and then it extends downwards into the troposphere. Therefore, the adjustment of the stratospheric circulation is an indication of monsoon circulation in the lower troposphere and foreshadows the onset of SCSSM.

The onset of SCSSM undergoes a northward process, as shown in Fig. 4b. Between 80°E and 135°E, a major abruptness is found in the west or the east of 100°E. To the east of 100°E, the abruptness occurs on 15 May with a center along 110°E, corresponding to the onset of SCSSM. To the west of 100°E, the abruptness is generally characterized by a stationary mode along 95°E, with a presage day between 26 April and 2 May. Therefore, due to the separation of the Pacific and Indian Ocean by the Indochina Peninsular, the atmospheric circulation exhibits a different evolution on the two sides, especially in the onset stage of summer monsoon.

Some studies have revealed the physical mechanisms re-

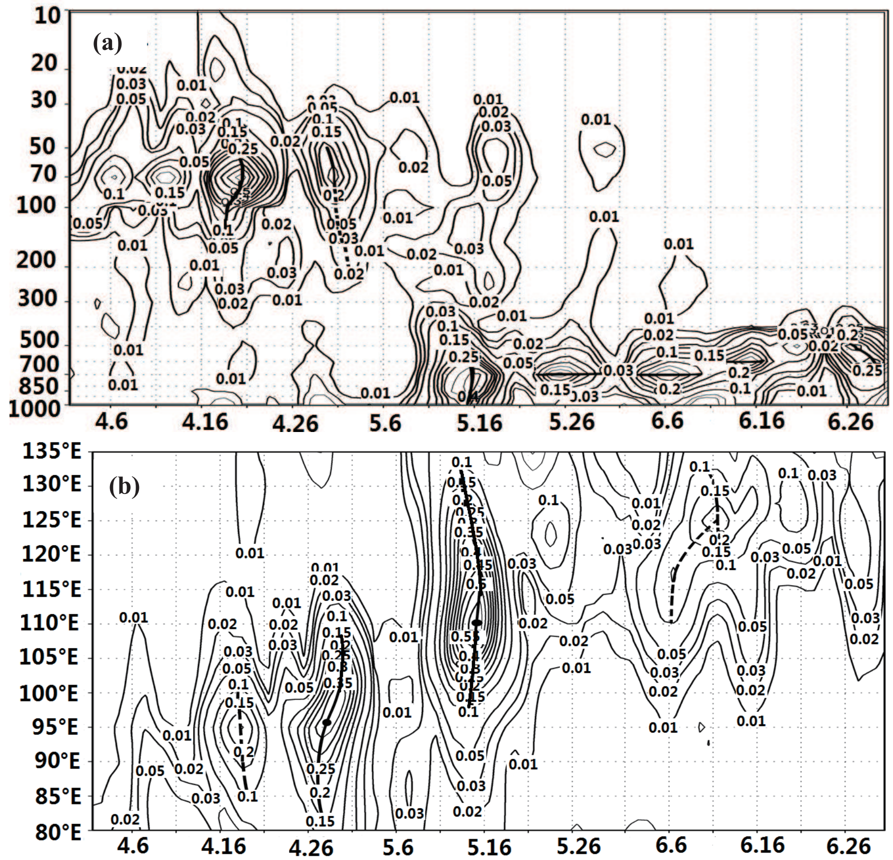

Fig. 4. (a) Height–time cross section of the daily normalized finite temporal variation for the 850 hPa mean wind field in the SCS region. Panel (b) is the same as (a) except for the longitude–time cross section along 7.5°N. The heavy lines show the major abrupt changes, and the dashed lines show the secondary transition. (Reprinted from Zeng et al., 2005)

sponsible for the onset of SCSSM (Chen et al., 2000b; Ding et al., 2004). Prior to the SCSMEX, four factors were identified: (1) the SST anomalies in the tropical ocean, especially ENSO events; (2) the activity of the tropical intraseasonal oscillation; (3) the midlatitude circulation; and (4) the thermal contrast between the Asian continent and the adjacent oceans, especially the heat source in the Tibetan Plateau. Following the SCSMEX, it has been well recognized that the seasonal evolution of the tropical large-scale circulation and the corresponding thermal conditions play a dominant role in the onset process. Under these large-scale circumstances of the seasonal evolution from boreal winter to summer, the propagation of the intraseasonal oscillation triggers the development of deep convection in the SCS and leads to the onset of SCSSM. Among these factors, the thermal contrast between the continent and ocean is a basic factor, the SST and the heat source in the Tibetan Plateau is a direct factor, and the midlatitude disturbance and tropical intraseasonal oscillation is a triggering factor.

2.3. *Intraseasonal oscillation of East Asian monsoon*

The intraseasonal oscillation (ISO) plays a very important role in modulation of the seasonal variation or the annual march of East Asian monsoon. Zhu and Yang (1989) showed that the EASM exhibits a clear ISO with bi-weekly and quasi-40-day periods. Miao and Lau (1991) found that the 30–60-day oscillation is phase-locked with the seasonal variation of summer monsoon rainfall. Based on power spectrum analysis and a band-pass filter, Ju et al. (2005) revealed that the ISO of EASM exhibits a wave-train pattern along the East Asian coast that propagates northward. They also noted that the monsoon activity in the tropics is generally opposite to that in the subtropics due to the activity of ISO.

As a dominant component of the EASM system, the WPSH is most evident during boreal summer. In general, the WPSH migrates northward in a stepwise fashion with two distinct northward jumps, as shown by its ridge line in Fig. 5a. In mid-June, it jumps northward for the first time, and the Mei-yu season in the Yangtze River valleys starts. The second northward jump usually occurs in late July. The WPSH shifts to its most northern position, signaling the end of the Mei-yu season in the above regions and the start of the rainy season in northern and northeastern China (Fig. 5b). Compared with the first jump, the second jump of the WPSH is much more evident. Su and Xue (2010) showed that the first jump is mainly caused by the enhancement of the convective activities in the SCS, while the second jump is influenced by both the convective activities over the WPWP and the circula-

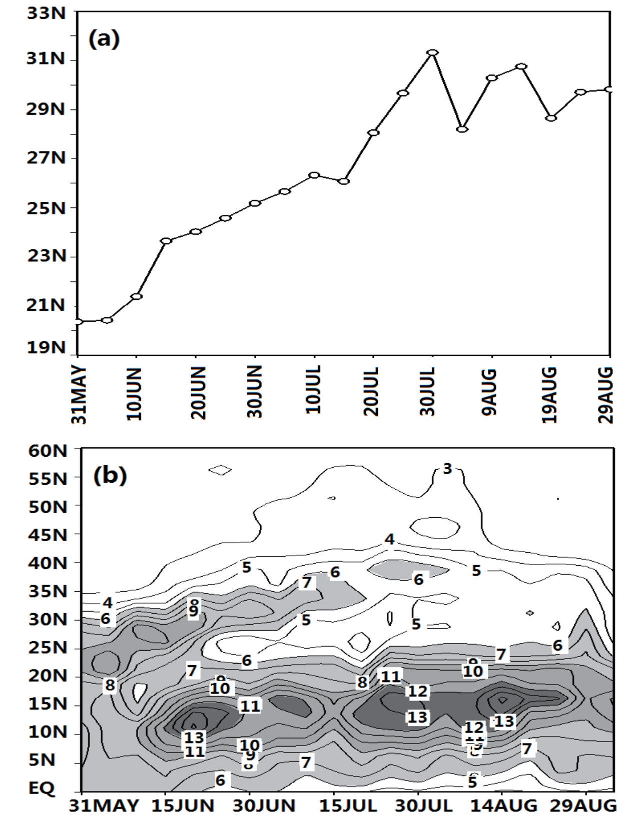

Fig. 5. (a) Ridge line of the WPSH (units: latitude) and (b) latitude–time cross section of precipitation (units: mm d^{-1}) averaged over 110°–130°E; regions larger than 6 mm d^{-1} are shaded. [Reprinted from Su and Xue (2010)]

tion systems in high latitudes. Through the phase-lock of the northeastward propagation of the Rossby wave-train from the WPWP and the downstream propagation of Rossby waves in high latitudes, the convective activities over the warm pool and the circulation systems in high latitudes play a key role in the second northward jump of the WPSH. In addition, the interactions between the WPSH and the release of latent heat on its western edge lead to a low-frequency oscillation of the WPSH.

Some other studies have focused on the intraseasonal variation of the WPSH. Usually, the intraseasonal activity of the WPSH possesses two modes during boreal summer (Tao et al., 2001). While the first mode exhibits a continuous westward extension from the central Pacific to west of 120°E with a period of 20–30 days, the second mode is characterized by a stagnant step between 125°E and 155°E during the westward extension. In addition, the activity of the WPSH with a shorter period of 5–10 days is related to the westerly between 35°N and 45°N. When a trough in the westerly extends southward to 30°N, the WPSH tends to be intensified. Tao and Wei (2006) further noted that the stationary Rossby wave in the upper troposphere over Eurasia propagates onto the coast of China (115°–130°E) along the subtropical jet, leading to a northward jump of the WPSH by exciting a longwave ridge there. As a result, hot weather appears in the Yangtze River valleys due to the maintenance of the ridge.

Besides EASM, recent studies have also noted the ISO in East Asian winter monsoon (EAWM) and air temperature and rainfall in China in winter. Liu and Yang (2010) showed that winter rainfall in South China is closely related to the tropical Madden–Julian oscillation (MJO). With the eastward movement of MJO from the western Indian Ocean to the western Pacific, a wet–dry oscillation with a 20-day period appears in South China. A typical example was the unusually severe storm and freezing rain that occurred in the winter of 2008, when the ISO prevailed in southern China (Tao and Wei, 2008). Besides the anomalous circulation in high latitudes of Eurasia, a large amount of moisture was transported into southern China with the ISO of southwest wind ahead of the trough over the Bay of Bengal, exciting severe freezing rain in southern China.

3. Interactions between East Asian monsoon and ENSO

3.1. *The influence of ENSO on EASM*

The severe flood and drought events that occur frequently during the summer monsoon season have motivated many Chinese meteorologists to look for predictors. In the early 1930s, Chinese meteorologists began to explore the possibilities of long-range weather forecasting in China using modern meteorological methods. Based on the limited observational data at that time, Tu (1937) systematically studied the relationships between the climate anomalies in China and the three atmospheric oscillations, i.e., the North Pacific Oscillation, the North Atlantic Oscillation (NAO) and the Southern Oscillation (SO), which were first identified by Sir Gilbert Walker. He found that a cold and dry winter often appears in China when the SO is intensified during the preceding fall, and vice versa. However, the correlation between the summer rainfall anomaly in China and the SO in the preceding winter or spring was relatively lower. This fact indicated that there is a higher predictability for the winter climate anomaly in China. Unfortunately, it seemed that there is difficulty in predicting the summer climate anomaly in China. These results were later demonstrated to be true, based on longer-term data. It is worth noting that, considering the limited available data and the lack of meteorological knowledge at that time, Tu's work was a truly remarkable achievement.

It is now known that the SO and El Niño are essentially the same phenomenon, which are a result of the interactions between the atmosphere and ocean in the tropical Pacific, later referred to as ENSO. Since the 1980s, it has been recognized that ENSO is the strongest interannual signal in the tropical ocean–atmosphere system, and that it plays a crucial role in the interannual variability of the global atmospheric circulation. The interaction between ENSO and EASM is obviously of primary importance in understanding the EASM variability and the prediction of summer rainfall in China. Of particular interest is the response of the monsoonal flows to SST in the equatorial eastern Pacific. Numerous studies have been devoted to the influence of ENSO on EASM and summer rainfall in China. Previous studies have noted the possible association of the tropical Hadley cell anomaly caused by the SST anomaly in the eastern Pacific with the WPSH and the rainfall anomaly in China during El Niño years (Chen, 1977; Xu, 1986). Later, Fu and Teng (1988) found that in the different stages of ENSO, the response of the EASM circulation to the ENSO signal is totally different. In the onset year, the WPSH tends to be weakened and retreats eastward. As a result, there is less rainfall over the Yangtze River valleys. However, in the succeeding year after the onset of ENSO (the decaying stage of ENSO), the WPSH tends to be intensified with a more westward extension, and there is more rainfall over the Yangtze River valleys. They also noted that the summer monsoon anomaly in China during the decaying stage of ENSO is much more significant, indicating that ENSO shows a more lagged effect on EASM than other regions, such as the Indian summer monsoon. The phase-dependent impact of ENSO on the East Asian climate is also evident in the seasonally evolving, dominant interannual variability modes (Wu et al., 2009a).

At the same time, Huang and Li (1988) showed that the influence of ENSO on EASM is more directly correlated with the convection activity largely driven by the WPWP SST than the SST anomaly in the equatorial eastern Pacific. Huang and Sun (1992, 1994) further found that the WPSH exhibits an obviously northward shift in early summer with an enhanced convection around the Philippines. This results in less rainfall in the Yangtze River valleys and more rainfall outside of this region. In contrast, there appears to be an almost opposite rainfall distribution in China along with a more southward WPSH when the convection activity around the Philippines is weaker than normal. Based on theoretical considerations and model experiments, they proposed an East-Asia–Pacific (EAP) teleconnection pattern caused by the convection anomaly mentioned above through the propagation of the planetary wave (Fig. 6). The EAP pattern is also evident in the atmospheric circulation fields that dominate the water vapor transport associated with the typical interannual variability modes of summer precipitation (Zhou and Yu, 2005). The EAP pattern provides a physical basis for summer rainfall prediction in China. The significant impact of the western Pacific SST on the interannual variability of the WPSH, in conjunction with the remote eastern Pacific forcing, has been demonstrated by numerical modeling (Wu and Zhou, 2008).

On the other hand, a recent study by Lin and Lu (2009) suggests that subtropical precipitation anomalies in East Asia, in turn, can significantly affect large-scale circulations and may be crucial for the maintenance of the EAP pattern. Diagnosis by using observational and reanalysis data indicated that the patterns are clearer in summers when the subtropical rainfall anomalies are greater. The simulated results using a linear baroclinic model indicated that a subtropical heat source, which is equivalent to the diagnosed positive subtropical precipitation anomaly, induces zonally elongated zonal wind anomalies that resemble the diagnosed ones in both the upper and lower troposphere over extratropical East

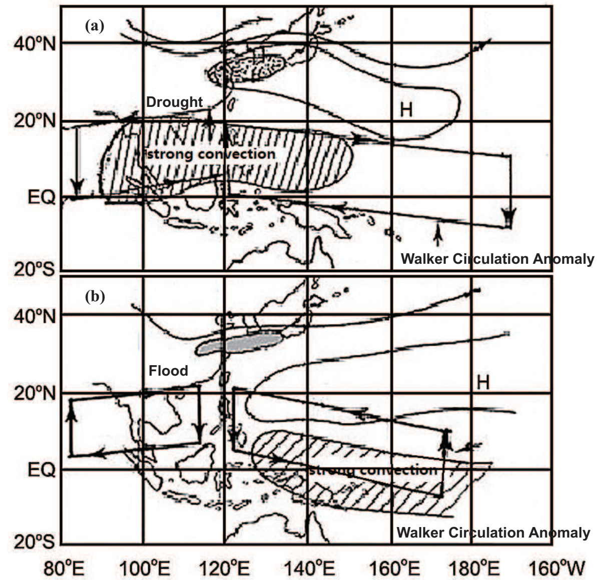

Fig. 6. Schematic diagram of the East Asia–Pacific teleconnection pattern showing relationships among the convective activities in the warm pool of the tropical western Pacific, the WPSH, and the summer rainfall distribution in China: the (a) warming and (b) cooling state of the warm pool. [Reprinted from Huang et al. (2006a)]

Asia. The results showed that there is a more complex relationship between subtropical rainfall variability in East Asia and the western Pacific SST anomaly.

Based on the concept of phase-dependent influence, it has recently been found that, while the overall summer-rainfall–SST relationship has a negative correlation over the western North Pacific (WNP), this relationship experiences a significant interannual variation (Wu et al., 2009b). During ENSO-developing (decaying) summers, the rainfall–SST correlation is significantly positive (negative). The positive correlation is attributed to the interplay between the anomalous Walker circulation and the CEFs associated with the enhanced WNP summer monsoon. The former leads to negative rainfall anomalies in the western Pacific, whereas the latter leads to a cold SST anomaly resulting from enhanced surface latent heat fluxes. The negative correlation is attributed to the maintenance of an anomalous Philippine Sea anticyclone from the El Niño winter peak to the subsequent summer. The anomalous anticyclone, on the one hand, suppresses the local rainfall, and on the other hand, induces a warm in situ SST anomaly through both enhanced solar radiation (resulting from a decrease in cloud amount) and the reduced surface latent heat flux (resulting from the decrease of the monsoon westerly). The rainfall–SST correlation is insignificant in the remaining summers. Thus, the overall weak, negative rainfall–SST correlation is attributed to the significant negative correlation of the ENSO-decaying summers.

The subtropical westerly jet over East Asia is an important component of the EASM system (Li et al., 2005a; Zhang et al., 2006). The meridional displacement of the jet stream likely plays a role in connecting El Niño events in the preceding winter and the eastern China rainfall anomaly in the subsequent early summer. Li (1992) and Lu (2005) found that there appears to be a clear signal of the SST anomaly in May and June associated with the summer rainfall anomaly in northern China. Recently, using station precipitation data, Lu and Lin (2009) found that after the El Niño peak in June, the precipitation is significantly suppressed in the Huaihe–Yellow River regimes, while it is enhanced in the Yangtze River valleys. They indicated that this relationship between ENSO and the eastern China rainfall anomaly is established possibly through the meridional displacement of the Asian jet stream in the upper troposphere, which results in suppressed precipitation in the Huaihe–Yellow River regimes. The enhanced precipitation in the Yangtze River valleys results from the WNP anticyclonic anomaly in the lower troposphere. They further suggested that this meridional displacement of the Asian jet is due to the effects of ENSO on the zonal flow in the NH. After the El Niño peak, the ENSO-related warming in the tropical troposphere persists into the following early summer. This increases the meridional gradient of temperature and, by thermal wind balance, leads to the enhancement of westerlies in the subtropics south of the westerly jet stream and the resultant southward displacement of the westerly jet stream.

Perhaps the best example showing the influence of ENSO on EASM and summer rainfall in China is the catastrophic flood in the Yangtze River valleys in the summer of 1998. It was reported that the flood caused the deaths of 3000 people and economic damage of 250 billion Yuan. This extreme disaster prompted Chinese meteorologists to carry out a series of studies (Tao et al., 1998; Huang et al., 1998; Lu, 2000). A very strong El Niño event occurred in 1997 and decayed in 1998. In the decaying stage of the ENSO cycle, the convection activities around the Philippines tended to be suppressed, and the WPSH tended to extend more southwestward. The southerly wind in the south flank of the WPSH brought a large amount of moisture from the tropics, which converged in the Yangtze River valleys. As a result, there were a series of heavy rainfall events in the summer of 1998. Therefore, the strong El Niño event played a crucial role in this severe flood, although other factors cannot be excluded.

A unique feature of the interannual variability of EASM is its pronounced biennial oscillation, which is often referred to as tropospheric biennial oscillation (TBO). Strong TBO signals are exhibited in many components of EASM systems, such as the WPSH and summer rainfall in China (Huang, 1988). The WPWP is believed to be a key area connecting the TBO and ENSO (Xu and Zhu, 1998; Huang et al., 2006a). If the warm pool is warmer in a particular year, the WPSH and the summer rain belt over China tends to extend more northward. This is due to a stronger convection around the Philippines and the associated EAP pattern; thus, there is more rainfall in northern China and less rainfall in the Yangtze River valleys. In the meantime, seawater upwelling is intensified due to the stronger convergence in the warm pool. As a result, the SST in the warm pool tends to be decreased along with a suppressed convection in the succeeding year; an opposite EAP pattern and summer rainfall distribution appears in China.

3.2. *Nonlinear response of EASM to ENSO*

The aforementioned studies have revealed the relationship between ENSO and EASM and the associated ENSO-type rainfall distribution in China. This classical theory provides us with an important basis for summer rainfall prediction in China. In fact, the present prediction system in China depends, to a certain degree, on the prediction of the ENSO signal in the model, and it does result in success in summer rainfall prediction in China (Zeng et al., 2003).

Observational analysis has shown that most ENSO events reach moderate intensity, and that strong ENSO events occur infrequently. When the ENSO signal is not so strong, it is possible that some other factors can, to some degree, modulate the response of the EASM circulation to the ENSO signal, thereby inducing a different rainfall distribution. In fact, if we examine summer rainfall patterns in China with ENSO year by year, it is easy to see that the rainfall anomaly distribution in some years is not coincident with, and is sometimes opposite to, the aforementioned relationship between ENSO and EASM, such as in 1995 (Zhao, 1999). Since the anomaly of EASM circulation and summer rainfall in China induced by a strong ENSO is much more significant than that induced by a moderate ENSO, only the strong ENSO signal is reflected in the previous composite or correlation analysis. For this reason, it is necessary to divide the ENSO events based on their intensities if the nonlinear response of EASM to ENSO is to be depicted precisely.

Based on the above considerations, Xue and Liu (2008) divided ENSO events into strong and moderate categories. They then analyzed the influence of ENSO with different intensities on EASM and summer rainfall in China based on a composite analysis. While the rainfall distribution in all composite ENSO years agrees well with the aforementioned relationship between ENSO and EASM, the rainfall pattern in the moderate ENSO years generally corresponds to the northern pattern, with more rainfall along the Yellow–Huaihe River regimes and the coastal areas of southern China and less rainfall in the Yangtze River valleys and southward. This rainfall pattern is very much different from the classical ENSO-type rainfall pattern, with more rainfall in the Yangtze River valleys. Since the rainfall anomaly induced by the strong ENSO is much larger than that induced by the moderate ENSO (e.g., the devastating flood in 1998 in the Yangtze River valleys), only the strong ENSO signal is represented in the previous result.

To further illustrate the influence of ENSO on EASM, Xue and Liu (2008) compared the composite WPSH at 500 hPa during the strong and moderate ENSO years with the climatological mean. Similar to the previous result, the WPSH tends to be enhanced with a more southwestward extension in the ENSO years. Also, the influence of ENSO on the WPSH tends to be enhanced from June to August, with the smallest difference from the climatological mean in June and the largest difference in August. This indicates a long lagging effect of ENSO on the EASM circulation. On the other hand, there is a significant difference between the strong and moderate ENSO years. While the influence of the strong ENSO starts earlier, with a large anomaly, the influence of the moderate ENSO is relatively weak. There is a small difference from the climatological mean in June. This difference tends to be enhanced in July and reaches its maximum in August. As a result, the influence of the moderate ENSO on the Mei-yu along the Yangtze–Huaihe River valleys during June–July is not so significant. A further comparison between two moderate ENSO years (1995 and 2003) shows that, due to the different influences of the circulation in high latitudes and the SH circulation in June and July, the WPSH may also exhibit a different change, thereby inducing a different rainfall distribution in China. In other words, the response of the EASM circulation to moderate ENSO can be, to a large degree, modulated by the internal atmospheric dynamics. Furthermore, comparison with the strong ENSO in 1983 shows that strong ENSO not only plays a direct role in summer rainfall in China, but also controls the influence of other factors, such as the SH circulation. Strong ENSO is essentially different from moderate ENSO, and therefore the intensity of ENSO must be divided in practical prediction. By comparing the EASM activities in the strong La Niña years of 1988 and 1989, Xue (2008) also showed that, due to the modulation of some other factors on La Niña signals, summer precipitation in China may exhibit a different pattern even in the background of two similar La Niña events. The results indicate that the response of EASM and summer rainfall in China to ENSO is essentially nonlinear.

Besides the EASM, the ESWM circulation exhibits a similar nonlinear response to the ENSO cycle. Based on a composite analysis, He et al. (2008) compared the EAWM circulation response to strong and weak ENSO with the tropical one. In the tropics, the response to an El Niño is generally opposite to a La Niña, and the anomalous intensity is also proportional to the ENSO intensity, i.e., the atmospheric response in the tropics exhibits a quasi-linear feature. By comparison, the responses of the EAWM circulation in mid-high latitudes are complex. The phase reversal of the circulation pattern is not evident for the warm and cold events as it is in the tropics. Moreover, the most significant signal is found when a strong El Niño occurs, characterized by the enhancement of the westerly jet in East Asia and a weaker EAWM. As a result, eastern China experiences a warmer winter due to the anomalous southerly wind along the East Asian coast. Instead, the influence of strong La Niña events is relatively weaker with a large uncertainty.

Besides the intensity of ENSO, recent studies have emphasized the influence of the spatial distribution of the SST anomaly in the tropical Pacific on EASM and summer rainfall in China. Different from canonical El Niño events, there is another type of El Niño with the most significant SST anomaly being in the central Pacific (CP-El Niño). Wang et al. (2009a) found that when the central Pacific is warmer (colder) in spring, the Mei-yu onset in the Yangtze River valleys tends to be later (earlier). Qian et al. (2009) further indicated that there is more Mei-yu rainfall in the Huaihe River valleys when a CP-El Niño occurs in spring. By contrast, a canonical El Niño in the eastern Pacific corresponds to more Mei-yu rainfall south of the Yangtze River valleys. More recently, Su and Xue (2011) showed that the two northward jumps of the WPSH are related with the SST anomalies in the different regions of the tropical Pacific. The first jump is positively correlated with the SST anomalies in the tropical central Pacific from the preceding winter to June. By contrast, the second jump is positively related to ENSO in the preceding winter, but this correlation tends to be weakened with the decay of ENSO and disappears in July. Due to the EASM activity being influenced by the two northward jumps of the WPSH, it is suggested that simply forecasting the intensity of ENSO without regard to the spatial structure of the SST anomalies will not adequately predict the associated rainfall anomalies in China.

3.3. *The role of EAWM and extratropical atmospheric disturbances in the ENSO cycle*

Since the seminal work of Bjerknes, ENSO has been considered to be a product of the interactions between the atmosphere and the ocean. Besides the influence of ENSO on EASM, the East Asian monsoon also plays a role in ENSO, especially in the onset of ENSO. Li (1989) found that, prior to the occurrence of an El Niño event, cold waves frequently appear in East Asia. A strong winter monsoon in East Asia leads to an enhanced convection and weakened trade winds in the western Pacific, which induces the 30–60-day oscillation and anomalous Kelvin wave. Li (1990) further indicated that there is an obvious interaction between ENSO and EAWM. While EAWM can excite an El Niño event, it can also be reduced by the El Niño. By using a coupled general circulation model, Li and Mu (1998) performed a series of numerical experiments and proved that a stronger winter monsoon in East Asia results in an obvious SST anomaly in the eastern Pacific. It is therefore suggested that a stronger winter monsoon plays a role in triggering the onset of an El Niño event.

The role of westerly bursts (or the westerly anomaly) over the western Pacific in triggering the onset of ENSO has been emphasized (Li, 1995; Huang et al., 1996). Fu and Huang (1997) found that these westerly bursts are closely related to the southward propagation of the westerly in East Asia along with a Eurasian teleconnection pattern in high latitudes. With the eastward propagation of the westerly, the SST in the central and eastern Pacific tends to increase. Li and Mu (2002) indicated that the westerly anomalies can induce the subsurface ocean temperature anomaly in the Pacific warm pool and its eastward propagation; they concluded that the ENSO cycle is essentially related to the subsurface ocean temperature anomalies in the tropical Pacific driven by the zonal wind anomalies over the western and central Pacific.

On the other hand, it should be noted that not all westerly anomalies associated with strong EAWM trigger the onset of ENSO. Zhang et al. (2000) showed that the westerly anomaly in the western Pacific undergoes two remarkable enhancements in the spring and summer of the onset year of an El Niño. Besides the eastward propagation of the westerly from the equatorial Indian Ocean, the strong convergence of the meridional wind from extratropical atmospheric disturbances in both hemispheres is more important to the enhancement of the westerly anomaly. Compared with the NH, the meridional wind to the east of Australia is more stable and makes a more significant contribution to the enhancement of the westerly anomaly.

In addition to triggering the onset of ENSO, extratropical atmospheric disturbances also play a role in the development and decay of ENSO (Xue and He, 2007). In the development phase of ENSO, the westerly anomaly in the equatorial central and eastern Pacific is further enhanced by the cyclonic anomaly in the southeastern Pacific and the associated southerly anomaly. It is also noted that the decay of ENSO is much faster than the development; other factors besides the classical Kelvin wave are therefore involved in the decay of ENSO. In fact, the rapid eastward movement of the anticyclonic anomaly in Australia results in a weakening of the cyclonic anomaly in the subtropical South Pacific; the Southern Oscillation pattern tends to disappear. Moreover, when ENSO reaches its mature phase, the deepened Aleutian low and the intensified anticyclonic anomaly (in particular, the wind anomaly in the subtropical North Pacific) enhances the subtropical cell in the ocean, inducing upwelling of surface water in the equatorial eastern Pacific, thereby accelerating the decay of ENSO.

The persistence of ENSO is also influenced by extratropical atmospheric disturbances (Yang and Li, 2005a; Li et al., 2008a). It has been found that the intensity of longer-duration ENSO is generally weaker than that of shorter-duration ENSO. For longer-duration ENSO, the decay of the anomalous cyclone in the eastern North Pacific and the development of the anomalous anticyclone in the WNP tend to be slower. In addition, the stronger winter monsoon and weaker summer monsoon in Australia lead to a longer duration of the westerly anomaly in the equatorial western Pacific. Therefore, the westerly anomaly in the equatorial western Pacific is favorable for the persistence of ENSO, while the easterly anomaly foreshadows the decay of ENSO.

4. Influence of the Indian Ocean and Atlantic Ocean on East Asian monsoon

4.1. *Influence of the Indian Ocean*

Chinese meteorologists have been aware since the early 1980s of the influence of the Indian Ocean SST on EASM and summer rainfall in China. These earlier studies noted that there is a significant correlation between summer rainfall in the Yangtze River valleys and the Indian Ocean's SST anomalies (Luo et al., 1985; Chen et al., 1985). Chen (1988) revealed that there is an opposite correlation of SST anomalies between the east and west of the tropical Indian Ocean, which is often related to ENSO. He further showed that the different types of zonal SST anomalies in the tropical Indian Ocean play a role in the position and intensity of the WPSH and EASM through the Walker circulation (Chen, 1991).

Since the discovery of the Indian Ocean dipole (IOD, or Indian Ocean zonal mode), more attention has been paid to the influence of the tropical Indian Ocean on EASM. Many studies have focused on the influence of the IOD on summer rainfall in China (e.g., Li and Mu, 2001; Yan et al., 2001; Xiao et al., 2002; Qian and Guan, 2007, among many others). In general, the results further demonstrate that there is a significant correlation between the spring IOD and summer rainfall in China, and that there is more rainfall in southern China associated with a positive phase of the IOD. When the ENSO signal is relatively weak, the IOD seems to be a plausible predictor. The influence of the IOD can be seen more clearly in 2003 and 2004, when the SST anomalies in the tropical Pacific were weak. Xiao and Liang (2006) revealed that the different summer rainfall distributions in these two years were to a large degree caused by the different phases of the IOD. The significant impact of the IOD on East Asian climate has also been demonstrated by a series of numerical experiments (Yan and Zhang, 2004; Yan et al., 2007). In a positive phase of the IOD, for instance, there appears to be an anomalous easterly in South Asia and an anomalous anticyclone near the Bay of Bengal, resulting in less rainfall in southern India and more rainfall in southern China.

Recent studies have revealed that the IOD is closely related with ENSO through the Walker circulation (Li et al., 2002; Mu and Li, 2002); therefore, the combined effects of the IOD and ENSO and their modulation on the response of EASM to the ENSO signal are also noted (Yang and Li, 2005b; Yang et al., 2006). Xiao et al. (2000) found that during El Niño years, SST anomalies with an east-warmer and west-colder distribution in the Indian Ocean enhance the influence of ENSO on EASM. This exaggerates the southern-flood and northern-drought rainfall pattern in China. Furthermore, Liu et al. (2008b) pointed out that the lesser amount of rainfall in northern China during El Niño years can be mitigated to a certain degree if the IOD is in a positive phase, while the co-occurrence of La Niña events and a negative phase of the IOD is not conducive to summer rainfall in northern China. They noted that there appear to be some regional features of summer rainfall in China under the combined effects of ENSO and the IOD during the different phases. Therefore, the effects of the IOD on EASM cannot be neglected, especially when the ENSO signal is weak.

There have been studies that have focused on the role of Indian Ocean SST anomalies in the onset of the SCSSM, which signals the seasonal transition from the winter circulation to summer circulation in the Asian monsoon region (Liang et al., 2006; Wen et al., 2006; Yuan and Li, 2009). There are two types of leading modes of SST variability in the Indian Ocean: the basin-scale warm/cold mode (IOBM), and the IOD. Both of these play significant roles in the onset of SCSSM. The IOBM warming induces an anomalous Walker circulation in the tropical Indo-Pacific region together with an anomalous descending motion and suppressed convection in the tropical western Pacific, thereby leading to a delayed onset. It is also suggested that the IOBM significantly prolongs the effect of ENSO on the onset of SCSSM in the succeeding year. A positive IOD in the preceding period usually corresponds to a delayed onset, such as in 1994, when there was a strong IOD event (Yuan and Li, 2009). In a similar way, the Indian Ocean SST anomaly has an impact on the intensity of SCSSM (Li et al., 2006).

Several physical mechanisms have been proposed to explain the influence of the Indian Ocean's SST anomaly on the EASM. Zhou and Wang (2006) found that the spring Hadley cell plays a role in linking the SST anomalies in the Indian Ocean and EASM. Wen et al. (2006) indicated that the influence can be realized through changing the intensity of the Indian summer monsoon. Yang et al. (2007) suggested that the Indian Ocean warming associated with ENSO induces robust climatic anomalies in summer in the Indo-west Pacific region, prolonging ENSO's influence after the tropical eastern Pacific SST has returned to a normal state. A numerical experiment indicated that, in response to the Indian Ocean warming, precipitation increases over most of the basin, forcing a Matsuno–Gill pattern in the upper troposphere with a strengthened South Asian high (Li et al., 2008c). Zhou et al. (2009b) demonstrated that a similar mechanism also works at an interdecadal scale; that is, the Indian Ocean warming results in an intensified South Asian high and a westward extension of the WPSH. Analysis of CLIVAR C20C models (i.e., the AGCMs forced by historical SSTs) revealed the dominance of the tropical Pacific's and Indian Ocean's SST anomalies in forcing the interannual variability of immense Asian monsoon circulation components (Zhou et al., 2009a). Liu et al. (2008a) found that there appears to be a series of Rossby wave trains in the NH troposphere associated with the IOD, initiating from India and extending northeastward. It has been further revealed that the influence of the IOD on the climate anomaly in the NH is dynamically linked by the energy propagation of planetary waves. Analysis of the output of Atmospheric Model Intercomparison Project (AMIP) models also shows that both the tropical Pacific and tropical Indian Ocean regions are important in forcing the interannual variability modes of the Asian–Australian monsoon (Zhou et al., 2009a).

In addition to the summer season, Wu et al. (2009a) revealed the seasonally evolving dominant interannual variability modes of the East Asian climate. The first two dominant modes account for 44% of the total interannual variance, corresponding to the post-ENSO and ENSO turnabout years, respectively. A diagnosis of the upper-level velocity potential and mid-level vertical motion fields revealed a season-dependent Indian Ocean forcing scenario. The Indian Ocean's basin-wide warming during El Niño's mature winter and the subsequent spring does not have a significant impact on the anomalous circulation in the WNP. This is because convection over the tropical Indian Ocean is suppressed by the remote forcing from the equatorial central-eastern Pacific. The basin-wide warming plays an active role in impacting the WNP anomalous anticyclone during ENSO's decaying summer through the atmospheric Kelvin wave or Hadley circulation, as suggested in many previous studies.

4.2. *The influence of the Atlantic Ocean*

Compared with the Pacific and Indian oceans, the influences of the tropical Atlantic Ocean on the interannual variability of EASM and the summer climate anomaly in China are less frequently mentioned in the literature. This is because of its great distance from the Asian monsoon region and the relatively weak signal of the SST anomaly. However, the catastrophic flood in the Yangtze River valleys in summer of 1998 prompted scientists to study the role of the Atlantic Ocean's SSTs in EASM. Lu and Dong (2005) showed that, in this case, the Atlantic SST anomalies had a significant impact on EASM in addition to the anomalous SSTs in the Pacific and Indian oceans. They used an atmospheric model to examine the impact of Atlantic SST anomalies on the climate anomalies of the WNP and East Asia during the summer of 1998. They did this by performing a series of simulations using global SSTs and subsets of SSTs, which were carried out to isolate the impact of the Atlantic Ocean. They further suggested that the impact from the Atlantic occurs as a result of a Rossby–Kelvin wave responding to the Atlantic SST anomalies. Actually, the main features of the precipitation anomalies in Asia during the summer of 1998 can be well captured by other models, possibly due to the strong impact of tropical SST anomalies in this particular case.

Besides the tropical Atlantic Ocean, many studies have emphasized the role of the NAO or Arctic Oscillation (AO) in climate anomalies in China. Wu and Huang (1999) found that with a high index of NAO the Siberian high tends to be weakened along with a weaker EAWM and above-normal temperatures in northern China. Xu et al. (2001) showed that the onset of Mei-yu in the Yangtze River valleys is positively correlated with NAO in the previous winter. Moreover, the earlier onset of Mei-yu often corresponds to a warmer SST in the North Atlantic, and vice versa. Using longer-term data, Gong et al. (2002) further indicated that there is a significant negative correlation between summer rainfall in the Yangtze River valleys and AO in May. When AO in spring is stronger, the jet stream in East Asia tends to move poleward, resulting in drier conditions. It is suggested that the signal of the NAO or AO is helpful for summer rainfall prediction in China. It has also been revealed that a positive phase of the cold season NAO is associated with springtime cooling downstream of the Tibetan Plateau and deficient spring rainfall in regions south of the Yangtze River valleys (Yu et al., 2004; Yu and Zhou, 2004).

In addition to short-term fluctuations, North Atlantic SSTs also exhibit a low-frequency fluctuation with a period of about 65–80 years. This is referred to as the Atlantic Multidecadal Oscillation (AMO). Observational analysis has indicated that during the positive (negative) phase of the AMO, China experiences warmer (cooler) summers, and eastern China experiences wetter (drier) conditions (Lu et al., 2006). This observational relationship between the AMO and summer climate in China can be confirmed by model simulations (Lu et al., 2008). Furthermore, it has been found that the

AMO can affect winter climate in China. Both observational analyses and simulated results by several AGCMs indicate that the AMO has an impact on the EAWM (Li and Bates, 2007). A recent study suggests that a positive phase of the AMO can lead to warmer air temperatures in all four seasons (Wang et al., 2009b). This implies that a transition in the AMO from its current positive phase to a future negative phase will alleviate the warming trend in China caused by greenhouse gases.

Other patterns of Atlantic SST fluctuation may also affect decadal variations of climate in China. Gu et al. (2009) indicated that both Mei-yu rainfall amounts and Mei-yu lengths exhibit a decadal fluctuation with a period of about 12 years. They suggested that such a fluctuation is related to the tripole-like SST anomalies in the preceding winter.

Various paleoclimate records have shown that the Asian monsoon has been punctuated by numerous sub-orbital timescale events, and that these events were coeval with those that happened in the North Atlantic. Based on numerical experiments, Wang et al. (2004) showed that a warmer North Atlantic, representing an intensified thermohaline circulation, may lead to a wetter climate over China. This is consistent with evidence derived from climate reconstructions. To illustrate a dynamical explanation for this climatic link between these two remote areas, Lu and Dong (2008) investigated the Asian summer monsoon's responses to the Atlantic Ocean forcing by applying an additional freshwater flux into the North Atlantic. Their simulated results showed that the weakened Atlantic thermohaline circulation, due to the freshwater flux, led to a significantly suppressed Asian summer monsoon. Furthermore, the weakened Atlantic thermohaline circulation can also modulate the ENSO–South Asian monsoon interaction, which suggests the existence of non-local mechanisms for the decadal-multidecadal modulation of the ENSO-monsoon relationship (Lu et al., 2008).

5. Role of land surface processes in East Asian monsoon

It is well-known that the intensity of monsoon is related to land surface processes as well as oceanic state. Early studies noted the influence of snow over the Tibetan Plateau during winter and spring on EASM. Zhang and Tao (2001) found that when there is more spring snow over the Tibetan Plateau, the local sensible heat from spring to summer becomes weak. As a result, more rainfall is found over the Yangtze River valleys due to a later onset and weaker EASM. Chen et al. (2000a) investigated the role of snow over the Tibetan Plateau based on the viewpoint of air–sea interaction, and suggested that the winter snowfall over the plateau can affect the activity of EAWM. The zonal wind and SST over the western Pacific are further changed through the Hadley cell over East Asia and convective activity in the SCS, thus exerting an influence on the WPSH and summer rainfall distribution in China. Chen (2001) pointed out that, besides the strong El Niño, the anomalous snowfall during the previous winter over the plateau also played a role in the serious flooding of 1998 in the Yangtze River valleys. The evolution of summer circulation in 1998 was similar to that in years with more snow, leading to a delayed northward movement of the WPSH and maintenance of the rain belt over the Yangtze River valleys. Accordingly, the plateau's snow cover is now successfully used to predict summer rainfall in China.

The influences of snow cover over Eurasia on East Asian climate have also been noted in recent years, particularly since the improved availability of satellite observational data. Chen and Sun (2003) found that a Eurasian teleconnection pattern can be excited by anomalous snow cover through a radiation effect, thus influencing the activity of EAWM. Due to a lagged effect on the atmospheric circulation, the winter snow can further play a role in EASM and summer climate in China. A recent study by Mu and Zhou (2010) showed that the total fresh snow extent (TFSE) in winter over northern Eurasia is closely related with summer climate anomalies in China. With more TFSE in winter, there is an anomalous cold low to the east of Lake Baikal and a lower surface air temperature in northeastern China during summertime. With an enhanced subtropical westerly jet in East Asia and a more northward location of the WPSH, a hot and dry summer occurs south of the Yangtze River valleys (Fig. 7). More importantly, this relationship is independent of ENSO and stable during the last 40 years. Furthermore, Mu and Zhou (2012) revealed the related physical mechanism, showing that the consistent seasonal evolution of land surface anomalies acts as a bridge for the lagged correlation. A larger TFSE in winter is followed by a slower northeastward melting progress of snow and frozen soil over northern Eurasia in spring. Subsequently, in summer, a lower soil temperature is found over East Asian middle and high latitudes due to more intensive melting of snow and frozen soil. The local cooling, through the anomalous meridional wind, is connected to the WPSH and climate anomaly in China by enhancing the East Asian jet. In particular, the signal of winter TFSE tends to be strengthened during the melting process in spring and becomes more significant in summer. Hopefully, the TFSE can be used as another indicator for predicting summer climate in China.

Like snow cover, prior soil moisture can also play a role in summer rainfall anomalies. It is generally believed that wetter soil moisture in spring may reduce land surface temperature and the associated thermal contrast between land and sea in summer, resulting in a weak EASM. Early studies were generally confined to numerical simulations due to limitations of observational data. Wang (1991) showed that the monthly climate anomaly in China is affected by the initial anomaly of soil moisture, with the affected area confined to the anomalous center and its south. Zeng et al. (1998) demonstrated that an atmospheric model coupled with an advanced land surface model including soil moisture can provide a more reasonable simulation of the intraseasonal features of the Asian summer monsoon. By introducing a soil moisture retrieval scheme into an operational prediction model, Guo et al. (2007) proved that a better prediction of summer rainfall in

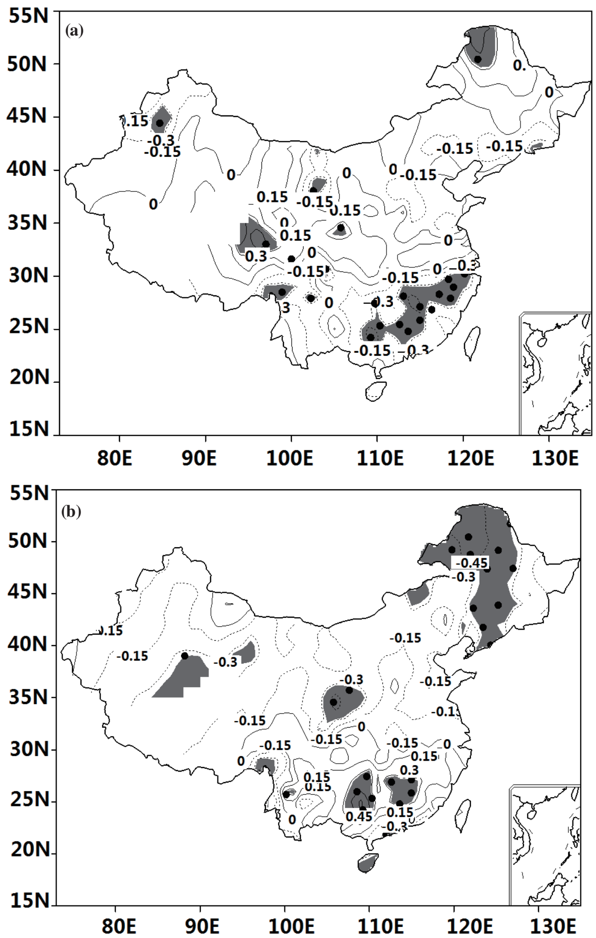

Fig. 7. Correlation of total fresh snow in winter with respect to (a) precipitation and (b) temperature in summer over China. Regions above the 95% significance level are shaded and the black dots indicate the positions of observation stations. [Reprinted from Mu and Zhou (2010)]

China can be expected with an improvement in the representation of the initial soil moisture. Based on a regional climate model, it was also shown that the simulation of surface air temperature and precipitation in China can be improved to a large degree by including the assimilation of soil moisture data (Hu et al., 2010; Zhang et al., 2012).

More recently, some studies have revealed a relationship between soil moisture anomalies in spring and summer rainfall in China using reanalysis data. Zuo and Zhang (2007) found that, corresponding to wetter soil moisture in spring from the Yangtze River valleys to northern China, there is more summer rainfall over the Yangtze River valleys. Liang and Chen (2010) showed that there is less summer rainfall in southern China if the local soil moisture in spring is drier than normal. Le et al. (2007) found that the EASM is positively correlated with soil moisture in spring in southwestern China. Zhan and Lin (2011) indicated that there is a positive correlation between rainfall in June and soil moisture in spring in the Yangtze River valleys. However, Dai and Zuo (2010) denied there is a significant connection between spring soil moisture and summer rainfall in China, except in some small areas. Clearly, there is great uncertainty in this area of study due to limited observational data; further work is needed to reveal a definite relationship between spring soil moisture and summer rainfall in China.

6. Interactions of the atmospheric circulation between the two hemispheres and East Asian monsoon

6.1. *Cross-equatorial flows and the essence of monsoon*

In the early 1930s, Li (1936a) pointed out that there is an interaction in atmospheric circulation between the two hemispheres. Based on the limited data available at the time, Li (1936a) found that a violent cold surge in East Asia invaded the SH across the Equator, resulting in rainfall in Darwin, northern Australia. It was similarly found that a cold surge in austral winter from Australia can induce the occurrence of typhoons in the tropical western Pacific (Li, 1936b). It should be noted that given the sparse distribution of weather stations in the tropics in the 1930s, Li's (1936a, b) work was a truly noteworthy advance. With the increase in the number of weather stations and the advent of satellite observations, the notion of interactions in the atmospheric circulations between the two hemispheres became increasingly clear. In general, a cold surge occurs at the polar region of the winter hemisphere, and the strong, cold air moves rapidly toward the Equator, resulting in precipitation in the summer hemisphere. The winter hemisphere circulation, therefore, plays an active role in the interactions. In fact, it is clear that the summer monsoon circulation in South Asia, and even part of the EASM circulation, initiates from the South Indian Ocean. Another branch of the EASM circulation initiates from the CEF between Sumatra and Sulawesi over Indonesia.

As a channel connecting the two hemispheres, the CEF plays an important role in the exchange of mass, momentum and energy between the two hemispheres. After the 1980s, Chinese meteorologists found other CEFs from Australia in addition to the Somali jet (Wang and Li, 1982; Tang et al., 1985). Based on more reliable data, Gao and Xue (2006) further proved that, besides the Somali jet, the CEF at 125°E is of secondary importance to EASM. Many studies have emphasized the role of CEF in EASM and summer rainfall in China. Huang et al. (1989) found that the Mei-yu rainfall in the Yangtze River valleys is positively correlated with cross-equatorial water vapor transport. Li et al. (1998) noted that there is an evident displacement of CEF during flooding years in China. Wang and Xue (2003) found that the Somali jet plays a role in inter-hemispheric water vapor transport, resulting in the summer rainfall anomaly in China. They also showed that the Somali jet usually foreshadows the variation of EASM, and thus the signal of the Somali jet is useful for summer rainfall prediction in China.

Recent studies have revealed that CEF is important to the onset of SCSSM (Li and Wu, 2002). The onset is directly influenced by the intensification and eastward extension of the equatorial westerly over the tropical Indian Ocean, which is associated with the intensification of the Somali jet. Gao and Xue (2006) indicated that two pentads prior to the onset of SCSSM there was a rapid enhancement of the Somali jet. This accelerated the eastward extension of the westerly over the Bay of Bengal and the eastward retreat of the WPSH over the SCS. In the meantime, the rapid enhancement of the CEF in the SCS was favorable for the northward march of the subtropical high. The SCSSM started, finally, under the combined actions of the two CEFs. Furthermore, the SCSSM onset tended to occur earlier when the two CEFs were stronger and established earlier, and vice versa.

The interactions of the atmospheric circulation between the two hemispheres can be indicated by mass transport across the Equator. Zeng and Li (2002) noted that two factors are important for this transport. One is the annual cycle of solar radiation, approximately represented by the zonal mean, and the other is the differences in the surface characteristics, including sea–land distribution and topography. On average, the former is about two times more important than the latter, and hence they are referred to as the first and second force, respectively. The two forces are in-phase over the Asian-Australian region, forming the most pronounced monsoon system over the globe. Conversely, the two forces counteract each other in the tropical eastern Pacific and Atlantic, which is why the trade wind prevails there. The results proved that the annual cycle of solar radiation plays a primary role in the formation of the tropical monsoon, while the difference in surface characteristics is of secondary importance.

6.2. *The role of the SH circulation in EASM*

An early study by Tao et al. (1962) showed that the alternating changes between the zonal and meridional circulations in East Asia are closely related to those in Australia during boreal summer. The prevailing meridional circulation in Australia often leads to that in the tropical latitudes in East Asia with an intense mass transport from the SH to the NH. The effects of cold air activity in Australia on EASM were also demonstrated in a numerical experiment (He et al., 1991). With the intensification of the Australian high (AH), the meridional perturbation propagates northward from Australia, resulting in a northward movement of the wind field and rainfall over East Asia.

Huang and Tang (1988) later noted the importance of the Mascarene high (MH) to EASM. Usually, after the intensification of the MH, the AH tends to be intensified through the energy dispersion of a Rossby wave in the SH westerly. Subsequently, the intensification of CEF results in the changes in EASM. Xue and He (2005) further found that both highs play a role in the east–west oscillation of the WPSH. Taking 1980 as a typical example, they showed that the two highs exhibit a biweekly oscillation, and that the AH downstream of the MH tends to be intensified with the intensification of the MH. Afterwards, the CEFs to the north of the two highs are affected, and the WPSH is further influenced through advection. The WPSH tends to be enhanced and extends westward with the intensification of the MH, while it tends to be weakened and retreats eastward with the intensification of the AH. As a result, the WPSH exhibits an obvious east–west oscillation. Moreover, the WPSH tends to extend westward continuously in boreal summer because the warm advection associated with the MH is much stronger than the cold advection associated with the AH. It is worth noting, in particular, that the low-frequency oscillation of the WPSH lags behind that of the MH or AH by 10–25 days. The two highs, therefore, are useful for mid-range forecasting of the WPSH and the associated Mei-yu rainfall.

The two highs also play a role in the interannual variation of summer rainfall in China. Based on correlation analysis and a case study, Xue et al. (2004) found that with a stronger MH in boreal spring, there is more rainfall from the Yangtze River valleys to Japan, while there is less rainfall outside of this region. Compared with the MH, the influence of the AH is confined to southern China. When the AH is stronger, there is more rainfall in southern China. Moreover, the relationship between the two highs and summer rainfall in China is generally reproduced by numerical experiments (Xue et al., 2003a). This result is of importance to summer rainfall prediction in China.

The SH circulation in the midlatitudes plays a role in EASM, especially in the seasonal transition from boreal spring to summer. He and Yang (1981) showed that there is a close relationship between the intensity of the southwest summer monsoon and the SH circulation pattern. When a meridional pattern appears in the SH, the southwest monsoon tends to be intensified. Tao et al. (1983) found that two pentads prior to the onset of the Asian summer monsoon, the westerly jet over 40°–160°E in the SH midlatitudes tends to be intensified along with the intensification of CEF, which plays a triggering role in the establishment of the EASM circulation. Zhu and Lu (1984) also noticed the role of SH cold air activity in the NH seasonal transition. He and Chen (1989) analyzed the influence of a quasi-40-day oscillation in the midlatitude SH on the Asian summer monsoon. They showed that after the outbreak of the SH cold air, the westerly to the south of the MH and AH and the easterly to the north tend to be intensified through the meridional propagation of the oscillation, resulting in the intensification of CEF and an active Asian summer monsoon. Based on the similarity theory proposed by Zeng and Zhang (1992), Xue et al. (2002) further showed that the earliest seasonal transition in the lower troposphere occurs in the Antarctic region at the end of March. The subsequent transition takes place in the SH subtropics in mid-April, finally resulting in the onset of SCSSM from middle to late May. All of these studies indicate that the SH circulation and EASM are closely connected through the CEFs, and that the SH circulation plays a leading role. Hence, the SH circulation is valuable for EASM prediction.

6.3. *The role of the Antarctic oscillation and sea-ice coverage in EASM*

As a dominant mode in the SH, the Antarctic oscillation (AAO) represents the out-of-phase relationship of sea level pressure between the subtropics and high latitudes. With a barotropic structure, the AAO is also evident in temperature and zonal winds (Gong and Wang, 1998). As a strong interannual signal, the AAO plays a role in the SH circulation, including the MH and AH. Correlation analysis indicates that the MH is mainly determined by the AAO, while the AH is influenced by both the AAO and ENSO (Xue et al., 2004). Composite analysis further shows that with the intensification of the AAO and MH, the Somali jet and the Indian monsoon westerly tend to be strengthened. Accordingly, the AH and the associated CEF become stronger, whereas the trade winds over the tropical western and central Pacific become weaker. In association with the above changes, convective activities near the Philippine Sea are largely suppressed. As a consequence, a Rossby wave train appears from East Asia via the North Pacific to the western coast of North America. In particular, when the AAO tends to be stronger during boreal spring through summer, there is more summer rainfall over the Yangtze River valleys and less rainfall outside of this region. The influence of the AAO has been further demonstrated based on longer data (Wang and Fan, 2005; Sun et al., 2008). Therefore, the AAO signal is of importance to summer rainfall prediction in China. It should be emphasized, however, that such an anomalous circulation pattern and associated rainfall distribution appear under a small difference in SST; hence, it is essentially different from the EAP pattern proposed by Huang and Li (1988).

Besides the AAO, Antarctic sea-ice coverage is also important to the prediction of EASM and summer rainfall in China. Fu (1981) found that Mei-yu in the Yangtze River valleys is negatively correlated with the Antarctic sea-ice in the preceding year. Peng and Wang (1989) showed that there is a negative relationship between Antarctic sea-ice and the intensity of the WPSH, with an eight-month lag in correlation. The ridge-line of the WPSH and the tropical cyclones landing in China are also influenced by Antarctic sea-ice (Zhao and Ji, 1989). Xue et al. (2003b) further indicated that when the Antarctic sea-ice tends to increase from boreal spring to summer, there is more rainfall in northern China and less rainfall in southern China. The effects of Antarctic sea-ice on the SH circulation as well as EASM have also been demonstrated in numerical experiments (Yang and Huang, 1992; Wang and Huang, 1994). Furthermore, there is a six-month lagged correlation of the AAO with Antarctic sea-ice, possibly due to the influence of the semi-annual oscillation in the SH high latitudes (Gao et al., 2003).

In summary, during the seasonal transition from boreal spring to summer, the SH circulation, including the AAO and the associated MH and AH, maintains seasonal persistence due to the effects of Antarctic sea-ice coverage. The EASM and summer rainfall in China are influenced by the SH circulation through the CEFs, as shown in Fig. 8 (Xue, 2005). Because of the predictability barrier in boreal spring, summer monsoon prediction based on the ENSO signal is largely limited. As stated above, the SH circulation, especially the AAO and Antarctic sea-ice coverage, may provide some valuable information for EASM prediction due to the seasonal persistence during boreal spring through summer. In other words, the predictability barrier can be overcome to a certain degree if the signal of the AAO is taken into account.

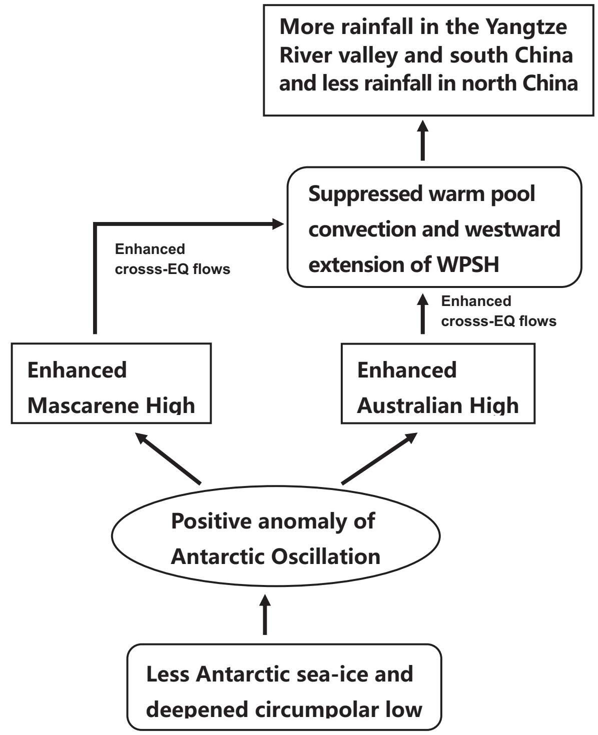

Fig. 8. Schematic diagram showing the influence of the major systems in the SH on EASM and summer rainfall in China. [Reprinted from Xue (2005)]

7. Interdecadal variations of the East Asian monsoon and climate anomalies in China

7.1. *The weakening of the East Asian monsoon during the late 1970s and climate shift in China*

In the last two decades, northern and northeastern China has suffered from severe and persistent droughts, while the Yangtze River basin and southern China have been dominated by much more significant heavy rainfall/flood events. Many studies have indicated that this is related to a notable interdecadal variation of EASM during the late 1970s together with an overall climate shift in China (Peng et al., 1999; Wang, 2001; Xue, 2001; Huang et al., 2006b; Ding et al., 2007; Zhou et al., 2008a). Following the weakening of EASM circulation, the WPSH has extended more southwestward. Accordingly, the summer rainfall regime has experienced an obvious abrupt shift in eastern China, with deficient rainfall and associated droughts in northern China and excessive rainfall and increased flooding conditions in the Yangtze River valleys, staring from the late 1970s. The weakening of EASM and the rainfall regime shift coincides well with other climate change signals that have been observed in other regions as well as in other variables (Yu and Zhou, 2007; Zhou et al., 2008b, 2008c).

Until now, different physical mechanisms have been proposed to explain the late 1970s climate shift. Xue (2001) noted that the atmosphere–ocean interaction in the western Pacific and Indian Ocean plays a role in the weakening of EASM. Gong and Ho (2002) found that changes in the WPSH are strongly associated with the variation of SSTs in the eastern tropical Pacific and tropical Indian Ocean, which is responsible primarily for the rainfall regime shift in China. This hypothesis was demonstrated by Zhou et al. (2009b), who examined the responses of five AGCMs to specified, identical Indian Ocean–Western Pacific (IWP) warming. The specified IWP warming led to a westward extension of the WPSH in all five AGCMs.

Other studies have emphasized the role of the Pacific decadal oscillation (PDO), which shows a clear phase transition on a decadal timescale (Zhu and Yang, 2003; Yang et al., 2005; Zhang et al., 2007; Gu et al., 2007). During the warm phase of the PDO, there is higher SST in the central and eastern Pacific but lower SST in the North Pacific. In this case, the northward moisture transport in East Asia is greatly weakened and cannot reach northern China, thus causing a decrease in precipitation or droughts. In contrast, the Yangtze River basin and southern China receive a large amount of moisture and have strong upward motion, creating favorable conditions for the frequent occurrence of heavy rainfall.

Since the monsoon circulation is driven by the thermal contrast between land and sea, the weakening of the EASM circulation is also related to land-surface conditions, in addition to the oceanic state. Xu et al. (2007) investigated the consistency of interdecadal variation in EASM with change in the sea–land springtime surface air temperature over eastern China and the adjacent oceans. They found that the springtime sea–land surface air temperature distribution after 1978 showed a shift in interdecadal trends. It is therefore suggested that the regional springtime sea–land surface air temperature in East Asia might have, in part, led to a weakening of the effect of sea–land thermal drive on EASM. Ding et al. (2009) noted that there was an abrupt increase in winter and spring snow over the Tibetan Plateau (TP) after 1977. Subsequently, the atmospheric heating fields over the TP assumed a significant weakening after the late 1970s. This weakening is closely related to the significantly reduced surface sensible heat flux into the atmosphere and the subsequent cooling over the TP and its surrounding atmosphere. The above interdecadal variability of heating fields over the land area in the Asian region has consistently reduced the land–sea thermal contrast in summer in the Asian monsoon region, thus leading to the weakening of EASM.

Congruent with the summer climate transition, the springtime climate over East Asia also exhibits a similar interdecadal scale transition. This is evident in both the springtime rainfall and the cooling tendency located downstream of the TP. It has been suggested that teleconnections associated with the interdecadal change of the NAO are one mechanism (Yu and Zhou, 2004; Li et al., 2005b; Xin et al., 2006). Yu et al. (2008) attempted to clarify the interdecadal climate change over East Asia within the context of 3D coherent structures. The results indicated that the decadal-scale shift of the East Asian climate exhibits a distinct 3D structure. The surface climate change is coherently connected with the temperature change over the middle and upper troposphere, with clear seasonal features. A prominent cooling trend is found over East Asia in the upper troposphere around 300 hPa. Accompanying this summer cooling, the upper level westerly jet stream over East Asia shifted southward and the EASM tended to be weakened, resulting in the tendency toward increased droughts in northern China and more flooding along the Yangtze River valleys. Yu and Zhou (2007) also regarded the spring and summer interdecadal scale climate changes as the seasonal manifestation of one phenomenon. The impact of springtime tropospheric cooling over East Asia on the surface climate has been demonstrated by numerical experiments (Xin et al., 2006). In addition, an extended analysis by Zhou and Zhang (2009) revealed an interdecadal variability of July–August tropospheric temperatures across the entire subtropical NH. A major mode was identified, with one significant cooling center over East Asia and two warming centers over the North Atlantic and North Pacific, respectively. Hence, the interdecadal climate transition of the East Asian climate may be a local manifestation of the NH climate shift.

Various numerical experiments have been performed to reveal the physical mechanisms involved in the weakening of the EASM. The weakening can usually be simulated by an atmospheric model forced by historical SST (Zeng et al., 2007; Fu et al., 2009). Li et al. (2008b) analyzed the ensemble runs from 1950–2000 by using two different AGCMs that were forced separately by observed tropical and global SSTs. They found that the observed SST forcing, primarily from the tropics and including both the Pacific and the Indian Ocean, was able to reproduce most of the observed atmospheric circulation changes associated with the weakening of the EASM since the 1970s. However, most atmospheric models fail to capture the major features of the interdecadal climate shift (Han and Wang, 2007), especially with respect to the monsoon's rainfall change. Despite reasonable simulation of the observed circulation changes, they fail to reproduce the relatively small-scale rainfall change patterns over East China (Li et al., 2008b). Recently, using the fourth generation AGCM with a relatively high resolution developed at the Institute of Atmospheric Physics, Chinese Academy of Sciences, Chen and Xue (2013) showed that the model simulates the decadal weakening of EASM circulation as well as the anomalous summer rainfall pattern in eastern China, i.e., the increase over the Yangtze River basin and the decrease over northern and southern China. Further analysis indicated that the decadal weakening of EASM is mainly driven by the warming in the tropical oceans, which is related with the phase transition of the PDO in the late 1970s. Hence, simulated results are model-dependent.

Although coupled atmosphere–ocean models forced by greenhouse gases can simulate the global warming trend during the latter half of the 20th century, they do not reproduce the weakening of EASM (Jiang and Wang, 2005; Yu et al., 2008). Therefore, although it can be argued that the weakening is caused by anthropogenic global warming, it is more likely attributable to the natural variability of the global atmosphere–ocean system (Chen and Xue, 2013).

7.2. *Interannual variability of the East Asian monsoon during different decades*

Many studies have shown that the interannual variability of EASM is modulated by the decadal climate background. In particular, the relationship between ENSO and EASM is variable during different decades (Wang, 2002). There is a high correlation and a low correlation period, and a larger interannual variability is found during the higher correlation period. This variable relationship also appears in a coupled ocean–atmosphere model (Jiang et al., 2004).

Gao and Wang (2007) examined the correlation between summer rainfall in China and SST anomalies in the tropical Pacific in the preceding winter. They found that the significance of ENSO on summer rainfall prediction in China decreased remarkably after the late 1970s. Before the late 1970s, when above-normal SSTs occurred over the central and eastern Pacific during the preceding winter, more summer rainfall could be found in northern China and south of the Yangtze River valleys and less summer rainfall over the Huaihe River regime, and vice versa. However, all of these relationships were found to obviously weaken after the late 1970s. For example, during 1951–1974 there were 43 stations in total whose summer rainfall anomalies could be predicted by the Niño3 SST anomaly of the preceding winter, with an accuracy of anomaly sign of greater than 67%, while the total number of such stations reduced to 15 during 1980–2003. Zhu et al. (2007) found that the significant differences in the ENSO-related atmospheric circulation anomalies in East Asia during different decades are probably responsible for the interdecadal variation between ENSO and EASM. Ye and Lu (2011) further indicated that the ENSO-related rainfall anomalies tended to be similar between early and late summer before the late 1970s; that is, the period characterized by a stronger ENSO–summer mean rainfall relationship. After the late 1970s, however, the anomalous rainfall pattern in eastern China was found to be almost reversed between early and late summer, resulting accordingly in a weakened relationship between ENSO and the total summer rainfall in eastern China. Therefore, the background of the interdecadal variation of the predictor must be fully considered when the effect of ENSO is taken into account in operational predictions of summer precipitation in China.

It is interesting to note that, with the decadal variation in the late 1970s, the SH circulation and its influence on summer rainfall in eastern China also changed (Sun et al., 2012). With a positive anomaly of the AAO in boreal spring, there was more rainfall over south of the Yangtze River and less rainfall over the Yangtze–Huaihe River valleys before the late 1970s. On the other hand, there has been more rainfall from south China to the Yangtze–Huaihe River valleys and less rainfall in northern and northeastern China after the late 1970s. Clearly, the influence of the AAO tends to intensify and extend more northward. It is therefore suggested that the AAO can be used as an important predictor of summer rainfall in China when the effect of ENSO as a predictor is weak, as is presently the case.

Wang and Huang (2006) indicated that the relationship of summer rainfall between northern China and India is also variable during different decades, with a higher correlation appearing during strong EASM periods. In general, a lower SST in the eastern Pacific is associated with more La Niña events and a higher correlation. After the late 1970s, the SST in the eastern Pacific tended to be enhanced due to the phase transition of the PDO. The relationship of summer rainfall between the two regions became weak, as found in the ENSO–EASM relationship mentioned above.

As well as the EASM, Xu et al. (1997) noted that the relationship between the EAWM and ENSO has also changed during different decades. This relationship is modulated by both the winter monsoon and the oceanic decadal background. When they are in-phase, a strong winter monsoon is favorable for the onset of an El Niño event. On the other hand, a strong winter monsoon corresponds to a La Niña event.

8. Concluding remarks

Because of the importance of the East Asian monsoon in controlling climate anomalies in China, Chinese scientists have invested great effort in monsoon studies since the 1930s. In recent years, the availability of a complete dataset and powerful computers have allowed Chinese scientists to explore many aspects of the East Asian monsoon in a more comprehensive fashion than was previously the case. These major advances have been reviewed in this paper, including those related to seasonal variation, interannual variation and interdecadal variation. The major conclusions can be summarized as follows:

First, as the monsoon is characterized by large-scale seasonal wind reversal, seasonality can therefore be used to describe the monsoon regions. In addition to the traditional tropical monsoon, there are the subtropical and temperate-frigid monsoons in the lower troposphere, the planetary monsoon in the upper troposphere, and the stratospheric monsoon. These regions with their large seasonality make up the global monsoon system, and exhibit a significant baroclinic structure. Similarities of atmospheric circulation have been proposed to describe the seasonal variation of monsoons, and it has been shown that the seasonal variation originates from the upper stratosphere and the coldest region of the lower troposphere.

The Asian monsoon exhibits clear patterns of seasonal variation, the most significant of which is the onset of SCSSM around mid-May, signaling the seasonal transition from winter to summer over the entire Asian summer monsoon system. Recent studies have shown that, instead of a regional phenomenon, the onset of SCSSM is connected with the seasonal variation of the global atmospheric circulation. The thermal contrast between the Asian continent and adjacent oceans plays a dominant role in the onset. The CEFs associated with the SH circulation and the stratospheric circulation may foreshadow the onset. Also evident is the ISO during the summer monsoon period. Different from the ISO in the tropical monsoon region, as represented by the active or break monsoon rain, the circulation system and rain belt in the East Asian monsoon region exhibit a northward movement in a stepwise fashion with two distinct jumps. In particular, the first and second jump of the WPSH are closely connected with the start and end of the Mei-yu period in the Yangtze River basin.

Due to the importance of summer rainfall prediction in China, the relationship between EASM and ENSO has been studied extensively. As the strongest signal in the coupled ocean–atmosphere system, ENSO plays a fundamental role in EASM and summer rainfall in China. It has been shown that, compared with tropical summer monsoons, such as Indian summer monsoon, ENSO has a long-delayed effect on EASM. In the succeeding year after the onset of El Niño events, a suppressed convection in the warm pool of the tropical western Pacific excites a Rossby wave train and the associated East-Asia–Pacific teleconnection pattern, and the WPSH is located more southwestward. As a result, there is more rainfall along the Yangtze River basin and less rainfall in southern and northern China. A typical example occurred in the summer of 1998, when the Yangtze River valleys experienced a devastating flood due to the strong ENSO event of 1997–98. Recent studies also revealed that there is a nonlinear relationship between the magnitude of ENSO and the EASM circulation and the associated summer rainfall in China; the composite summer rainfall in China in moderate ENSO years exhibits a northern rainfall pattern, which is totally different from the classical ENSO-type rainfall pattern. In addition, the summer rainfall anomaly in China is sensitive to the spatial distribution of SST anomalies in the tropical Pacific. These results show a more complex relationship between ENSO and EASM than previously thought. Furthermore, extratropical atmospheric disturbances, including a stronger EAWM, play a triggering role in the onset of ENSO, indicating that the monsoon and ENSO are an interactive system.

The Indian Ocean and Atlantic Ocean also play a role in EASM. Chinese scientists have noted the influence of the Indian Ocean on EASM since the early 1980s, and recent studies have revealed the influence of the IOD on EASM, especially when the ENSO signal is relatively weak. Moreover, the Indian Ocean acts as a charger, largely prolonging the effect of ENSO on EASM in the succeeding year. The influence of the Atlantic Ocean, especially the NAO, has also been noted in recent years. These results provide additional information that is useful for summer rainfall prediction in China.

Besides the oceanic state, there is now ample evidence that land surface processes play a role in the EASM interannual variability. When there is more spring snow on the TP, for instance, the local sensible heat during spring through summer tends to be weakened, leading to a weaker EASM and more rainfall in the Yangtze River basin. A recent study also noted that the total fresh snow extent in winter over Eurasia is closely related with summer climate anomalies in China, providing a new predictor for summer climate prediction in China. Soil moisture is believed to be another factor that may influence the EASM. Compared with snow cover, however, there is uncertainty regarding the relationship between spring soil moisture and summer rainfall in China, largely due to insufficient observational data.

There is interaction of the atmospheric circulation between the two hemispheres, and the SH circulation exerts an influence on EASM through the CEFs. With the intensification of the AAO, the MH and AH in the southern subtropics, along with the CEFs, tend to be enhanced. Correspondingly, the WPSH tends to be intensified and located more southwestward, thereby inducing an ENSO-like rainfall anomaly in East Asia. It is also noted that the SH circulation plays a leading role during the seasonal transition from boreal winter to summer. In the meantime, the SH circulation maintains a seasonal persistence due to Antarctic sea-ice coverage. It is therefore suggested that the signal of the SH circulation, especially the AAO, is valuable for the seasonal forecasting of summer rainfall in China.

In addition to interannual variability, the East Asian monsoon also exhibits an interdecadal variability, the most significant feature of which is the weakening of EASM since the late 1970s. Following this weakening, summer rainfall patterns in China have changed, with more rainfall over the Yangtze River valleys and less rainfall over northern China. Different physical mechanisms have been proposed to explain this unique climate shift, including the phase transition of the PDO and global warming. Also noteworthy is that the interannual variability of EASM has changed after this climate shift. For instance, the relationship between summer rainfall in China and ENSO has tended to weaken since the 1970s, making seasonal forecasts in China based on ENSO more unreliable. Further studies are needed to reveal the nature of this weakening relationship between EASM and ENSO.

Recent studies have shown that the East Asian monsoon is a complex, nonlinear phenomenon involving atmospheric, oceanic and land-based processes, and it exhibits variability on a variety of time scales, ranging from intraseasonal and interannual to interdecadal time scales. It is influenced by many factors, including external factors (e.g., ENSO) and internal atmospheric dynamics (e.g., the AAO). It is now recognized that the prediction of the monsoon is limited by the high-frequency variability associated with its internal dynamics. To further enhance monsoon predictability, it is important to determine in what ways the distribution of these high-frequency signals interact with the large-scale stationary patterns induced by the slowly changing boundary conditions.

Although marked progress has been made in monsoon studies in China over the years, the physical mechanisms for the occurrence of droughts and floods in China and the associated East Asian monsoon variability are still not fully understood. While it is generally accepted that the mean monsoon system is highly stable, state-of-the-art climate models are relatively poor in simulating the East Asian monsoon compared to other monsoon regions. Although the prediction of monsoon rainfall in China using dynamical models has made great advances, it is far from satisfactory (Wang et al., 2015). It is unclear at this stage whether the inability of current models to simulate and predict monsoon rainfall is due to model deficiencies or the intrinsic lack of predictability of the monsoon. In addition, understanding, modeling and predicting monsoons are of great importance to the projection of future climate change due to the increase in the concentration of greenhouse gases. The East Asian monsoon region is one of a few places for which nearly all climate models project an enhanced interannual variability of summer rainfall in association with global warming (Lu and Fu, 2010). Therefore, our ability to predict the interannual changes in monsoon circulation and rainfall is a critical requirement for the sustainable development of China. There is a vital need in the near future to obtain a complete picture of the spatial and temporal aspects of the East Asian monsoon in order to advance our understanding and awareness of the monsoon to a new level and to provide guidance for the improvement of seasonal prediction systems in China.

Acknowledgements. The authors would like to thank Prof. WANG Huijun for his help in organizing the writing of this paper. The authors have benefited from the insightful comments and suggestions of three anonymous reviewers. They also thank Dr. SU Tonghua for preparing some of figures. This work was supported by the Chinese Academy of Sciences (Grant No. XDA05110201) and the National Natural Science Foundation of China (Grant No. 41475052).

REFERENCES

Chen, H., and F. Xue, 2013: Numerical simulation of the decadal variation of East Asian summer monsoon and summer rainfall in eastern China. *Chinese J. Atmos. Sci.*, **37**, 1143–1153. (in Chinese)

Chen, H. S., and Z. B. Sun, 2003: The effects of Eurasian snow cover anomaly on winter atmospheric general circulation. Part I, observational studies. *Chinese J. Atmos. Sci.*, **27**, 304–316. (in Chinese)

Chen, L. T., 1977: The effects of the anomalous sea-surface temperature of the equatorial Eastern Pacific Ocean on the tropical circulation and rainfall during the rainy period in China. *Chinese J. Atmos. Sci.*, **1**, 1–12. (in Chinese)

Chen, L. T., 1988: Zonal anomalies of sea surface temperature in the tropical Pacific and Indian Ocean and the influence on Asian summer monsoon. *Chinese J. Atmos. Sci.*, **12** (Special Issue), 142–148. (in Chinese)

Chen, L. T., 1991: Effects of zonal difference of sea surface temperature anomalies in the Arabian Sea and the South China Sea on summer rainfall over the Yangtze River. *Chinese J. Atmos. Sci.*, **15**, 33–42. (in Chinese)

Chen, L. T., 2001: The role of the anomalous snow cover over the Qinghai-Xizang Plateau and ENSO in the great floods of 1998 in the Changjiang River valleys. *Chinese J. Atmos. Sci.*, **25**, 184–192. (in Chinese)

Chen, L. T., Z. H. Jin, and S. H. Luo, 1985: The variability of SST over the Indian Ocean and the South China Sea and its linkage with the atmospheric circulation. *Acta Oceanologica Sinica*, **7**, 103–110. (in Chinese)

Chen, Q. J., B. Gao, and Q. Zhang, 2000a: Studies on relation of snow cover over the Tibetan Plateau in winter to the winter-summer monsoon change. *Chinese J. Atmos. Sci.*, **24**, 477–492. (in Chinese)

Chen, Y. L., X. Z. Bai, and Y. P. Zhao, 2000b: A study on the relationships between the onset of the South China Sea summer monsoon and the anomalies of tropical ocean and atmospheric circulations. *Climatic and Environmental Research*, **5**, 388–399. (in Chinese)

Dai, C. Y., and Z. Y. Zuo, 2010: Relationship between previous winter and spring soil moisture and summer climate in eastern China. *Meteorological Sciences and Technology*, **38**, 300–305. (in Chinese)

Ding, Y. H., 1994: *Monsoons over China*. Kluwer Academic Publishers, Dordrecht, Boston, 419 pp.

Ding, Y. H., and Coauthors, 2004: South China Sea monsoon experiment and the East Asian monsoon. *Acta Meteorologica Sinica*, **62**, 561–586. (in Chinese)

Ding, Y. H., Z. Y. Wang, and Y. Sun, 2007: Interdecadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. *Int. J. Climatol.*, **28**, 1139–1161.

Ding, Y. H., Y. Sun, Z. Y. Wang, Y. X. Zhu, and Y. F. Song, 2009: Interdecadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part II: Possible causes. *Int. J. Climatol.*, **29**, 1926–1944.

Fu, C. B., 1981: The possible linkage between variability of Meiyu over the Yangtze River valleys and state of the Antarctic snow and ice. *Chinese Science Bulletin*, **26**, 484–486. (in Chinese)

Fu, C. B., and X. L. Teng, 1988: Relationship between summer climate in China and El Niño/southern oscillation phenomenon. *Chinese J. Atmos. Sci.*, **12**(S1), 133–141. (in Chinese)

Fu, J. J., S. L. Li, and D. H. Luo, 2009: Impact of global SST on decadal shift of East Asian summer climate. *Adv. Atmos. Sci.*, **26**, 192–201, doi: 10.1007/s00376-009-0192-2.

Fu, Y. F., and R. H. Huang, 1997: Impacts of the westerly anomalies over East Asia on westerly burst over the western tropical Pacific and the occurrence of ENSO events. *Chinese J. Atmos. Sci.*, **21**, 485–492. (in Chinese)

Gao, H., and F. Xue, 2006: Seasonal variation of the cross-equatorial flows and their influences on the onset of South China Sea summer monsoon. *Climatic and Environmental Research*, **11**, 57–68. (in Chinese)

Gao, H., and Y. G. Wang, 2007: On the weakening relationship between summer precipitation in China and ENSO. *Acta Meteorologica Sinica*, **65**, 131–136. (in Chinese)

Gao, H., F. Xue, and H. J. Wang, 2003: Influence of interannual variability of Antarctic oscillation on mei-yu along the Yangtze and Huaihe River valleys and its importance to prediction. *Chinese Science Bulletin*, **48**(S2), 61–67.

Gong, D. Y., and S. W. Wang, 1998: Antarctic oscillation. *Chinese Science Bulletin*, **43**, 734–738.

Gong, D. Y., and C. H., Ho, 2002: Shift in the summer rainfall over Yangtze River valleys in the late 1970s. *Geophys. Res. Lett.*, **29**, 78-1–78-4, doi: 10.1029/2001GL014523.

Gong, D. Y., J. H. Zhu, and S. W. Wang, 2002: Significant relationship between spring AO and the summer rainfall along the Yangtze River. *Chinese Science Bulletin*, **47**, 948–951.

Gu, W., C. Y. Li, and J. Pan, 2007: Relationship between interdecadal variation of North Pacific equatorial Indian Ocean SST and transition of rainfall pattern in east China around the 1970s. *Climatic and Environmental Research*, **12**, 113–123. (in Chinese)

Gu, W., C. Y. Li, X. Wang, W. Zhou, and W. J. Li, 2009: Linkage between Mei-yu precipitation and North Atlantic SST on the decadal timescale. *Adv. Atmos. Sci.*, **26**, 101–108, doi: 10.1007/s00376-009-0101-5.

Guo, W. D., Z. G. Ma, and H. J. Wang, 2007: Soil moisture: an important factor of seasonal precipitation prediction and its application. *Climatic and Environmental Research*, **12**, 20–28. (in Chinese)

Han, J. P., and H. J. Wang, 2007: Interdecadal variability of the East Asian summer monsoon in an AGCM. *Adv. Atmos. Sci.*, **24**, 808–818, doi: 10.1007/s00376-007-0808-0.

He, J. H., and L. Z. Chen, 1989: Quasi-40 day oscillation over the mid-latitude of the Southern Hemisphere with their relation to the summer monsoon over the Northern Hemisphere. *Journal of Nanjing Institute of Meteorology*, **12**, 11–18. (in Chinese)

He, J. H., J. Li, and Y. P. Li, 1991: Numerical experiment with processes for effect of Australian cold air activity on East Asian summer monsoon. *Acta Meteorologica Sinica*, **49**, 162–160. (in Chinese)

He, J. H., H. M. Xu, B. Zhou, and L. J. Wang, 2000: Large scale features of SCS summer monsoon onset and its possible mechanism. *Climatic and Environmental Research*, **5**, 333–344. (in Chinese)

He, S. X., and Z. F. Yang, 1981: The relationship between the intensity of summer southwest monsoon over northwest Pacific and the circulation patterns of the Southern Hemisphere. *Chinese J. Atmos. Sci.*, **5**, 50–59. (in Chinese)

He, X. C., Y. H. Ding, and J. H. He, 2008: Response characteristics of the East Asian winter monsoon to ENSO events. *Chinese J. Atmos. Sci.*, **32**, 335–344. (in Chinese)

Hu, Y. M., Y. H. Ding, and F. Liao, 2010: An improvement on summer regional climate simulation over East China: importance of data assimilation of soil moisture. *Chinese Science Bulletin*, **55**, 865–871.

Huang, J. Y., 1988: Representation of quasi-biennial oscillation in rainfall in China. *Chinese J. Atmos. Sci.*, **12**, 267–273. (in Chinese)

Huang, R. H., and W. J. Li, 1988: Influence of the heat source anomaly in the tropical western Pacific on western Pacific subtropical high in summer and its physical mechanism. *Chinese J. Atmos. Sci.*, **12**, 107–116. (in Chinese)

Huang, R. H., and F. Y. Sun, 1992: Impact of the tropical western Pacific on the East Asian summer monsoon. *J. Meteor. Soc. Japan*, **70**(1B), 243–256.

Huang, R. H., and F. Y. Sun, 1994: Impact of the convection activities over the western tropical Pacific warm pool on the intraseasonal variability of the East Asian summer monsoon. *Chinese J. Atmos. Sci.*, **18**, 456–465. (in Chinese)

Huang, R. H., Y. F. Fu, and X. Y. Zang, 1996: Asian monsoon and ENSO cycle interaction. *Climatic and Environmental Research*, **1**, 38–54. (in Chinese)

Huang, R. H., Y. H. Xu, P. F. Wang, and L. T. Zhou, 1998: The features of the catastrophic flood over the Changjiang River basin during the summer of 1998 and cause exploration. *Climatic and Environmental Research*, **3**, 300–313. (in Chinese)

Huang, R. H., J. L. Chen, G. Huang, and Q. L. Zhang, 2006a: The quasi-biennial oscillation of summer monsoon rainfall in China and its cause. *Chinese J. Atmos. Sci.*, **30**, 545–560. (in Chinese)

Huang, R. H., R. S. Cai, J. L. Chen, and L. T. Zhou, 2006b: Interdecadal variations of drought and flooding disasters in China and their association with the East Asian climate system. *Chinese J. Atmos. Sci.*, **30**, 730–743. (in Chinese)

Huang, S. S., and Z. H. Yu, 1962: On the structure of the subtropical highs and some associated aspects of the general circulation of atmosphere. *Acta Meteorologica Sinica*, **31**, 339–359. (in Chinese)

Huang, S. S., and M. M. Tang, 1962: Some aspects of the latitudinal variation of the subtropical highs. *Journal of Nanjing Institute of Meteorology*, **2**, 41–56. (in Chinese)

Huang, S. S., and M. M. Tang, 1988: Medium-range oscillation and teleconnection of the atmospheric circulation systems over the northwest Pacific and South Indian Oceans. *Scientia Meteorologica Sinica*, **8**, 1–18. (in Chinese)

Huang, S. S, M. M. Tang, and X. Q. Yang, 1989: Influence of variations of the circulation system over the south Indian Ocean on the East Asian summer monsoon and the Northern hemispheric general circulation of the atmosphere. *International Conference on East Asia and Western Pacific Meteorology and Climate*, P. Sham and C. P. Chang, Eds., World Scientific, In: 105–118.

Jiang, D. B., and H. J. Wang, 2005: Natural interdecadal weakening of East Asian summer monsoon in the late 20th century. *Chinese Science Bulletin*, **50**, 1923–1929.

Jiang, D. B., H. J. Wang, H. Drange, and X. M. Lang, 2004: Instability of the East Asian summer monsoon-ENSO relationship in a coupled global atmosphere-ocean GCM. *Chinese J. Geophys.*, **47**, 976–981. (in Chinese)

Ju, J. H., C. Qian, and J. Cao, 2005: The intraseasonal oscillation of East Asian summer monsoon. *Chinese J. Atmos. Sci.*, **29**, 187–194.

Le, Y. L., Y. Luo, and P. W. Guo, 2007: A study on the relationship between spring soil moisture over China and East Asian summer monsoon. *Journal of Tropical Meteorology*, **23**, 474–482. (in Chinese)

Li, C. Y., 1989: Frequent activities of stronger aerotroughs in East Asia in wintertime and the occurrence of the El Niño event. *Science in China*, **32**(B), 976–985.

Li, C. Y., 1990: Interaction between anomalous winter monsoon in East Asia and El Niño events. *Adv. Atmos. Sci.*, **7**, 36–46, doi: 10.1007/BF02919166.

Li, C. Y., 1992: An analytical study on the precipitation in the flood period over Huabei area. *Acta Meteor. Sinica*, **50**, 41–49. (in Chinese)

Li, C. Y., 1995: Westerly anomalies over the equatorial western Pacific and Asian winter monsoon. *Proceedings of the International Scientific Conferences on the TOGA Program*, WCRP-91-WMO/TP. No.717, 557–561.

Li, C. Y., and M. Q. Mu, 1998: Numerical simulations of anomalous winter monsoon in East Asia exciting ENSO. *Chinese J. Atmos. Sci.*, **22**, 481–490. (in Chinese)

Li, C. Y., and X. Qu, 2000: Large scale atmospheric circulation evolutions associated with summer monsoon onset in the South China Sea. *Chinese J. Atmos. Sci.*, **24**, 1–14. (in Chinese)

Li, C. Y., and M. Q. Mu, 2001: The dipole in the equatorial Indian Ocean and its impacts on climate. *Chinese J. Atmos. Sci.*, **25**, 433–443. (in Chinese)

Li, C. Y., and M. Q. Mu, 2002: A further study of essence of the

ENSO. *Climatic and Environmental Research*, **7**, 160–174.

Li, C. Y., and J. B. Wu, 2002: Important role of the Somali cross-equator flow in the onset of the South China Sea summer monsoon. *Chinese J. Atmos. Sci*., **26**, 185–192. (in Chinese)

Li, C. Y., M. Q. Mu, and P. Jing, 2002: Indian Ocean temperature dipole and SSTA in the equatorial Pacific Ocean. *Chinese Science Bulletin*, **47**, 236–239.

Li, C. Y., J. T. Wang, S. Z. Lin, and H. R. Cho, 2005a: The relationship between East Asian summer monsoon activity and northward jump of the upper-air westerly jet location. *Chinese J. Atmos. Sci*., **29**, 1–20. (in Chinese)

Li, C. Y., M. Q. Mu, G. Q. Zhou, and H. Yang, 2008a: Mechanism and prediction studies of the ENSO. *Chinese J. Atmos. Sci.*, **32**, 761–781. (in Chinese)

Li, D. H., Y. M. Zhu, Y. K. Tan, and G. Zhang, 2006: Relationships between spring ocean sea surface temperature anomalies in the tropical Indian Ocean and the strength of South China Sea summer monsoon. *Climatic and Environmental Research*, **11**, 514–524. (in Chinese)

Li, H., A. Dai, T. Zhou, and J. Lu, 2008b: Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950–2000. *Climate Dyn.*, **34**, 501–514.

Li, J., R. C. Yu, T. J. Zhou, and B. Wang, 2005b: Why is there an early spring cooling shift downstream of the Tibetan Plateau? *J. Climate*, **18**, 4660–4668.

Li, S., and G. T. Bates, 2007: Influence of the Atlantic multidecadal oscillation on the winter climate of East China. *Adv*. *Atmos. Sci.*, **24**, 126–135, doi: 10.1007/s00376-007-0126-6.

Li, S., J. Lu, G. Huang, and K. Hu, 2008c: Tropical Indian Ocean basin warming and East Asian summer monsoon: A multiple AGCM study. *J. Climate*, **21**, 6080–6088.

Li, X. Z., 1936a: Studies on the invasion of cold surges in East Asia. *Met. Zeitschr.*, **53**, 74. (in German) [also in: *Collected Papers of the Modern Sciences in China-Meteorology (1919–1949)*, China Science Press, Beijing, 1955, 35–118. (in Chinese)]

Li, X. Z., 1936b: Studies on typhoon. *Veroff. D. Met. Inst. D. Univ. Berlin* (in Germany), **1**, 28. [also in: *Collected Papers of the Modern Sciences in China – Meteorology (1919–1949)*, China Science Press, Beijing, 1955, 119–146. (in Chinese)]

Li, Z. Z., Y. A. Li, and S. Y. Chao, 1998: Relationship between flood and disasters over China and cross-equatorial flow. *Quart. J. Appl. Meteor.*, **9**(S), 132–136. (in Chinese)

Liang, L. N., and H. S. Chen, 2010: Possible linkage between spring soil moisture anomalies over South China and summer rainfall in China. *Transactions of Atmospheric Sciences*, **33**, 536–546. (in Chinese)

Liang, Z. N., Z. P. Wen, and L. J. Wu, 2006: Relationship between the Indian Ocean sea surface temperature anomaly and the onset of South China Sea summer monsoon. I., Coupling analysis. *Chinese J. Atmos. Sci.*, **30**, 619–634. (in Chinese)

Lin, Z. D., and R. Y. Lu, 2009: ENSO's effect on eastern China rainfall in the following early summer. *Adv*. *Atmos. Sci.*, **26**, 333–342, doi: 10.1007/s00376-009-0333-4.

Liu, D. Q., and X. Q. Yang, 2010: Mechanism responsible for the impact of Madden–Julian oscillation on the wintertime rainfall over eastern China. *Scientia Meteorologica Sinica*, **30**, 684–693. (in Chinese)

Liu, N., Q. L. Zhou, Z. Y. Guan, and S. L. Mei, 2008a: The response of the climate anomaly in the troposphere of the Northern Hemisphere to the SST dipole in the tropical Indian Ocean and its dynamical mechanism. *Progress in Natural Sciences*, **18**, 668–673. (in Chinese)

Liu, X. F., H. Z. Yuan, and Z. Y. Guan, 2008b: Effects of ENSO on the relationship between IOD and China summer rainfall. *Journal of Tropical Meteorology*, **24**, 502–506. (in Chinese)

Lu, R. Y., 2000: Anomalies in the tropics associated with the heavy rainfall in East Asia during the summer of 1998. *Adv. Atmos. Sci.*, **17**, 205–220, doi: 10.1007/s00376-000-0004-y.

Lu, R. Y., 2005: Interannual variation of North China rainfall in rainy season and SSTs in the equatorial eastern Pacific. *Chinese Science Bulletin*, **50**, 2069–2073.

Lu, R. Y., and B. W. Dong, 2005: Impact of Atlantic SST anomalies on the summer climate in the western North Pacific during 1997–1998. *J. Geophys. Res*., **110**, D16102, doi: 10.1029/2004JD005676.

Lu, R. Y., and B. Dong, 2008: Response of the Asian summer monsoon to a weakening of Atlantic thermohaline circulation. *Adv. Atmos. Sci.*, **25**, 723–736, doi: 10.1007/s00376-008-0723-z.

Lu, R. Y., and Z. D. Lin, 2009: Role of subtropical precipitation anomalies in maintaining the summertime meridional teleconnection over the western North Pacific and East Asia. *J. Climate*, **22**, 2058–2072.

Lu, R. Y., and Y. Fu, 2010: Intensification of East Asian summer rainfall interannual variability in the twenty-first century simulated by 12 CMIP3 coupled models. *J. Climate*, **23**, 3316–3331.

Lu, R. Y., B. W. Dong, and H. Ding, 2006: Impact of the Atlantic Multidecadal Oscillation on the Asian summer monsoon. *Geophys. Res. Lett.*, **33**, L24701, doi: 10.1029/2006GL027655.

Lu, R. Y., W. Chen, and B. W. Dong, 2008: How does a weakened Atlantic thermohaline circulation lead to an intensification of the ENSO-south Asian summer monsoon interaction? *Geophys*. *Res. Lett.*, **35**, L08706, doi: 10.1029/2008GL033394.

Luo, S. H., Z. H. Jin, and L. T. Chen, 1985: A correlation analysis of summer rainfall in the Yangtze River with surface temperature in Indian Ocean and South China Sea. *Chinese J. Atmos. Sci.*, **9**, 314–320. (in Chinese)

Miao, J. H., and K. M. Lau, 1991: Low frequency oscillation (30–60 day) of summer monsoon rainfall over East Asia. *Chinese J. Atmos. Sci.*, **15**, 65–71. (in Chinese)

Mu, M. Q., and C. Y. Li, 2002: Indian Ocean dipole and its relationship with ENSO mode. *Acta Meteorologica Sinica*, **16**, 489–497. (in Chinese)

Mu, S. N., and G. Q. Zhou, 2010: Relationship between winter northern Eurasian fresh snow extent and summer climate anomalies in China. *Chinese J. Atmos. Sci.*, **34**, 213–226. (in Chinese)

Mu, S. N., and G. Q. Zhou, 2012: Mechanism for the correlation of winter fresh snow extent over northern Eurasia and summer climate anomalies in China: Anomalous seasonal transition of land as a bond. *Chinese J. Atmos. Sci.*, **36**, 297–315. (in Chinese)

Peng, G. B., and P. K. Wang, 1989: Influence of the Antarctic sea-ice on the North-west Pacific subtropical high and its background of ocean-atmospheric circulation. *Chinese Science Bulletin*, **34**, 56–58. (in Chinese)

Peng, J. Y., Z. B. Sun, and W. J. Zhu, 1999: The catastrophe of atmospheric general circulation and China dry and wet pattern in the late 1970s. *Journal of Nanjing Institute of Meteorology*, **22**, 300–304. (in Chinese)

Qian, W., and Z. Y. Guan, 2007: Relationships between SSTA of the tropical Indian Ocean and summer rainfall in southern China. *Journal of Nanjing Institute of Meteorology*, **30**, 9–16. (in Chinese)

Qian, W. H., J. Zhu, Y. G. Wang, and J. L. Fu, 2009: Regional relationship between the Jiang-Huai Meiyu and the equatorial surface-subsurface temperature anomalies. *Chinese Science Bulletin*, **54**, 113–119.

Su, T. H., and F. Xue, 2010: The intraseasonal variation of summer monsoon circulation and rainfall in East Asia. *Chinese J. Atmos. Sci.*, **34**, 611–628. (in Chinese)

Su, T. H., and F. Xue, 2011: Two northward jumps of the summertime western Pacific subtropical high and their associations with the tropical SST anomalies. *Atmos. Oceanic Sci. Lett.*, **4**, 98–102.

Sun, D., F. Xue, and T. J. Zhou, 2012: The influence of the Southern Hemisphere circulation on summer rainfall in China under the different decadal background. *Climatic and Environmental Research*, **17**, 51–62. (in Chinese)

Sun, J. Q., H. J. Wang, and W. Yuan, 2008: A possible mechanism for the co-variability of the boreal spring Antarctic oscillation and the Yangtze River valleys summer rainfall. *Int. J. Climatol.*, **29**, 1276–1284.

Tang, M. M., S. S. Huang, and D. P. Zhou, 1985: The temporal-spatial variation of the global cross-equatorial flows. *Journal of Tropical Meteorology*, **11**, 287–296. (in Chinese)

Tao, S. Y., and F. K. Chu, 1964: The 100-mb flow patterns in southern Asia in summer and its relation to the advance and retreat of the west-Pacific subtropical anticyclone over the Far East. *Acta Meteorologica Sinica*, **34**, 385–395. (in Chinese)

Tao, S. Y., and L. X. Chen, 1987: A review of recent research of the East Asian summer monsoon in China. *Monsoon Meteorology*, C.-P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 60–92.

Tao, S. Y., and J. Wei, 2006: The westward, northward advance of the subtropical high over the west Pacific in summer. *J. Appl. Meteor. Sci.*, **17**, 513–525. (in Chinese)

Tao, S. Y., and J. Wei, 2008: Severe snow and freezing-rain in January 2008 in southern China. *Climatic and Environmental Research*, **13**, 337–350. (in Chinese)

Tao, S. Y., X. J. Zhao, and X. M. Chen, 1958: The relationship between Meiyu in Far East and the behavior of circulation over Asia. *Acta Meteorologica Sinica*, **29**, 119–134. (in Chinese)

Tao, S. Y., S. Y. Xu, and Q. Y. Guo, 1962: The characteristics of the zonal and meridional circulation over the tropical and subtropical regions in Eastern Asia in summer. *Acta Meteorologica Sinica*, **32**, 91–103. (in Chinese)

Tao, S. Y., S. X. He, and Z. F. Yang, 1983: An observational study on the onset of the summer monsoon over Eastern Asia in 1979. *Chinese J. Atmos. Sci*., **7**, 347–355. (in Chinese)

Tao, S. Y., Q. Y. Zhang, and S. L. Zhang, 1998: The great floods in the Changjiang River valleys in 1998. *Climatic and Environmental Research*, **3**, 290–299. (in Chinese)

Tao, S. Y., Q. Y. Zhang, and S. L. Zhang, 2001: An observational study on the behavior of the subtropical high over the west Pacific during summer. *Acta Meteor. Sinica*, **59**, 747–758.

Tu, C. W., 1937: Linkage between weather in China and the global atmospheric oscillations and applications in long-range forecast of summer drought and flood in China. *J. Meteorol.*, **13**, 627–697. (in Chinese)

Tu, C. W., and S. S. Huang, 1944: The advance and retreat of the summer monsoon in China. *Acta Meteorologica Sinica*, **18**, 81–92. (in Chinese)

Wang, H. J., 2001: The weakening of the Asian monsoon circulation after the end of 1970s. *Adv. Atmos. Sci.*, **18**, 376–386, doi: 10.1007/BF02919316.

Wang, H. J., 2002: The instability of the East Asian summer monsoon-ENSO relations. *Adv. Atmos. Sci.*, **19**, 1–11, doi: 10.1007/s00376-002-0029-5.

Wang, H. J., and F. Xue, 2003: The interannual variability of Somali jet and its influences on the inter-hemispheric water vapor transport and the East Asian summer rainfall. *Chinese J. Geophys*., **46**, 11–20.

Wang, H. J., and K. Fan, 2005: Central-north China precipitation as reconstructed from the Qing dynasty: Signal of the Antarctic atmospheric oscillation. *Geophys. Res. Lett.*, **32**, L24705, doi: 10.1029/2005GL024562.

Wang, H. J., and Coauthors, 2015: A review on seasonal climate prediction research in China. *Adv. Atmos. Sci*., **32**(2), doi: 10.1007/s00376-014-0016-7. (in press)

Wang, J., J. H. He, X. F. Liu, and B. G. Wu, 2009a: Interannual variability of the Meiyu onset over the Yangtze-Huaihe River valleys and the analyses of its previous strong influence signal. *Chinese Science Bulletin*, **54**, 687–695.

Wang, J. Z., and M. C. Li, 1982: Cross-Equator flow from Australia and monsoon over China. *Chinese J. Atmos. Sci.*, **6**, 1–10. (in Chinese)

Wang, S. W., and J. B. Huang, 2006: The instable teleconnection of summer rainfall between north China and India. *Progress in Natural Sciences*, **16**, 980–985. (in Chinese)

Wang, S. W., T. J. Zhou, J. N. Cai, J. H. Zhu, Z. H. Xie, and D. Y. Gong, 2004: Abrupt climate change around 4 ka BP: Role of the thermohaline circulation as indicated by a GCM experiment. *Adv. Atmos. Sci.*, **21**, 291–295, doi: 10.1007/BF 02915716.

Wang, W. Q., 1991: Numerical experiments of the soil temperature and moisture anomalies' effects on the short term climate. *Chinese J. Atmos. Sci.*, **15**, 115–123. (in Chinese)

Wang, Y. M., S. L. Li, and D. H. Luo, 2009b: Seasonal response of Asian monsoonal climate to the Atlantic Multidecadal Oscillation. *J. Geophys. Res.*, **114**, D02112, doi: 10.1029/2008JD 010929.

Wang, Z. M., and S. S. Huang, 1994: The responses of atmospheric circulations to Antarctic sea ice anomalies in July. *Scientia Meteorologica Sinica*, **14**, 311–321. (in Chinese)

Wen, Z. P., Z. N. Liang, and L J. Wu, 2006: The relationship between the Indian Ocean sea surface temperature anomaly and the onset of the South China Sea summer monsoon. II. Analyses of mechanisms. *Chinese J. Atmos. Sci.*, **30**, 1138–1146. (in Chinese)

Wu, B., and T. J. Zhou, 2008: Oceanic origin of the interannual and interdecadal variability of the summertime western Pacific subtropical high. *Geophys. Res. Lett.*, **35**, L13701, doi: 10.1029/2008GL034584.

Wu, B. Y., and R. H. Huang, 1999: Effects of the extremes in the North Atlantic Oscillation on East Asian winter monsoon. *Chinese J. Atmos. Sci.*, **23**, 641–651(in Chinese)

Wu, B., T. Zhou, and T. Li, 2009a: Seasonally evolving dominant interannual variability modes of East Asian Climate. *J. Climate*, **22**, 2992–3005.

Wu, B., T. Zhou, and T. Li, 2009b: Contrast of rainfall-SST relationships in the western North Pacific between the ENSO developing and decaying summers. *J. Climate*, **22**, 4398–4405.

Xiao, Z. N., and H. L. Liang, 2006: The meridian pattern of summer rainfall in 2004 and its relationship with Indian Ocean dipole. *Chinese J. Atmos. Sci.*, **30**, 791–801. (in Chinese)

Xiao, Z. N., J. H. Sun, and C. Y. Li, 2000: Influence of the Indian Ocean SSTA on Asian climate during an ENSO period. *Chinese J. Atmos. Sci.*, **24**, 461–469. (in Chinese)

Xiao, Z. N., H. M. Yan, and C. Y. Li, 2002: Relationship between dipole oscillation of SSTA of Indian Ocean Region and precipitation and temperature over China. *Journal of Tropical Meteorology*, **18**, 335–344. (in Chinese)

Xin, X. G., R. C. Yu, T. J. Zhou, and B. Wang, 2006: Drought in late spring of South China in recent decades. *J. Climate*, **19**, 3197–3206.

Xu, H. M., J. H. He, and M. Dong, 2001: Interannual variability of the Meiyu onset and its association with the NAO and SST over North Atlantic. *Acta Meteorologica Sinica*, **59**, 694–706. (in Chinese)

Xu, J. J., and Q. G. Zhu, 1998: East-Asian monsoon QBO and its relation to ENSO variability. *J. Nanjing Inst. Meteor.*, **21**, 23–31. (in Chinese)

Xu, J. J., Q. G. Zhu, and N. Shi, 1997: The interaction of East Asian winter monsoon with ENSO cycle and their interdecadal variations in last century. *Chinese J. Atmos. Sci.*, **21**, 641–648. (in Chinese)

Xu, Q., 1986: A correlation analysis of the south oscillation and the activities of the western Pacific subtropical high during the flood period in China (June to October). *Chinese Science Bulletin*, **31**, 1567–1569. (in Chinese)

Xu, X. D., X. H. Shi, L. A. Xie, and Y. F. Wang, 2007: Consistency of interdecadal variation in the summer monsoon over eastern China and heterogeneity in springtime surface air temperatures. *J. Meteor. Soc. Japan*, **85A**, 311–323.

Xue, F., 2001: Interannual to Interdecadal variation of East Asian summer monsoon and its association with the global atmospheric circulation and sea surface temperature. *Adv. Atmos. Sci.*, **18**, 567–575, doi: 10.1007/s00376-001-0045-x.

Xue, F., 2005: Influence of the Southern circulation on East Asian summer monsoon. *Climatic and Environmental Research*, **10**, 401–408. (in Chinese)

Xue, F., 2008: East Asian summer monsoon anomalies in strong La Niña years and comparison of summer precipitation in China between 1989 and 1999. *Chinese J. Atmos. Sci.*, **32**, 423–431. (in Chinese)

Xue, F., and Q. C. Zeng, 1999: Diagnostic study on seasonality and interannual variability of wind field. *Adv. Atmos. Sci.*, **16**, 537–543, doi: 10.1007/s00376-999-0029-9.

Xue, F., and J. X. He, 2005: Influence of the southern hemispheric circulation on east-west oscillation of the western subtropical high. *Chinese Science Bulletin*, **50**, 1532–1536.

Xue, F., and J. X. He, 2007: The influence of the extratropical atmospheric disturbances on ENSO. *Chinese J. Geophys.*, **50**, 1130–1138.

Xue, F., and C. Z. Liu, 2008: The influence of moderate ENSO on summer rainfall in eastern China and its comparison with strong ENSO. *Chinese Science Bulletin*, **53**, 791–800.

Xue, F., Y. H. Lin, and Q. C. Zeng, 2002: On the seasons of general atmospheric circulation and their abrupt changes. Part III, climatology. *Chinese J. Atmos. Sci.*, **26**, 307–314. (in Chinese)

Xue, F., D. B. Jiang, L. M. Lang, and H. J. Wang, 2003a: Influence of the Mascarene high and Australian high on summer monsoon in East Asia: Ensemble simulation. *Adv. Atmos. Sci.*, **20**, 799–809, doi: 10.1007/BF02915405.

Xue, F., P. W. Guo, and Z. H. Yu, 2003b: Influence of interannual variability of Antarctic sea ice on summer monsoon in eastern China. *Adv. Atmos. Sci.*, **20**, 97–102, doi: 10.1007/BF03342053.

Xue, F., H. J. Wang, and J. H. He, 2004: Interannual variability of Mascarene high and Australian high and their influences on East Asian summer monsoon. *J. Meteor. Soc. Japan*, **82**, 1173–1186.

Yan, H. M., H. S. Yan, and Y. Q. Xie, 2001: The SSTA signal characteristic analysis over Indian Ocean during flood season in China. *Journal of Tropical Meteorology*, **17**, 109–116. (in Chinese)

Yan, H. M., H. Yang, and C. Y. Li, 2007: Numerical simulations on the climate impacts of temperature dipole in the equatorial Indian Ocean. *Acta Oceannologica Sinica*, **29**, 31–39. (in Chinese)

Yan, X. Y., and M. Zhang, 2004: A study of the Indian Ocean dipole influence on climate variations over East Asian monsoon region. *Climatic and Environmental Research*, **9**, 435–444. (in Chinese)

Yang, H., and C. Y. Li, 2005a: Lasting time of El Niño and circulation anomaly. *Chinese J. Geophysics*, **48**, 860–869.

Yang, H., and C. Y. Li, 2005b: The influence of anomalous associated mode of tropical Pacific-Indian Ocean temperature on the South Asia high. *Chinese J. Atmos. Sci*., **29**, 99–110. (in Chinese)

Yang, H., X. L. Jia, and C. Y. Li, 2006: The tropical Pacific-Indian Ocean temperature anomaly mode and its effect. *Chinese Science Bulletin*, **51**, 2878–2884.

Yang, J. L., Q. Y. Liu, S. P. Xie, Z. Y. Liu, and L. X. Wu, 2007: Impact of the Indian Ocean SST basin mode on the Asian summer monsoon. *Geophys. Res. Lett.*, **34**, L02708, doi: 10.1029/2006GL028571.

Yang, X. Q., and S. S. Huang, 1992: A numerical experiment of climate effect of Antarctic sea ice during the Northern Hemisphere summer. *Chinese J. Atmos. Sci*., **16**, 80–89. (in Chinese)

Yang, X. Q., Q. Xie, Y. M. Zhu, X. G. Sun, and Y. J. Guo, 2005: Decadal to interdecadal variability of precipitation in North China and associated atmospheric and oceanic anomaly patterns. *Chinese J. Geophys*., **48**, 789–797. (in Chinese)

Ye, H., and R. Y. Lu, 2011: Subseasonal variation in ENSO-related East Asian rainfall anomalies during summer and its role in weakening the relationship between the ENSO and summer rainfall in Eastern China since the late 1970s. *J. Climate*, **24**, 2271–2284.

Yu, R. C., and T. J. Zhou, 2004: Impacts of winter-NAO on March cooling trends over subtropical Eurasia continent in the recent half century. *Geophys. Res. Lett.*, **31**, L12204, doi: 10.1029/2004GL019814.

Yu, R. C., and T. Zhou, 2007: Seasonality and three-dimensional structure of the interdecadal change in East Asian monsoon. *J. Climate*, **20**, 5344–5355.

Yu, R. C., B. Wang, and T. Zhou, 2004: Climate effects of the deep continental stratus clouds generated by Tibetan Plateau. *J. Climate*, **17**, 2702–2713.

Yu, R. C., T. Zhou, J. Li, and X. G. Xin, 2008: Progress in the studies of three-dimensional structure of interdecadal climate change over eastern China. *Chinese J. Atmos. Sci.*, **32**, 893–905. (in Chinese)

Yuan, Y., and C. Y. Li, 2009: Possible impacts of the tropical Indian Ocean SST anomaly modes on the South China Sea summer monsoon onset. *Chinese J. Atmos. Sci.*, **33**, 325–336. (in Chinese)

Zeng, G., Z. B. Sun, W. C. Wang, Z. H. Lin, and D. H. Ni, 2007: Interdecadal variation of East Asian summer monsoon simulated by NCAR Cam3 driven by global SSTs. *Climatic and Environmental Research*, **12**, 211–224. (in Chinese)

Zeng, Q. C., 2005: About King Shun's poem "southerly wind". *Climatic and Environmental Research*, **10**, 283–284. (in Chinese)

Zeng, Q. C., and B. L. Zhang, 1992: On the seasons of general atmospheric circulation and their abrupt changes. Part I, general concept and method. *Chinese J. Atmos. Sci.*, **16**, 329–336. (in Chinese)

Zeng, Q. C., and B. L. Zhang, 1998: On the seasonal variation of atmospheric general circulation and the monsoon. *Chinese J. Atmos. Sci.*, **22**, 805–813. (in Chinese)

Zeng, Q. C., and J. P. Li, 2002: Interactions between the northern and southern hemispheric atmospheres and the essence of monsoon. *Chinese J. Atmos. Sci.*, **26**, 433–448. (in Chinese)

Zeng, Q. C., B. L. Zhang, Y. L. Liang, and S. X. Zhao, 1994: East Asian summer monsoon: A case study. *Proc. Indian Natrl. Sci. Acad.*, **60**(A), 81–96.

Zeng, Q. C., Y. J. Dai, and F. Xue, 1998: Simulation of the Asian monsoon by IAP AGCM coupled with an advanced land surface model (IAP94). *Adv. Atmos. Sci.*, **15**, 1–16, doi: 10.1007/s00376-998-0013-9.

Zeng, Q. C., Z. H. Lin, and G. Q. Zhou, 2003: Dynamical extra-seasonal climate prediction system IAP DCP-II. *Chinese J. Atmos. Sci.*, **27**, 289–303. (in Chinese)

Zeng, Q. C., D. L. Zhang, M. Zhang, R. T. Zuo, J. X. He, 2005: The Abrupt seasonal transitions in the atmospheric general circulation and the onset of monsoons. Part I, basic theoretical method and its application to the analysis of climatological mean observations. *Climatic and Environmental Research*, **10**, 285–302. (in Chinese)

Zhan, Y. L., and Z. H. Lin, 2011: The relationship between June precipitation over mid-lower reaches of the Yangtze River basin and spring soil moisture over the East Asian monsoon region. *Acta Meteorologica Sinica*, **25**, 355–363.

Zhang, B. L., and Q. C. Zeng, 1998: On the seasons of general atmospheric circulation and their abrupt changes. Part II, case study of particular year. *Chinese J. Atmos. Sci.*, **22**, 130–136. (in Chinese)

Zhang, M., D. L. Zhang, R. T. Zuo, J. X. He, and Q. C. Zeng, 2005: The Abrupt seasonal transitions in the atmospheric general circulation and the onset of monsoons. Part II, the onset of summer monsoon in South China Sea region. *Climatic and Environmental Research*, **10**, 301–314. (in Chinese)

Zhang, Q. Y., J. M. Lü, L X. Yang, J. Wei, and J. B. Peng, 2007: The interdecadal variation of precipitation pattern over China during summer and its relationship with the atmospheric internal dynamic processes and extra-forcing factors. *Chinese J. Atmos. Sci.*, **31**, 1290–1300. (in Chinese)

Zhang, S. L., and S. Y. Tao, 2001: The influences of snow cover over the Tibetan Plateau on Asian summer monsoon. *Chinese J. Atmos. Sci.*, **25**, 372–390. (in Chinese)

Zhang, W. J., T. J. Zhou, and H. Zhi, 2012: A numerical experiment on the effect of soil moisture to summer climate over China. *Acta Meteorologica Sinica*, **70**, 78–90.

Zhang, Y. C., X. Y. Kuang, W. D. Guo, and T. J. Zhou, 2006: Seasonal evolution of the upper-tropospheric westerly jet core over East Asia. *Geophys. Res. Lett.*, **33**, L11708, doi: 10.1029/2006GL026377.

Zhang, Z. Q., Y. H. Ding, and Z. C. Zhao, 2000: On the westerly wind outbursts in equatorial western Pacific during the onset and development phases of ENSO and before. *Acta Meteorologica Sinica*, **58**, 11–25. (in Chinese)

Zhao, H. G., and J. Z. Ji, 1989: The characters of spatial-temporal variation of the Antarctic sea ice coverage and its effects on the atmospheric circulation. *Meteorology*, **15**, 3–8. (in Chinese)

Zhao, Z. G., 1999: *Summer Drought and Flood in China and Environmental Background*. China Meteorological Press, 297 pp. (in Chinese)

Zhou, B. T., and H. J. Wang, 2006: Relationship between the boreal spring Hadley circulation and the summer precipitation in the Yangtze River valleys. *J. Geophys. Res.*, **111**, D16109, doi: 10.1029/2005JD007006.

Zhou, T. J., and R. C. Yu, 2005: Atmospheric water vapor transport associated with typical anomalous summer rainfall patterns in China. *J. Geophys. Res.*, **110**, D08104, doi: 10.1029/2004JD005413.

Zhou, T. J., and J. Zhang, 2009: Harmonious inter-decadal changes of July-August upper tropospheric temperature across the North Atlantic, Eurasian continent and North Pacific. *Adv. Atmos. Sci.*, **26**, 656–665, doi: 10.1007/s00376-009-0920-8.

Zhou, T. J., L. J. Li, H. M. Li, and Q. Bao, 2008a: Progress in climate change attribution and projection studies. *Chinese J. Atmos. Sci.*, **32**, 906–922. (in Chinese)

Zhou, T. J., R. Yu, H. Li, and B. Wang, 2008b: Ocean forcing to changes in global monsoon precipitation over the recent half century. *J. Climate*, **21**, 3833–3852.

Zhou, T. J., L. X. Zhang, and H. M. Li, 2008c: Changes in global land monsoon area and total rainfall accumulation over the last half century. *Geophys. Res. Lett.*, **35**, L16707, doi: 10.1029/2008GL034881.

Zhou, T. J., B. Wu, and B. Wang, 2009a: How well do atmospheric general circulation models capture the leading modes of the interannual variability of Asian–Australian monsoon? *J. Climate*, **22**, 1159–1173.

Zhou, T. J., and Coauthors, 2009b: Why the western Pacific subtropical high has extended westward since the late 1970s. *J. Climate*, **22**, 2199–2215.

Zhu, K. Z., 1934: Southeast monsoon and rainfall in China. *Acta Geographica Sinica*, **1**, 1–27. (in Chinese)

Zhu, F. K., and L. H. Lu, 1984: A possible mechanism for the effects of the Southern Hemisphere on the seasonal transition over the Northern Hemisphere in early summer. *Acta Meteorologica Sinica*, **42**, 449–458. (in Chinese)

Zhu, Q. G., and S. Yang, 1989: The northward advance and oscillation of the East Asian summer monsoon. *Journal of Nanjing Institute of Meteorology*, **12**, 249–257. (in Chinese)

Zhu, Y. M., and X. Q. Yang, 2003: Relationship between Pacific decadal oscillation (PDO) and climate variabilities in China. *Acta Meteorologica Sinica*, **61**, 641–654. (in Chinese)

Zhu, Y. M, X. Q. Yang, X. Y. Chen, S. S. Zhao, and X. G. Sun, 2007: Interdecadal variations of the relationship between ENSO and summer interannual climate variability in China. *J. Trop. Meteor.*, **13**, 132–136. (in Chinese)

Zuo, Z. Y., and R. H. Zhang, 2007: The relationship between summer precipitation and spring soil moisture over East China. *Chinese Science Bulletin*, **52**, 3310–3312.