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Characteristics, Processes, and Causes of the Spatio-temporal Variabilities of the East Asian Monsoon System

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ABSTRACT

Recent advances in the study of the characteristics, processes, and causes of spatio-temporal variabilities of the East Asian monsoon (EAM) system are reviewed in this paper. The understanding of the EAM system has improved in many aspects: the basic characteristics of horizontal and vertical structures, the annual cycle of the East Asian summer monsoon (EASM) system and the East Asian winter monsoon (EAWM) system, the characteristics of the spatio-temporal variabilities of the EASM system and the EAWM system, and especially the multiple modes of the EAM system and their spatio-temporal variabilities. Some new results have also been achieved in understanding the atmosphere–ocean interaction and atmosphere–land interaction processes that affect the variability of the EAM system. Based on recent studies, the EAM system can be seen as more than a circulation system, it can be viewed as an atmosphere–ocean–land coupled system, namely, the EAM climate system. In addition, further progress has been made in diagnosing the internal physical mechanisms of EAM climate system variability, especially regarding the characteristics and properties of the East Asia-Pacific (EAP) teleconnection over East Asia and the North Pacific, the "Silk Road" teleconnection along the westerly jet stream in the upper troposphere over the Asian continent, and the dynamical effects of quasi-stationary planetary wave activity on EAM system variability. At the end of the paper, some scientific problems regarding understanding the EAM system variability are proposed for further study.

Key words: East Asian monsoon system, spatio-temporal variations, climate system, EAP teleconnection

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1. Introduction

The East Asian monsoon (EAM) system features strong southerly wind in summer, [i.e., the East Asian summer monsoon (EASM)], and strong northerly wind in winter, [i.e., the East Asian winter monsoon (EAWM)]. Generally, the southerly wind transports water vapor over eastern China, Korea, and Japan in summer, but in winter the dry northwesterly wind prevails over North China, Central China, Northeast China, Korea, and Japan, and northeasterly wind prevails over East China, South China, and the Indo-China Peninsula. The strong summer monsoon flow transports a large amount of water vapor into East Asia, causing severe climate disasters such as floods in South China, and droughts in the Yangtze-Huaihe River valley, and extremely hot summers in eastern China, Korea, and Japan (Huang et al., 1998a, 2008; Huang and Zhou, 2002). In contrast, the strong winter monsoon flow can bring a large amount of cold and dry air into East Asia and can cause climate disasters such as low temperatures and severe snow storms in Northwest China, Northeast China, North China, Korea, and Japan in winter and severe dust storms in Northwest China and North China in spring (Chen et al., 2000; Huang et al., 2007b; Gu et al., 2008; Wang and Chen, 2010b). In addition, the strong EAWM can trigger strong convective activities over the Maritime Continent around Borneo and Indonesia (Chang et al., 1979; Lau and Chang, 1987; Wang and Chen,

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2010a). Moreover, many studies have shown that the EAM system plays an important role in global climate variability, especially in climate variability over East Asia (e.g., Tao and Chen, 1987; Chen et al., 1991; Ding, 1994; Chang et al., 2000a, b; Huang et al., 2003, 2004a, 2007a).

Climate variability in China is mainly influenced by the EAM system (Zhu, 1934; Tu and Huang, 1944; Tao and Chen, 1987). The interannual and interdecadal variabilities of EAM system are quite significant. Therefore, climatic disasters such as droughts and floods in summer and severe cold surges, freezing rain, and low temperature in winter frequently occur in China (Huang and Zhou, 2002; Huang, 2006; Gu et al., 2008; Huang et al., 2011c, 2012b; Barriopedro et al., 2012). Especially since the 1980s, severe climatic disasters have caused huge damage to agricultural and industrial production across China. The economic losses due to droughts and floods can reach more than 200 billon CNY (∼US$30 billion) each year (Huang et al., 1999; Huang and Zhou, 2002). For example, the particularly severe floods that occurred in the Yangtze River basin and the Songhuajiang River and Nenjiang River valleys in the summer of 1998 caused economic losses as high as 260 billion CNY (∼US$38 billion; Huang et al., 1998b). From the winter of 2009 to the summer of 2010, China experienced many severe climatic disasters: the severe low temperatures and snowstorms in Northeast China, Northwest China, and North China from November 2009 to January 2010 (Wang and Chen, 2010b), the particularly severe drought in Southwest China from the autumn of 2009 to the spring of 2010 (Barriopedro et al., 2012; Huang et al., 2012b), severe floods in South China and the Yangtze River basin during May–July, particularly severe floods in the middle and eastern Northeast China from late July to early August and in late August, and severe hot summer in Northwest China, South China, the Yangtze River basin and North China. The economic losses caused by these severe climatic disasters far exceeded those in 1998. Moreover, the persistent droughts in North China and southern Northeast China since the late 1990s have not only caused huge losses in agriculture and industry but also have seriously affected the water resources and ecological environment in these regions. For example, a ∼20% reduction was observed in the nationwide hydroelectrical production due to the depleted water reservoirs during the 2009–2010 Southwest China droughts (Barriopedro et al., 2012).

These climatic disasters are closely associated with the spatio-temporal variabilities of the EAM system (Huang, 2006). EAM system variability is influenced not only by the internal dynamical and thermodynamical processes of the atmosphere but also by the interactions among various spheres of the atmosphere–ocean–land coupled system. Webster et al. (1998) proposed that the Asian–Australian monsoon could be viewed as an atmosphere–ocean–land coupled system. Similarly, the EAM system can also be regarded as a atmosphere–ocean–land coupled system. We named it the EAM climate system to distinguish it from the general circulation system proposed by Tao and Chen (1987) (see also Huang et al., 2004a, 2007a). The EAM climate system includes EAM circulation, the western Pacific subtropical high, the mid- and high-latitude disturbances in the atmosphere, thermal states of the western Pacific warm pool and associated convective activity around the Philippines, the thermal state of the tropical Indian Ocean, the ENSO cycle in the tropical Pacific in the Ocean, the dynamical and thermal effects over the Tibetan Plateau, the land surface processes in the arid and semiarid areas of Northwest China, and snow cover over the Eurasian continent and the Tibetan Plateau. The characteristics of the spatio-temporal variabilities of this system and their impacts on climatic disasters in China have been analyzed further in recent years. The internal and external physical processes that influence these variabilities have also been discussed in more detail recently.

In this study, we summarized the advances in the studies on the characteristics, causes, and processes of the spatio-temporal variability of the EAM system, especially of the spatio-temporal variations of the EASM and EAWM systems, the impacts and processes of the atmosphere–ocean–land coupled system on EAM system variability and the internal dynamic and thermodynamic mechanisms of EAM system variability. The review mainly focuses on research progress in China during the past five years.

2. Climatological characteristics of the EASM system

Because there are close associations among the South Asian monsoon (SAM), the East Asian monsoon (EAM), and the North Australian monsoon (NAM), some scholars have considered them as three subsystems of the Asian–Australian monsoon system (e.g., Webster et al., 1998). However, the characteristics of EAM system are different from those of SAM and NAM systems. According to the study by Tao and Chen (1987), the EASM system has both tropical and subtropical properties because it is influenced by the western Pacific subtropical high and the disturbances over middle latitudes in addition to tropical systems. In contrast, the South Asian summer monsoon (SASM) is only a tropical monsoon. Therefore, the characteristics of the spatio-temporal variation of the EASM system may be different from those of the South Asian summer monsoon (SASM) system.

2.1 *Characteristics of circulation structure in the EASM system*

Tao and Chen (1985) showed that the main components of the EASM system include the Indian SW monsoon flow, the Australian cold anticyclone, the cross-equatorial flow along the east to 100°E, the monsoon trough (or ITCZ) over the South China Sea (SCS) and the tropical western Pacific, the western Pacific subtropical high and the tropical easterly flow, the mei-yu (or baiu in Japan, or changma in Korea) frontal zones, and the disturbances over mid-latitudes. Their results suggest that the EASM system is a relatively independent monsoon circulation system, although it is linked to the SASM.

Recently, Chen and Huang (2006) analyzed the climatological characteristics of wind structure of the EASM system over the area (0°–45°N, 100°–140°E) and the SASM system over the area (0°–25°N, 60°–100°E) in boreal summer, respectively. Their results show that the vertical structure of zonal flow in the EASM region includes a vertical easterly shear in the region south of 25°N, such as the SCS and the tropical western Pacific, and the vertical westerly shear in the subtropical region to the north of 25°N, such as the mainland of China, Korea, and Japan (Fig. 1a). In contrast, the SASM system is purely a tropical monsoon, with strong zonal flow and vertical easterly shear, i.e., low-level westerly wind and high-level easterly wind (Fig. 1b).

Moreover, as shown in Fig. 2a, the EASM system is composed of tropical and subtropical summer monsoons with significant meridional flow and verti-

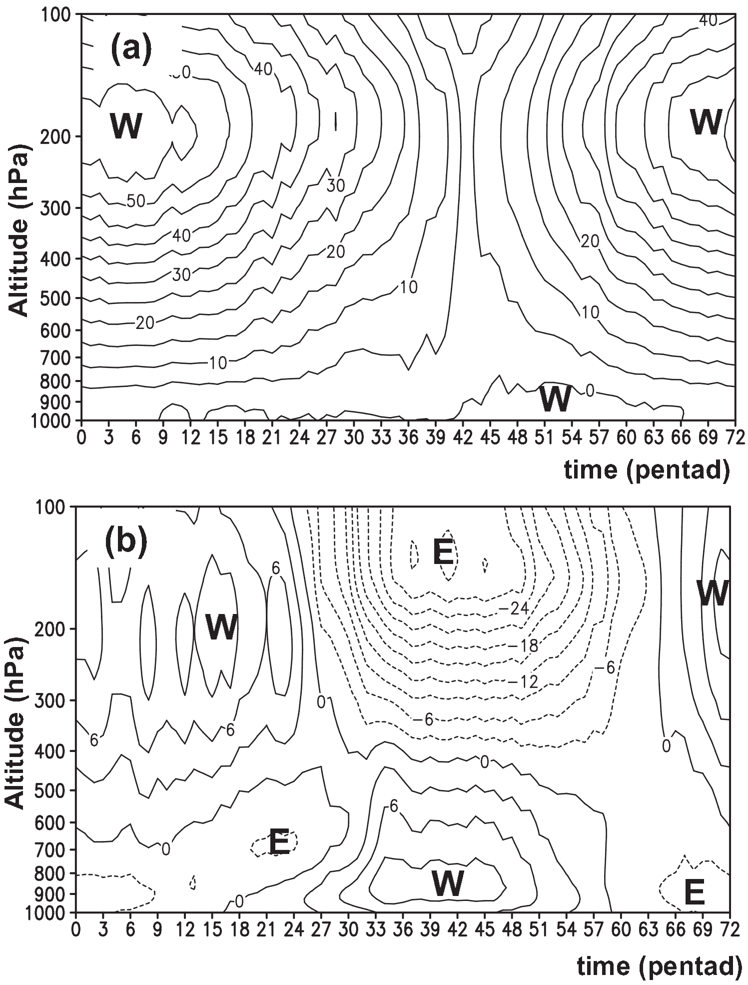

Fig. 1. Altitude-time cross section of zonal wind averaged for 1979–2003 over (a) East Asia (20°–45°N, 100°–140°E) and (b) South Asia (0°–25°N, 60°–100°E) based on NCEP/NCAR reanalysis data (Kalnay et al., 1996). Unit: m s^{-1}. The solid and dashed lines in panels (a) and (b) indicate the westerly and easterly winds, respectively.

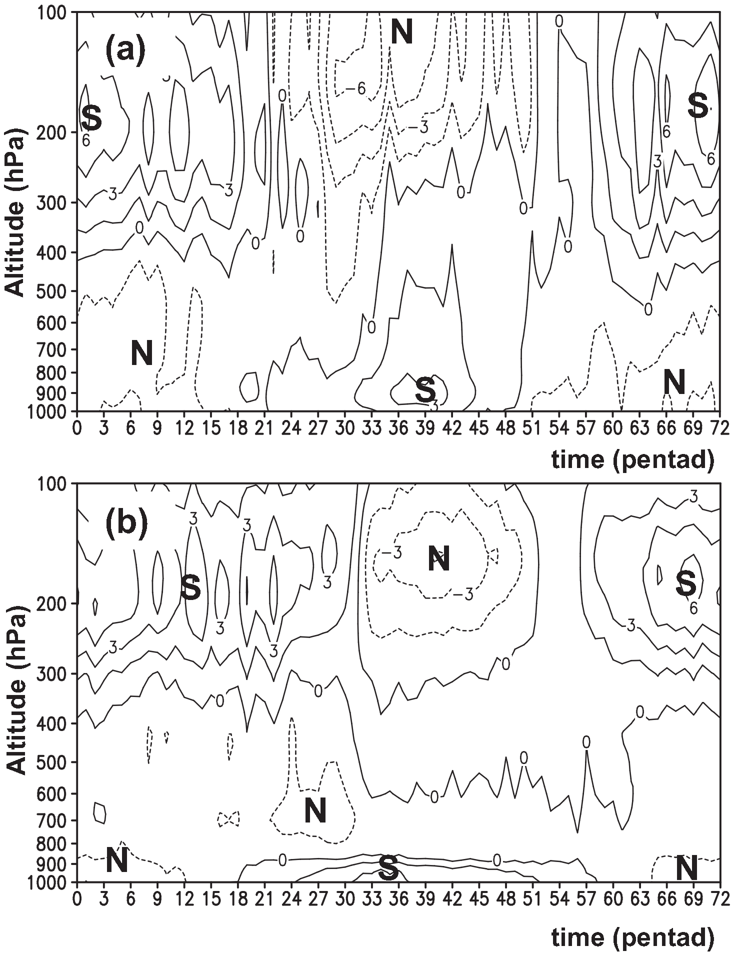

Fig. 2. As in Fig. 1, except for the meridional wind.

cal northerly shear, i.e., low-level southerly wind and high-level northerly wind. Compared with the meridional component of wind field in the SASM system (Fig. 2b), the low-level southerly wind and the upper-level northerly wind in the EASM region (Fig. 2a) are stronger than those in the SASM system.

The differences between the annual wind cycle in the EAM system and in the SAM system can also be seen from the altitude–time cross sections of zonal and meridional winds over East Asia and South Asia (Figs. 1 and 2). The strong westerly wind prevails in the lower troposphere below 500 hPa, and the strong easterly wind prevails in the upper troposphere (above 500 hPa) from early June over South Asia (Fig. 1b). However, from early October, the westerly wind becomes easterly in the lower troposphere below 700 hPa, while the easterly wind becomes westerly in the upper troposphere above 500 hPa over this region. Therefore, in the SAM region, the annual wind cycle between summer and winter monsoons is obvious according to the zonal wind field. However, a comparison of Fig. 1a with Fig. 1b shows that the seasonal reversal of zonal wind in the troposphere over East Asia is not as significant as that in the SAM region. As shown in Fig. 2a, the seasonal reversal of meridional wind obviously occurs in both the lower troposphere and the upper troposphere over East Asia in early June and mid-September, respectively.

From these analyses, the annual cycle between summer and winter monsoons mainly appears in the meridional component of wind field in the EAM region, different from that in the SAM system.

2.2 *Characteristics of water vapor transports in the EASM region*

Recently, Chen and Huang (2007) analyzed water vapor transports over the EASM and the SASM regions using ERA-40 reanalysis data for the period 1979–2002. Their results showed that the characteristic of water vapor transports in the EASM region is greatly different from that in the SASM region. The climatological EASM rainfall is mainly influenced by

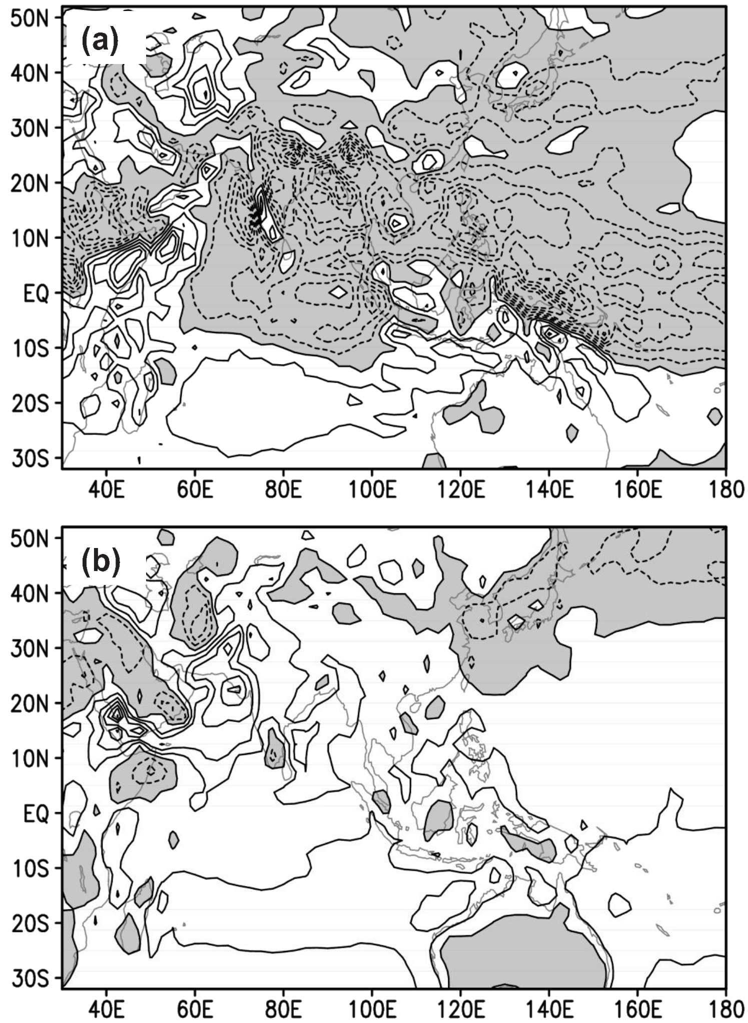

Fig. 3. Distributions of the divergence of water vapor transport due to (a) the divergence of wind field and (b) the moisture advection in the Asian monsoon region during boreal summer based on ERA-40 reanalysis data (Uppala et al., 2005). Units: mm d^{-1}. The solid and dashed lines in panels (a) and (b) indicate divergence and convergence, respectively. Areas of convergence are shaded.

three branches of water vapor transport coming from the Bay of Bengal, the South China Sea, and the tropical western Pacific. Their study showed that in the SASM region, the zonal transport of water vapor is dominant and the meridional transport is relatively smaller, but the meridional transport of water vapor is dominant in the EASM region. As shown in Figs. 3a and 3b, the convergence of water vapor transports that are closely associated with monsoon rainfall are caused by moisture advection and the convergence of wind fields in the EASM region, but those are mainly due to the convergence of wind fields in the SASM region. This result is in good agreement with the analysis by Huang et al. (1998a).

Huang and Chen (2010) analyzed the differences between the summertime water vapor transports in the EASM region and those in the arid and semiarid regions of Northwest China using the daily ERA-40 reanalysis data. The results show some obvious differences between the summertime water vapor transport in the EASM region and that in arid and semiarid regions. Because a large amount of water vapor is transported by the Asian summer monsoon flow from the Bay of Bengal, the South China Sea, and the tropical western Pacific into the EASM region, the meridional water vapor transport fluxes are larger than the zonal water vapor transport fluxes in South China and the Yangtze River valley. In contrast, the summertime zonal water vapor transport fluxes are larger than the meridional water vapor transport fluxes in the arid and semiarid region of Northwest China due to the strong mid-latitude westerlies. The water vapor divergence in these regions mainly depends on moisture advection. Moreover, either zonal or meridional water vapor transport fluxes in the arid and semiarid regions are approximately 10% of those in the EASM region, which causes very small amounts of summertime rainfall in Northwest China, resulting in drought conditions.

2.3 *Characteristics of rainfall cloud system in the EASM system*

Recently, Du et al. (2011) reported that the rainfall cloud system in the EASM region is different from that in the SASM region, due to the differences of the circulation structure and water vapor transport between the EASM region and the SASM regions. They analyzed the characteristics of spatio-temporal distributions of convective rainfall and stratiform rainfall from Tropical Rainfall Measuring Mission (TRMM) precipitation data for 12 years. Their results show that the spatial distributions of convective rainfall and stratiform rainfall mainly exhibit a variation with latitude in the EASM region (Fig. 4). In the subtropical monsoon region to the north of 25°N, the ratio of stratiform rainfall with respect to the total rainfall is ∼60% in summer. This ratio increases in proportion to latitude north of 25°N, and it varies with regions. In the low latitudes south of 25°N, in contrast, summertime rainfall is mainly due to convective cloud systems, contributing ∼50% of the total annual rainfall, and this ratio is constant in this region. Thus, summertime rainfall cloud systems in the EASM system are mainly due to stratiform cloud systems to the north of 25°N and to convective cloud systems south of 25°N. In contrast, summertime rainfall cloud systems in the SASM system are mainly due to convective cloud systems. Fu et al. (2003), and Liu and Fu (2010) analyzed the seasonal characteristics of convective rainfall and stratiform rainfall in Asian monsoon region and the climatological characteristics of convective rainfall and stratiform rainfall in summer over South China, using the TRMM data for the period 1998–2007. Their results also show that stratiform rainfall amount is comparative to convective rainfall amount in South China. These studies can explain that the summertime rainfall cloud systems in the EASM system are a mixing of stratiform cloud systems with convective cloud systems. This mixture may make it difficult to numerically model cumulus parameterization in the EASM system (e.g., Cheng et al., 1998).

These results make it clear that the EASM system is different from the SASM system and is a relatively independent monsoon system, although it is also in-

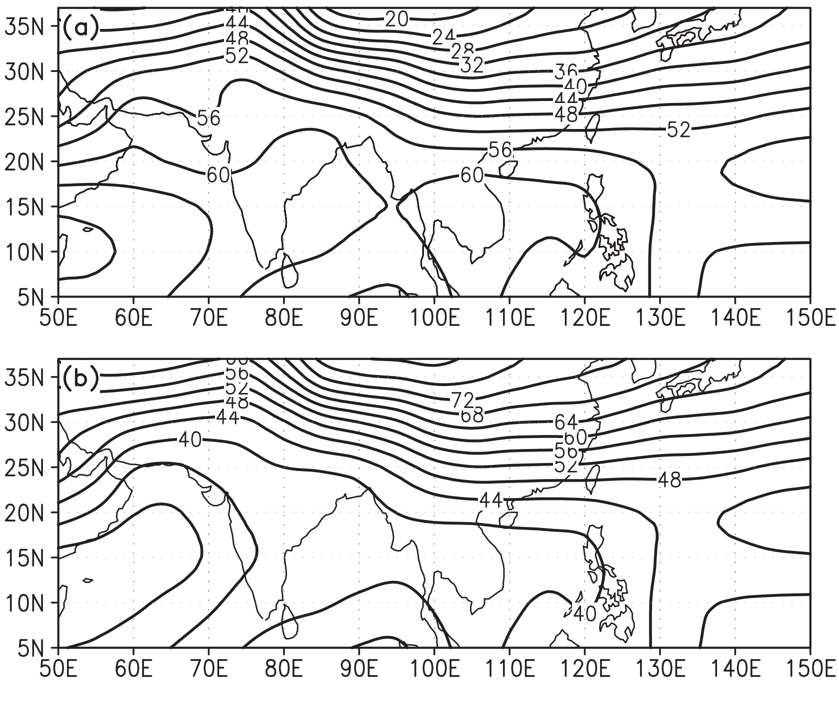

Fig. 4. Distributions of the average summertime rainfall (percentage) for 1988–2009 due to (a) convective rainfall and (b) stratiform rainfall based on TRMM data.

fluenced by the SASM system.

3. Characteristics of the spatio-temporal variabilities of the EASM system

EASM system variability is influenced not only by the SASM and the western Pacific subtropical high (e.g., Tao and Chen, 1987; Huang and Sun, 1992) but also by mid- and high-latitude disturbances (e.g., Tao and Chen, 1987); therefore, the spatio-temporal variations of the EASM system are significant and very complex. These variations have an important effect on the spatio-temporal variations of climate disasters in China (e.g., Huang et al., 2007a, 2008, 2011c). In this section, we focus on the spatio-temporal variabilities of EASM system, especially summer monsoon rainfall in East Asia.

3.1 *Interannual variations of onset and northward advances of the EASM system*

The early or late onset of the ASM has an important impact on the interannual variability of summer monsoon rainfall in East Asia (Huang et al., 2005, 2006c). To investigate the interannual variability of onset date and process of the SCSM, we defined an index for measuring SCSM onset. Generally, the appearance of strong convective activity and the southwesterly flow over the SCS signals the onset of the SCSM. However, many definitions of the SCSM onset have been devised (e.g., Wang et al., 2004). For example, Tao and Chen (1987) suggested that the earliest onset of Asian summer monsoon (ASM) occurs over the SCS and the Indo-China Peninsula; it is generally called the South China Sea monsoon (SCSM) in China. Ding and He (2006) proposed that the earliest onset of the ASM occurs over the tropical eastern Indian Ocean. Compared with other definitions of SCSM onset, we also preferred the definition proposed by Liang and Wu (2002) (e.g., Huang et al., 2005, 2006c). Huang et al. (2005, 2006c) pointed out that the SCSM onset is closely associated with the thermal state of the tropical western Pacific and the convective activity around the Philippines. To explain the impact of convective activity over the tropical western Pacific on the SCSM onset, the relationship between the SCSM onset date and convective activity around the Philippines (i..e,, 10°–20°N , 110°–140°E) in spring was analyzed by Huang et al. (2006c) using the observation data of high cloud amount (HCA) obtained by geostationary meteorological satellite (GMS) satellite. An out-of-phase relationship between the SCSM onset date and the HCA around the Philippines in spring is observed (Fig. 5). The correlation coefficient between them reaches −0.76, which exceeds the 99% confidence level. Therefore, the convective activity around the Philippines has a great influence on the onset of SCSM. In a spring with strong convective activity around the Philippines, which generally occurs during a warming

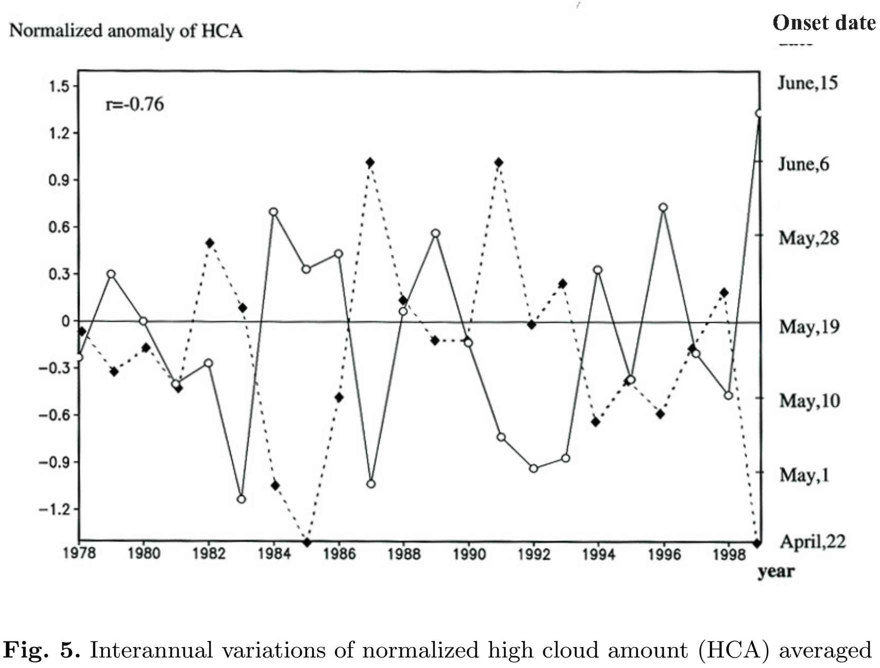

Fig. 5. Interannual variations of normalized high cloud amount (HCA) averaged for the area around the Philippines (10°–20°N, 110°–140°E) in spring (solid line) and the SCSM onset date (dashed line) based on observed HCA data from Monthly Report on Climate System, JMA.

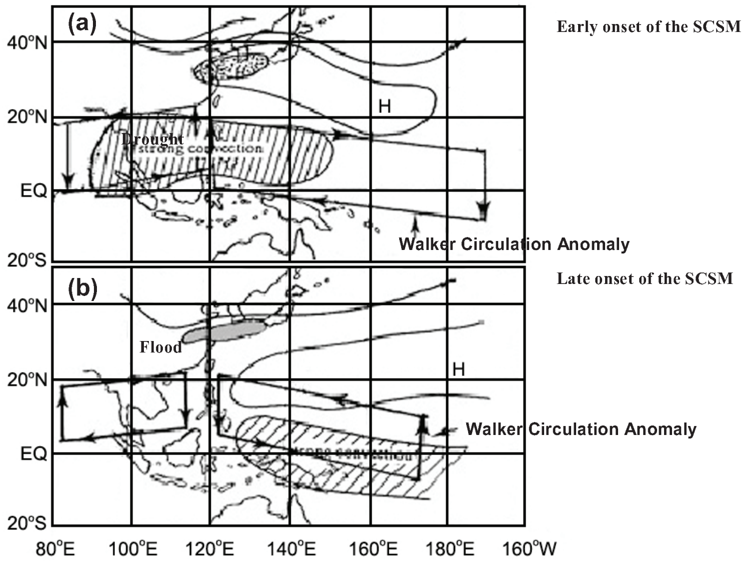

Fig. 6. Schematic map of the relationships among the thermal states of the tropical western Pacific (TWP, 0°–14°N, 130°–150°E) in spring, the convective activity around the Philippines, the western Pacific subtropical high, the onset of SCSM and the summer monsoon rainfall in East Asia in (a) the warming and (b) the cooling state of the TWP.

period in the tropical western Pacific, the SCSM onset is early. On the other hand, the SCSM onset is late in a spring with weak convective activity around the Philippines, which is generally found in a cooling period of the tropical western Pacific. The interannual variability of SCSM onset date is very large and is closely associated with the thermal states of the tropical western Pacific, especially the convective activity around the Philippines in spring.

Huang et al. (2006c) also analyzed the influence of the thermal state of the tropical western Pacific on the SCSM onset process, Their results show that when the tropical western Pacific is in a warming state in spring, the twin anomalous cyclones can appear early over the Bay of Bengal and Sumatra before the onset of the SCSM, due to the eastward shift of the western Pacific subtropical high. Thus, the southwesterly flow and strong convective activities are intensified over Sumatra, the Indo-China Peninsula, and the SCS in mid-May. This leads to an early onset of the SCSM (Fig. 6a). On the other hand, when the tropical western Pacific is in a cooling state in spring, the twin anomalous anticyclones are located over the equatorial eastern Indian Ocean and Sumatra from late April to mid-May due to the westward shifts of the western Pacific subtropical high. Thus, the southwesterly flow and convective activities cannot be intensified early over the Indo-China Peninsula and the SCS. Only when the western Pacific subtropical high moves eastward, the weak trough located over the Bay of Bengal can be intensified and becomes a strong trough. As a result, the strong southwesterly wind and convective activities generally intensify over the Indo-China Peninsula and the SCS in late May. This leads to late onset of the SCSM (Fig. 6b). In addition, some studies suggest that the onset of SCSM is also associated with the atmospheric circulation anomalies over middle and high latitudes, and with 30–60-day low frequency oscillation over the tropics (He et al., 2003; Wen et al., 2006).

Following the onset of the SCSM, the monsoon moves northward over East Asia. Huang and Sun (1992) discussed well the dependence of the northward advance of the EASM system on the thermal state of the tropical western Pacific. Huang et al. (2005) further investigated the interannual variations of the intraseasonal variability, i.e., the northward advances and southward retreat of EASM system. Their results show that the northward advances of the EASM system after its onset over the SCS are also influenced by the thermal state of the tropical western Pacific in summer, and that there are close relationships among the thermal states of the tropical western Pacific, the convective activity around the Philippines, the western Pacific subtropical high, and the summer monsoon rainfall in East Asia. As shown in Fig. 6a, when the thermal state in the tropical western Pacific is warming (i.e., the warm sea water is accumulated in the

West Pacific warm pool in summer), convective activity is intensified from the Indo-China Peninsula to the east of the Philippines. In this case, the western Pacific subtropical high shifts unusually northward, and the summer monsoon rainfall may be below normal in the Yangtze River and Huaihe River basins of China, South Korea, and Japan. Drought may occur in these regions. On the other hand, when the thermal state in the tropical western Pacific is in a cooling state, the convective activity is weak around the Philippines in summer, in this case, the western Pacific subtropical high may shift southward (Fig. 6b). The summer monsoon rainfall may be above normal in the Yangtze-Huaihe River valley of China, South Korea, and Southwest Japan. Therefore, following a spring with late onset of the SCSM, severe floods may occur in the Yangtze-River valley, and droughts will be caused in North China in summer, such as in the summers of 1998 and 2010.

These results suggest that the thermal state of the tropical western Pacific, especially the oceanic heating content (OHC) anomaly in the Niño west region (i.e., 0°–14°N, 130°–150°E) in spring (March–May) and summer can be considered as a physical factor affecting the SCSM onset and summertime droughts and floods in the Yangtze-Huaihe River valley, South Korea and Japan. A conceptual map of seasonal prediction for summertime droughts and floods in eastern China is shown in Fig. 6.

3.2 *Characteristics of multi-modes in the spatio-temporal variabilities of the EASM system*

The multi-modal characteristics of the spatio-temporal variabilities of the EASM system are shown not only in monsoon rainfall but also in the water vapor transport in this system. Huang et al. (2006b, 2007a) analyzed the spatio-temporal variabilities of the summertime (June–August) precipitation in eastern China using the observed precipitation data at 160 stations in China. They proposed that the spatial distribution of the EASM system variability is characterized by multiple modes. In the following section, the characteristics of multi-modes of the spatio-temporal variabilities of the EASM system are discussed.

Recently, Huang et al. (2011c) further analyzed the leading modes of summertime precipitation anomalies in eastern China using precipitation data of 516 observational stations of China using the empirical orthogonal function (EOF) method. The result also shows that two leading modes characterize the spatio-temporal variations of the summertime precipitation anomalies in eastern China. The first mode exhibits a meridional tripole pattern in spatial distribution (Fig. 7a) with typical quasi-biennial period (Fig. 7b). In addition, a clear interdecadal change can be seen around the 1980s. As shown in Fig. 8b, the second mode exhibits obvious interdecadal variability, characteristic of the meridional dipole pattern in spatial distribution shown in Fig. 8a. Therefore, the spatio-temporal variabilities of EASM system are characterized by multiple modes.

The interannual variability of EASM system with the meridional tripole pattern in spatial distribution has a significant impact on the distributions of summertime droughts and floods in eastern China. For example, the summertime monsoon rainfall amounts in the summers of 1980, 1983, 1987, and 1998 were above normal in the Yangtze-Huaihe River valley and below normal in South China and North China. During these summers, severe floods were recorded in the Yangtze-Huaihe River valley, while droughts were recorded in South China and North China. In contrast, the summertime monsoon rainfall amounts in the summers of 1976 and 1994 were below normal in the Yangtze-Huaihe River valley and above normal in South China and North China. Thus, severe droughts were recorded in the Yangtze-Huaihe River valley, while floods occurred in South China in these two summers.

These studies show that quasi-biennial oscillation appears not only in the interannual variability of the SASM system (e.g., Yasunari and Suppiah, 1988) but also in the interannual variability of the EASM system. Therefore, as explained by Ding (2007), the quasi-biennial oscillation may be a leading mode of the Asian summer monsoon, including the EASM and SASM systems.

The multi-modal characteristics of the spatio-temporal variability of the EASM system are shown not only in the spatio-temporal variability of monsoon rainfall but also in water vapor transport associated with the EASM system. Recently, Huang et al. (2011c) analyzed further the spatio-temporal variability of water vapor transport fluxes in the EASM system using the moisture and wind fields of ERA-40 reanalysis (6-h intervals, figures not shown). According to their analysis, the meridional tripole pattern and meridional dipole pattern are also the first two leading modes in the zonal water vapor transport fluxes in the EASM region. Obvious interannual variability can also be seen with quasi-biennial rhythm and interdecadal change in the corresponding time series of the EOF1 of zonal water vapor transports in the EASM region. From the late 1950s to the early 1970s, the northward water vapor transport was strong, but it became weaker from the early 1970s to the early 1990s, and it again became strong from the early 1990s to the late 1990s. However, from the analysis by Zhou et al. (2010) using

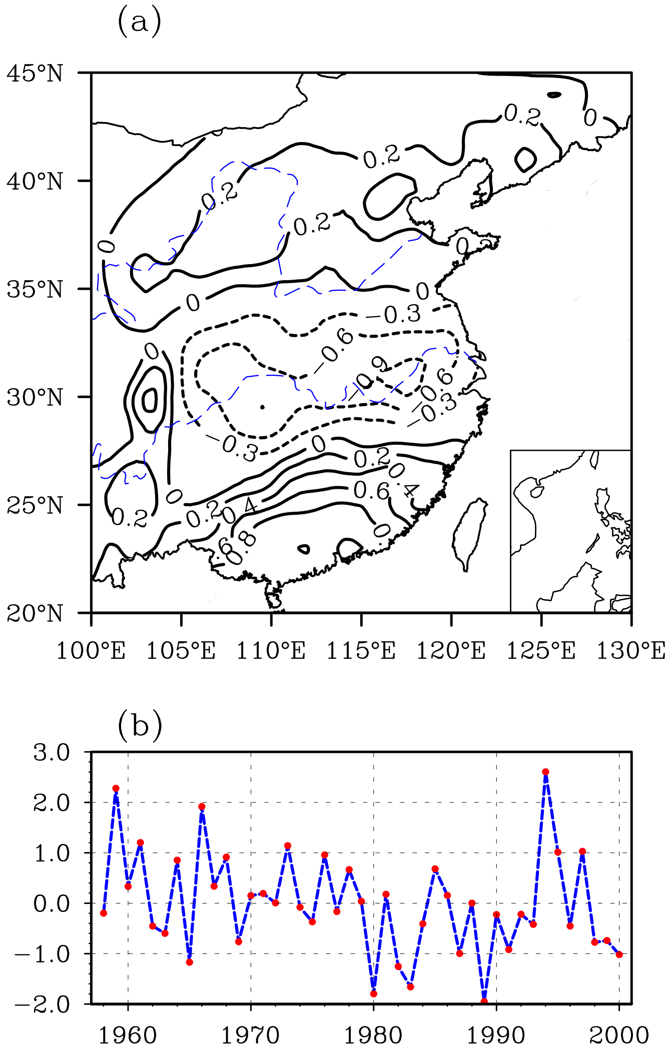

Fig. 7. (a). Spatial distribution and corresponding time coefficient series of the first EOF mode of summertime (JJA) rainfall in eastern China for 1958–2000 based on observed precipitation data at 756 China stations. The solid and dashed lines in (a) indicate positive and negative values, respectively. EOF1 explains 15.3% of the total variance.

NCEP/NCAR reanalysis data, it can be seen that the corresponding time coefficients of EOF1 of summertime water vapor transport field exhibited a decreasing trend from 1951 to 2005. Huang et al. (2011c) also showed that the multiple modes of the spatio-temporal variability of monsoon rainfall in eastern China are closely associated with those of water vapor transport over East Asia.

3.3 *Interdecadal variability of the EASM system*

The EASM system has not only obvious interannual variability but also significant interdecadal variability, especially in monsoon rainfall over East Asia. Huang et al. (1999) analyzed the interdecadal variations of summer monsoon rainfall and reported that the summer monsoon rainfall in North China obviously decreased from the late 1970s to the early 1990s, causing prolonged severe droughts in this region. They also described an opposite phenomenon that appeared in the Yangtze River and the Huaihe River valleys and Northwest China. In these regions, summer rainfall obviously increased from the late 1970s. Chen et al. (2004) systematically discussed the characteristics of the climate change in China during the last 80 years. Their results also show that the interdecadal fluctuations of summer (June–August) monsoon rainfall are more obvious than surface air temperature in East

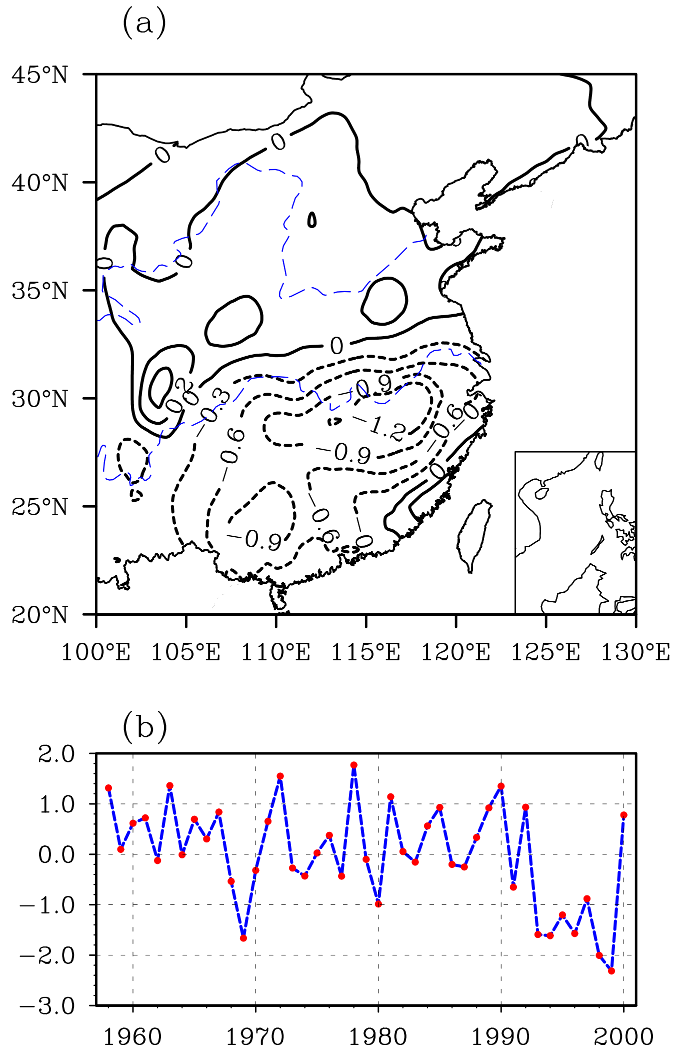

Fig. 8. As in Fig. 7, except for the EOF2, which explains 13.2% of the total variance.

Asia.

Recently, many studies have shown that the EASM rainfall underwent significant interdecadal variations not only in the late 1970s but also in the early 1990s (e.g., Kwon et al., 2007; Ding et al., 2008; Deng et al., 2009; Wu et al., 2010; Huang et al., 2011c). This interdecadal oscillation may be also presented in the corresponding time coefficient series of the EOF1 and EOF2 of summer rainfall in eastern China (Figs. 7b, 8b). The oscillation exhibits a meridional tripole pattern or a meridional dipole pattern in the spatial distribution (Figs. 7a and 8a). As described by Huang et al. (2011c), these two leading modes of monsoon rainfall variability in the EASM region exhibit significant interdecadal variability. This variability can be clearly seen from the interdecadal variation of summer monsoon rainfall anomalies in eastern China during the periods 1958–1997, 1978–1992, 1993–1999, and 1999–2009 (figures not shown), and latitude-time cross section of summer (June–August) rainfall anomalies in eastern China (averaged over 110°–120°E, Fig. 9). As shown in Fig. 9, the distributions of summertime monsoon rainfall anomalies in eastern China exhibited a "+, −, +" meridional tripole pattern from the south to the north during 1958–1977 period. During 1978–1992, opposite anomaly distributions to those during 1958–1977 appeared in this region. But during 1993–1998, because the role of the second leading mode of the summertime monsoon rainfall variability over eastern China was intensified (Fig. 9), the anomaly distributions of summertime rainfall appeared in a meridional tripole pattern combination of "+, −, +" and a meridional dipole pattern "+, −" from the south to the north, which caused the obvious increase of summer monsoon rainfall in South China.

The results analyzed by Huang et al. (2011c) also

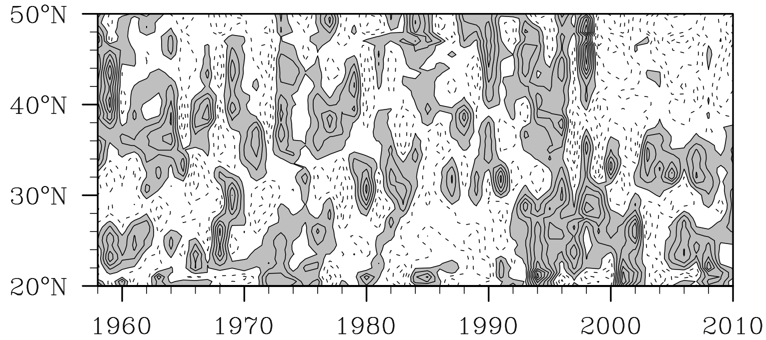

Fig. 9. Latitude-time cross section of summertime (JJA) rainfall anomalies (percentage) along 115°E (average for 110°–120°E) in eastern China based on precipitation data at 756 observation stations. The solid and dashed lines indicate positive and negative anomalies, respectively. Positive anomalies are shaded.

show that the interdecadal variability of leading modes of summertime monsoon rainfall variability in eastern China is closely associated with the interdecadal variability of water vapor transport fluxes by summer monsoon flow over East Asia. Furthermore, their results show that the interdecadal variability of water vapor transport fluxes over East Asia is associated with not only the interdecadal variation of the East Asia/Pacific (EAP) teleconnection of summer circulation anomalies over East Asia (e.g., Nitta, 1987; Huang and Li, 1987, 1988) but also the interdecadal variation of the Eurasian (EU) teleconnection of summer circulation anomalies over middle and high latitudes (e.g., Wallace and Gutzler, 1981). Li et al. (2011) also pointed out that there is a long-term change in summer water vapor transport over South China during recent decades.

However, according to the analysis of Huang et al. (2011c), a interdecadal variation of summer water vapor transport over East Asia, which is closely associated with the summer monsoon circulation, occurred in the late 1980s. This result agrees with those obtained from monsoon circulation by Wu et al. (2009) and Zhang et al. (2008). Thus, there is small difference between the interdecadal variability of summer monsoon rainfall in eastern China (e.g., Kwon et al., 2007; Ding et al., 2008; Deng et al., 2009; Huang et al., 2011c) and the interdecadal variability of summer monsoon circulation over East Asia (e.g., Zhang et al. 2008; Wu et al., 2009). Summer rainfall variability depends not only on the moisture advection by the monsoon flow but also on the convergence of the monsoon circulation.

The studies mentioned here mainly focused on the interdecadal variability of summer climate over East Asia occurred in about 1978 and 1992, respectively (e.g., Huang et al., 1999, 2004a, 2006a, 2011c; Zhang et al., 2007; Kwon et al., 2007; Ding et al., 2008; Deng et al., 2009). Recently, Huang et al. (2011b) described a climate jump in the late 1990s in the summer monsoon rainfall in China, especially in North China, Northeast China, and Northwest China. This climate jump was characterized by the decrease of summer rainfall in North China, Northeast China and the eastern part of Northwest China and the increase in the Huaihe River valley (Fig. 9). Thus, the rainfall anomaly distributions caused by this climate jump appeared a meridional dipole pattern, with droughts in the northern part but floods in the southern part of China. The interdecadal variation of the summer rainfall anomalies in eastern China is closely associated with the zonal mean flow in the upper troposphere over East Asia (e.g., Huang et al., 2012a). As shown in Fig. 10, a transition of zonal mean flow anomalies at 200 hPa over East Asia from the meridional tripole pattern to the meridional dipole pattern over the region from 10°N to 55°N of East Asia occurred in the late 1990s. This trend agrees with the interdecadal variability of the JJAS mean rainfall in the late 1990s. Moreover, Huang et al., (2011b) studied the interdecadal variability of July–September (JJAS) mean rainfall in northern China using the daily observational rainfall data for 1961–2008 in China. Their study show that the summer monsoon rainfall became weak in northern China including the southern part of Northwest China, North China, and the Northeast China. This result further demonstrates the climate jump in the late 1990s.

The analysis by Huang et al. (2011b) of the upper-level circumglobal teleconnection in boreal summer also revealed the cause of the interdecadal variation of the JJAS rainfall in northern China during in the late 1990s. To study the relationship between them, two indices (CGTI-1 and CGTI-2) were defined following Ding and Wang (2005). These two indices were defined as the normalized geopotential height anomaly at 200

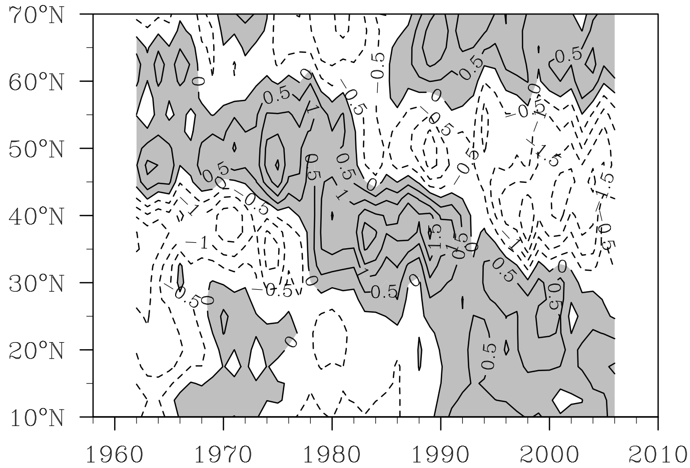

Fig. 10. Latitude-time cross section of the 9-year running mean summer time (JJA) zonal wind anomalies at 200 hPa averaged for 100°–140°E over East Asia based on NCEP/NCAR reanalysis data. Units: m s^{-1}. Solid and dashed lines indicate positive and negative anomalies, respectively. The positive anomalies are dashed. The climatological mean is based on the period 1971–2008.

hPa averaged over the area (35°–40°N, 60°–70°E) and the difference of the normalized geopotential height at 200 hPa between the area (40°–50°N, 20°–10°W) and the area (60°–65°N, 15°–25°E) in June–September. The correlation coefficient between the CGTI1 index and the normalized JJAS mean rainfall anomaly averaged for North China was 0.50 (Fig. 11a), which exceeded the 99% confidence level. The correlation coefficient between the CGTI-2 index and the JJAS mean rainfall averaged for Northwest China reached 0.53 (Fig. 11b), also exceeding the 99% confidence level. From Figs. 11a and b, it can be seen that both the CGTI-1 index and the CGTI-2 index as well as the JJAS mean rainfall in both North China and Northwest China, were mostly below normal after 1999, different from those before 1999. Therefore, from the interdecadal variation of the upper-level circumglobal teleconnection, it can also be seen that an interdecadal variation of the EASM system occurred in the late 1990s.

4. Characteristics of the spatio-temporal variabilities of the EAWM system

East Asia is a region of strong winter monsoon. The EAWM system includes the following: (1) the Siberian High, (2) the Aleutian Low, (3) strong northwesterly wind over North China, Northeast China, Korea and Japan, strong northeasterly wind along the coast of Southeast China, South China, and the Indo-China Peninsula, (4) the East Asian trough at 500 hPa over Northeast China, and (5) the East Asian jet with its maximum in the upper troposphere over Southeast Japan (e.g., Chen et al., 1991; Ding, 1994). The East Asian jet is associated with intense baroclinicity, large vertical wind shear and strong cold advection (e.g., Ding, 1994; Chen et al., 2003; Wang et al., 2010). The spatio-temporal variabilities of the EAMW system are also very complex.

4.1 *Interannual variability of the EAWM system*

The strength of the EAWM system has been a major concern in most previous studies on the interannual variability of the EAWM system. As reviewed by Wang and Chen (2010a), many indices have been defined to describe the EAWM strength (e.g., Chen and Graf, 1998; Wu and Wang, 2002; Jhun and Lee, 2004; Li and Yang, 2010; Wang and Chen, 2010a). For example, Chen and Graf (1998) and Chen et al. (2000) defined the EAWM index as the normalized meridional wind anomalies at 10 m averaged over the East China Sea (25°–40°E, 120°–140°E) and the South China Sea (10°–25°N, 110°–130°E) from November to March of the following year. Wu and Wang (2002) defined the EAWM index as the sum of zonal sea-level pressure differences (110°E minus 160°E) over 20°–70°N with a 2.5°×2.5° interval in latitude and longitude. Their results show significant interannual variations in the EAWM strength.

Recently, Huang et al. (2007b) investigated the characteristics of the interannual variability of the EAWM strength using the index defined by Wu and Wang (2002). They reported that the strength of

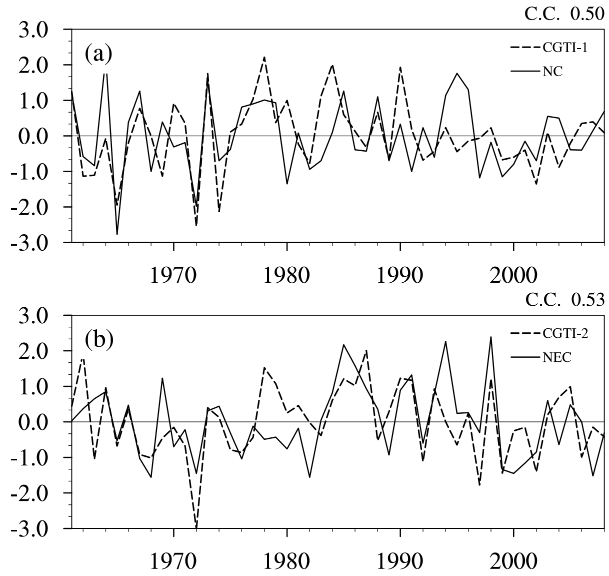

Fig. 11. The time series of (a) the CGT-I index and (b) CGTI-2 index and the normalized JJAS mean rainfall anomalies averaged for (a) North China and (b) Northwest China. The definitions of the CGTI-1 index and the CGTI-2 index follow Ding and Wang (2005).

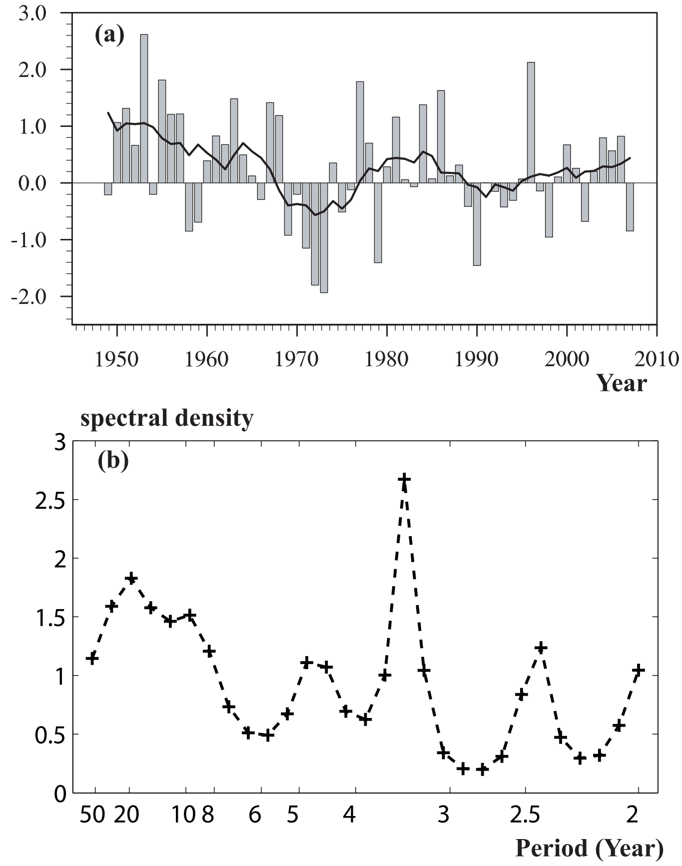

Fig. 12. (a) Interannual variations of the EAWM index and (b) the dominant period analyzed by using the entrophy spectrum analysis based on NCEP/NCAR reanalysis data. The definition of the EAWM index follows Wu and Wang (2002).

the EAWM has a significant interannual variability with an oscillation of approximately 4 years (Fig. 12). Their results also show an obvious difference between the EAWM intensity in the winter of 2005 (December 2005–February 2006) and 2006 (December 2006–February 2007), which caused the different winter climate anomalies in the Northern Hemisphere, especially in East Asia. A similar phenomena also occurred in January 2008 and the winter of 2009. Prolonged cooling and severe snowstorms struck most of China in January 2008, causing 129 deaths and the economic losses of 150 billion CNY (∼US$21 billion) (e.g., Gu et al., 2008; Wang et al., 2009b). In the winter of 2009, frequent severe cold weather afflicted many areas of mid-latitude Northern Hemisphere, including northern China, with record-breaking blizzards, snowstorms, and low temperatures, which caused extensive traffic damage and great losses to agriculture and fisheries (e.g., Wang and Chen, 2010b).

4.2 *Characteristic of multiple modes in the spatio-temporal variabilities of the EAWM system*

In recent years, the variability of EAWM system has been recognized as complex and as having multimodal characteristics (e.g., Kang et al., 2006, 2009; Wang et al., 2009a, 2010; Wang and Chen, 2010a). Based on the observations from 160 stations in China, Kang et al. (2006, 2009) first identified two leading modes of wintertime surface air temperature in China on both interdecadal and interannual time scales. The first leading mode reflects a variability of surface air temperature in whole China, which is related to the strength of the EAWM system. The second leading mode describes a surface air-temperature oscillation between the northern and southern parts of China. Moreover, Wu et al. (2006) also suggested that there are also two distinct modes in the spatio-temporal variations of the EAWM system, and that these two leading distinct modes mainly reflect the variability of meridional and zonal winds in winter, respectively. In addition, from the EOF analysis of the wintertime surface air temperature in East Asia, Wang et al. (2010) also obtained a northern mode and a southern mode for the wintertime surface air temperature variability in East Asia.

Like the second leading modes of the spatio-temporal variations of the EAWM system, the pathway of the EAWM exhibits significant interannual variation, associated with the tilt of the East Asian trough (EAT) axis in winter (Wang et al., 2009a). When the tilt of the EAT axis is small, the southern pathway is strong. In this case, the major cold air flows along the coast of China and penetrates into

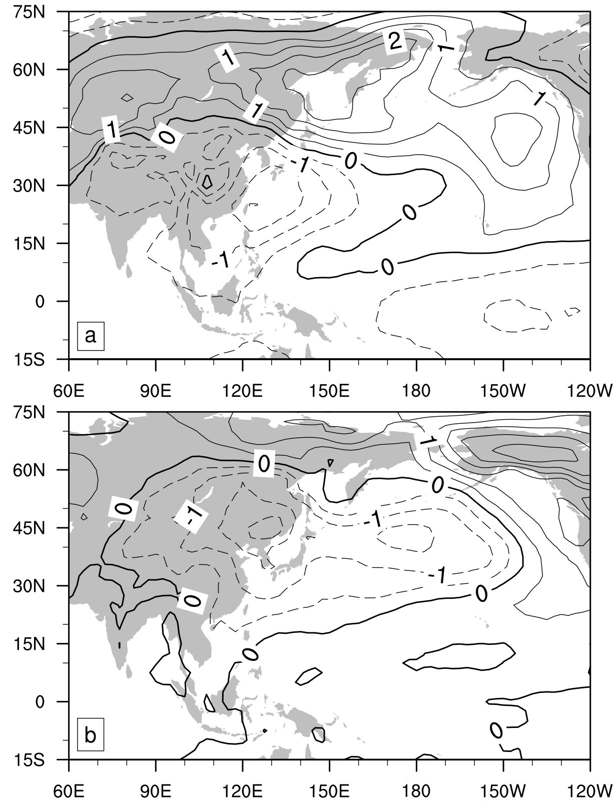

Fig. 13. Distributions of the 850-hPa air temperature anomalies for five strong winters with (a) strong southern EAWM pathway and (b) strong eastern EAWM pathway based on ERA-40 reanalysis data. The solid and dashed contours indicate positive and negative anomaly, respectively. Contour intervals are 0.5°C.

the Southern Hemisphere, which leads to significant cooling in the SCS and Southeast Asia and warming in the northern part of East Asia (Fig. 13a). Thus, the tropical rain belt in Southeast Asia can be pushed southward by stronger northerly wind, and more precipitation can be observed in the East Asian continent (Wang et al., 2009a). In contrast, when the tilt of the EAT axis is large, the eastern pathway is strong. In this case, more cold air flows into the North Pacific with a weakened southern branch of airflow, and the climate anomalies are generally reversed (Fig. 13b). Therefore, the variability of the EAWM pathway has a modulation effect on the regional climate in East Asia and Southeast Asia. Further analysis implies that the North Pacific SST can influence the interannual variability of the EAWM pathway through the atmosphere–ocean interaction. When warm SST anomalies are observed over the North Pacific from the preceding summer to autumn, the EAWM tends to take the southern pathway in the following winter, and when cold SST anomalies are observed, the

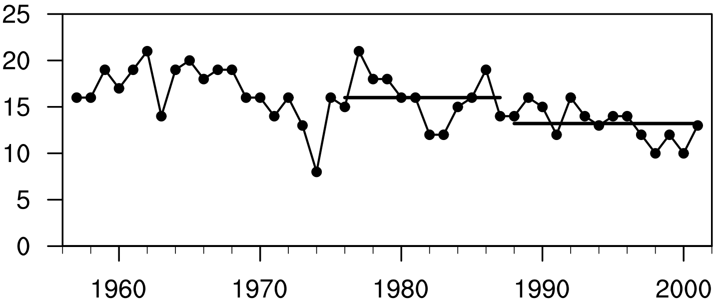

Fig. 14. Number of general cold surges that occurred in China for the extended winter, NDJFMA, of 1957–2001, recorded in the CMA cold surge almanac.

EAWM tends toward the eastern pathway in the following winter (Wang et al., 2009a).

4.3 *Interdecadal variability of the EAWM system*

The EAWM system is characterized by obvious interdecadal variability in addition to interannual variability (e.g., Jhun and Lee, 2004; Huang and Wang, 2006; Wang et al., 2009b; Wang and Chen, 2010a). Observational studies have revealed that the strength of the EAWM system was significantly weakened after 1987 (e.g., Huang and Wang, 2006; Kang et al., 2006; Wang et al., 2009b; Wang and Chen, 2010a). Compared with the period 1976–1987, both the Siberian High/Aleutian Low (Wang et al., 2009a) and the sea surface wind stress along the coasts of East Asia (Cai et al., 2006) weakened for the period of 1988-2001, which accompanied fewer cold waves (Wang et al., 2009b) and frequent warm winters (Wang and Ding, 2006; Kang et al., 2006) in China. Wang et al. (2009b) analyzed the numbers of cold waves in China for the winters during 1957–2001 according to the data recorded in the NCC-CMA cold-wave almanac and revealed that an average of 15.4 general cold waves occurred each winter. There were 16 cold waves per year for the strong EAWM period 1976–1987, but there were only 13.2 cold waves per year for the weak EAWM period 1988–2001 (Fig. 14).

Although the decreasing trend for the number of cold waves over China for 1988–2001 is clear (e.g., Wang and Ding, 2006; Wang et al., 2009b), the frequency of severe cold winters tended to increase from the early 21st century (e.g., Ding and Ma, 2007; Huang et al., 2008; Ma et al., 2008; Hong and Li, 2009; Lu and Chang, 2009; Wen et al., 2009; Wang and Chen, 2010b). It suggests that the continuous warm winters after 1987 in China have ended before 2008 (e.g., Ma et al., 2008; Wang et al., 2009b). Thus, it is possible that the EAWM system may undergo another interdecadal variation from recent years (Wei et al., 2011).

4.4 *Impact of the EAWM system variability on wintertime rainfall in China and the marine environment over the offshore area of China*

The studies mentioned in the previous section show that the EAWM system variability has an important impact on surface air temperature over China. The EAWM system variability also has a significant impact on precipitation. Wang and Feng (2011) identified two major modes of wintertime (December–February) precipitation over China through EOF method. The first mode (EOF1) reflects the strength of precipitation over southeastern China with a clear 2–4-year period. Its interdecadal variations suggest that the wintertime precipitation over southeastern China was below normal before the mid-1980s and above normal thereafter, and underwent a slight decreasing trend in recent years. The second mode (EOF2) delineates an out-of-phase relationship between South China and the middle and lower reaches of the Yangtze River as well as the northern part of Xinjiang, with a clear 2–4-year period, too. They further suggested that EOF1 is closely related to ENSO and the strength of the EAWM. The variation of EOF2 is closely associated with a barotropic wave train across the Eurasian continent originating from the North Atlantic.

Zhou (2011) investigated the impact of the EAWM system variability on late winter (January–March, JFM) rainfall over southeastern China using observational data for 1951–2003. His study showed a significant correlation between the EAWM variability and JFM rainfall over southeastern China. In a winter (JFM) with the weak EAWM, the southwesterly wind anomalies at 700 hPa dominate over the SCS, which can transport more water vapor from the Bay of Bengal and the SCS into southeastern China. In this case, the westerly jet is weakened over East Asia and displaces southward, contributing to the intensification of ascending motion over southeastern China, and

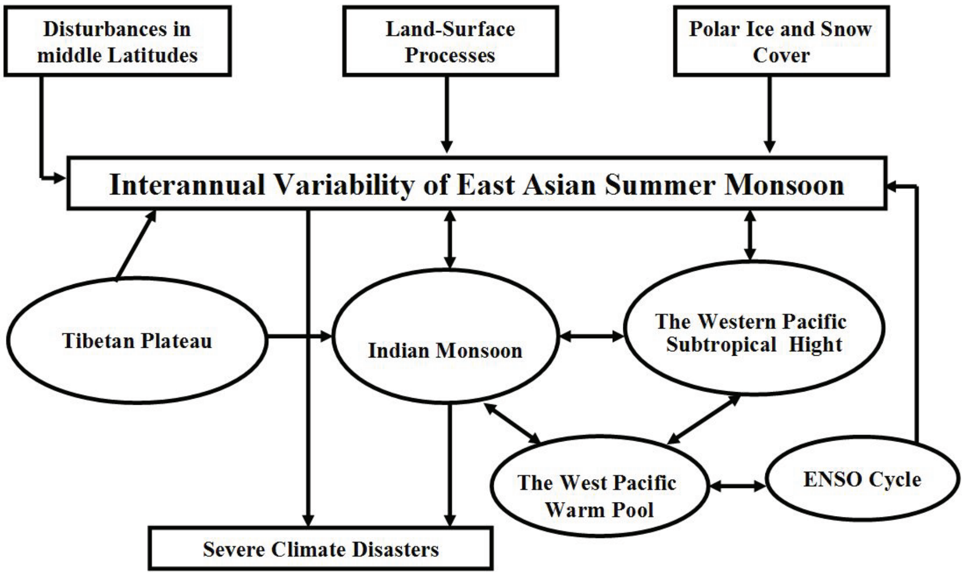

Fig. 15. Schematic map of components of the EAM climate system.

causing the increase of wintertime (JFM) rainfall in southeastern China. Gu et al. (2008) investigated the impact of the EAWM variability on wintertime snow storms in China, especially on severe blizzards, freezing rain, and low temperatures in January 2008. Their results show that the East Asian trough stayed in a stable state for long time in January 2008, leading to the continuous southward-intrusion of cold air along the Mongolian Plateau to Central China, Southwest China, and South China. Meanwhile, the western Pacific subtropical high shifted anomalously northward and westward, which led to the northward transport of a large amount of wet air along the west edge of the subtropical high from the Bay of Bengal and the SCS, and the southwest flow with wet air converged with cold air from the Mongolian Plateau in the Yangtze River valley. Thus, prolonged heavy snowfall and low temperature occurred in Central China, South China, the eastern part of Southwest China, and the Yangtze River valley in January 2008.

The EAWM system variability has a significant impact not only on severe cold waves and heavy snowfall in China but also on the marine environment in the offshore area of China including the Bohai Sea, the Yellow Sea, the East China Sea, and the SCS and its adjacent ocean. Cai et al. (2006, 2011) suggest that the sea surface wind stresses, especially the meridional sea surface wind stresses, have been weakened over the offshore area of China and its adjacent ocean from the 1980s, due to the weakened EASM and the EAWM systems. The weakened wind stress has caused obvious warming in the underling ocean, providing a favorable marine environment for the frequent occurrence of red tides in the offshore area of China.

5. Influence of atmosphere–ocean–land interactions on the EAM system variability

As shown by Webster et al. (1998), the monsoon is not only an atmospheric circulation system but also an atmosphere–ocean–land coupled system. The interannual and interdecadal variabilities of EAM system are influenced not only by many circulation system such as the SASM system, the western Pacific subtropical high, the disturbances in middle and high latitudes (e.g., Tao and Chen, 1987) but also by other factors such as thermal states of the West Pacific warm pool and convective activity around the Philippines, ENSO cycles in the tropical Pacific, the thermal state of the tropical Indian Ocean, the dynamical and thermal effects over the Tibetan Plateau, and the land surface process in the arid and semiarid area of Northwest China and the snow cover on the Tibetan Plateau and the Eurasian continent and so on. As shown in Fig. 15, these factors affecting the EAM system variability are various components of an atmosphere–ocean–land coupled system, and these components are interactions. Therefore, this coupled system may be called the EAM climate system (e.g., Huang et al., 2004a, 2006a, 2007a; Huang, 2009).

To understand the causes of the EAM climate system variability, it is necessary to analyze the interactive processes between the atmosphere and oceans and between the atmosphere and land surface in the EAM climate system. However, because the interactions among these components of the EAM climate system are complex, only the impacts of atmosphere–ocean and atmosphere–land coupling components of this climate system on the EAM system variability are simply discussed in the following sections.

5.1 *Thermal effect of the tropical western Pacific on the EAM system variability*

The tropical western Pacific is the region with the highest SSTs in the global sea surface. Due to the warm state of this region, the atmosphere–ocean interaction is very strong, and the ascending branch of the Walker circulation extends over the region. This leads to strong convergence of air and moisture and strong convective activity and heavy rainfall there (Cornejo-Garrido and Stone, 1977; Hartmann et al., 1984). Thus, the tropical western Pacific has an important thermal effect on EAM system variability.

Many important studies (e.g., Nitta, 1987; Huang and Li, 1987, 1988; Kurihara, 1989; Huang and Sun, 1992) show that the thermal states of tropical western Pacific and convective activity around the Philippines play important roles in the interannual variability of the EASM system. Huang et al. (2005) investigated the relationship between the intraseasonal variations of the western Pacific subtropical high and the thermal state of the tropical western Pacific in summer; they showed a close relationship between the anomalous northward shift of the western Pacific subtropical high and the intensified convective activities around the Philippines. When the tropical western Pacific is in a warming state in summer, and convective activities are strong around the Philippines, there are abrupt northward shifts of the western Pacific subtropical high from South China to the Yangtze-Huaihe River valley in early or mid-June and from the Yangtze-Huaihe River valley to North China and Northeast China in late June or early July. Thus, the summer monsoon rainfall may be weak in the Yangtze-Huaihe River valley. In contrast, when the tropical western Pacific is in a cooling state in summer and convective activities are weak around the Philippines, no abrupt northward shifts of the western Pacific subtropical high occur from South China to the Yangtze-Huaihe River valley in early or mid-June and from the Yangtze-Huaihe River valley to North China and Northeast China in late June or early July. Thus, the mei-yu front is maintained for long time, and the summer monsoon rainfall may be strong in the Yangtze-Huaihe River valley. The schematic map is shown in Fig. 6.

Huang et al. (2004b, 2006b) investigated the interannual variability of thermal state of the tropical western Pacific and its impact on interannual variability with the quasi-biennial oscillation of the EASM system. There is a dominant quasi-biennial oscillation in the interannual variations of thermal state of the tropical western Pacific, and it reveals that the oscillation has a great impact on the interannual variability with the quasi-biennial oscillation of the EASM system (Huang et al., 2006b). When the tropical western

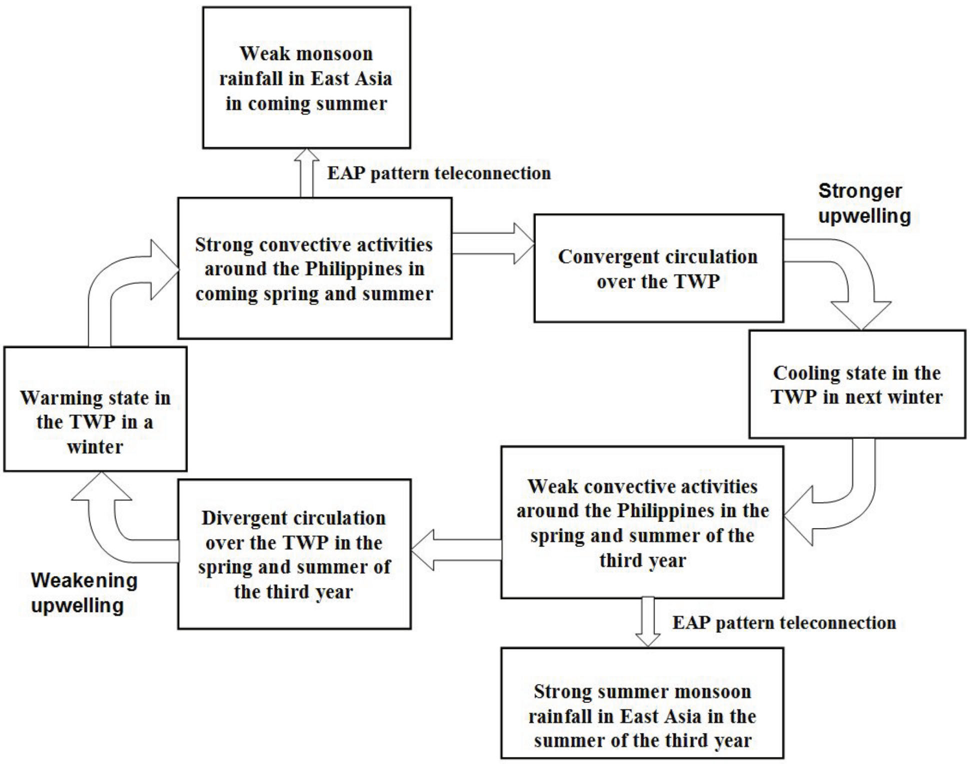

Fig. 16. Conceptive diagram of the quasi-biennial oscillation of the EASM system related to the atmosphere–ocean coupling system over the tropical western Pacific.

Pacific is in a warming state in a winter and coming spring, convective activity generally is stronger around the Philippines in coming spring and summer (Fig. 16b). This can cause the northward shift of the western Pacific subtropical high due to the EAP pattern teleconnection (e.g., Nitta, 1987; Huang and Li, 1987, 1988), which leads to weak monsoon rainfall in the Yangtze River valley of China, Japan, and South Korea. At the same time, the convergence due to the strong convective activity around the Philippines can cause strong upwelling in the tropical western Pacific, which brings a cooling state into the tropical western Pacific in the next winter. Because a cooling state appears in the tropical western Pacific in the following winter, weak convective activity occurs around the Philippines in the spring and summer of the third year. This causes the southward shift of the western Pacific subtropical high due to the EAP pattern teleconnection, which leads to strong monsoon rainfall in the Yangtze River valley of China in the summer of the third year. At the same time, the divergence due to the weak convective activity around the Philippines causes weak upwelling in the tropical western Pacific in the spring and summer of the third year, which brings another warming state into the tropical western Pacific. The period of the process is approximately 2–3 years.

The thermal state of the tropical western Pacific has a significant effect not only on the interannual variability of the EASM system but also on the intraseasonal variability of this system, as described in section 3 (e.g., Huang et al., 2005, 2006b).

5.2 *Impact of ENSO cycles in the tropical Pacific on the EAM system variability*

It is well known that ENSO cycles are one of the most important phenomena of atmosphere–ocean interaction in the tropical Pacific and has a great influence on EAM system variability. Huang and Wu (1989) first showed that summer monsoon rainfall anomalies over East Asia depend on the stages of ENSO cycle in the tropical Pacific. This dependence is also reflected in the runoff from (at least) spring (e.g., Chen et al., 2009). From the composite analyses of summer monsoon rainfall anomalies for different stages of ENSO cycles during the period 1951–2000, Huang and Zhou (2002) concluded that droughts in North China tend to occur in the developing stage of El Niño events, but floods tend to occur in the Yangtze River valley of China during the decaying stage of El Niño events (Fig. 17). For example, severe floods occurred in the Yangtze River valley in the summers of 1998 and 2010, These two summers belong to the decaying state of El Niño events that occurred in 1997 and 2009. The modeling study by Sun and Yang (2005) also showed different interannual anomalous atmospheric circulation patterns over East Asia during different stages of an El Niño event.

Huang and Wu (1989) were the first to describe the important impact of El Niño decaying phase on EASM system variability, generally called the delayed impact of El Niño. Later, Zhang et al. (1996) and Zhang and Huang (1998) investigated the process and mechanism of the delayed impact of El Niño events on EASM system variability and pointed out that this delayed effect may be due to the appearance of an anomalous anticyclonic circulation in the lower troposphere over the tropical western Pacific after the mature phase of El Niño events. The southwesterly anomalies on the western side of the anticyclonic anomaly circulation intensify the southwesterly flow, causing the southwest monsoon over Southeast China to strengthen. Wang et al. (2003) further studied the formation mechanism of the anomalous anticyclonic circulation over the tropical western Pacific. Their study showed that in a winter during the mature stage of El Niño, the weakening convective activities over the tropical western Pacific caused by the weakening Walker circulation and negative anomalies of SST in the tropical western Pacific can trigger a cooling Rossby wave train in the tropical western Pacific and can form an anomalous anticyclonic circulation in the lower troposphere over the tropical western Pacific. This anomalous circulation can be maintained into following spring.

ENSO cycles also significantly influence the transitions between the EAWM and EASM. Chen (2002) and Huang et al. (2004b) proposed that the EAM system variability is associated with ENSO cycles. Chen (2002) analyzed the composite distributions of meridional wind anomalies at 850 hPa and rainfall anomalies for various stages of ENSO cycles. These composite distributions show that in the winter before the developing stage of El Niño, anomalous northerly winds occur along the coastal areas of China (strong EAWM), and an anomalous cyclonic circulation occurs over the tropical western Pacific, which contribute to the development of El Niño. In the following summer, the western Pacific subtropical high is weak, leading to northeasterly anomalies over the Yangtze-Huaihe River valley and the southeastern coast of China. Thus, a weak EASM occurs in the summer when El Niño is developing. When El Niño reaches its mature phase in the following winter, an anticyclonic anomaly circulation begins to appear over the tropical western Pacific (e.g., Zhang et al., 1996; Zhang and Huang, 1998; Wang et al., 2003), and anomalous southwesterly winds prevail in the southeastern coast of China and the SCS. This suggests that a weak EAWM may appear in the winter

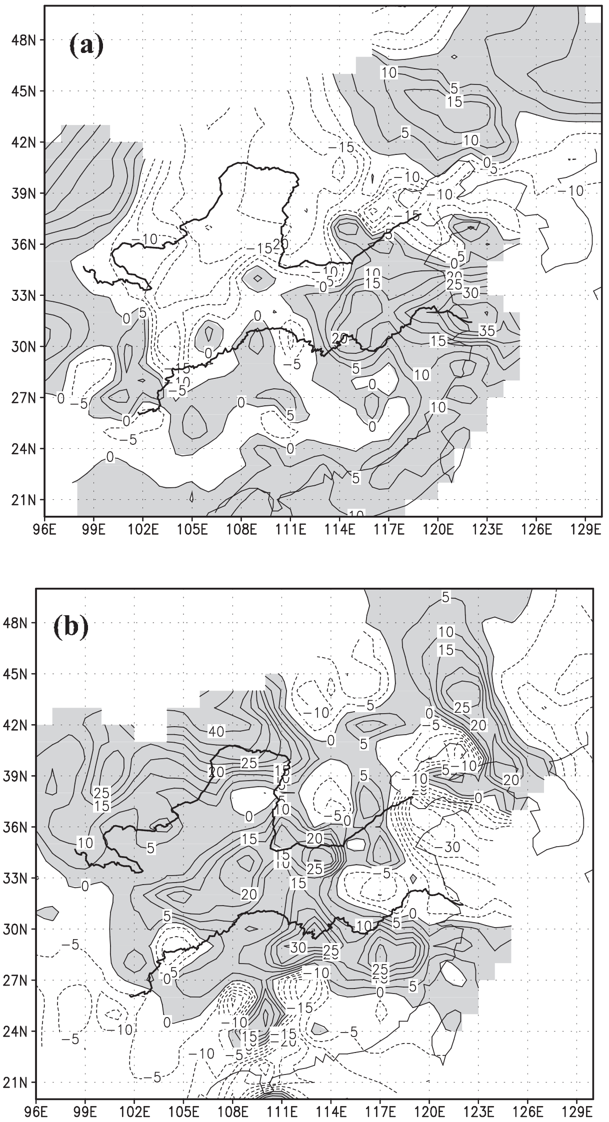

Fig. 17. Composite distributions of summer (JJA) rainfall anomalies (in percentages) over China (a) for the summers in the developing stage and (b) for the summers in the decaying stage of El Niño events occurred during the period from 1951 to 2000. The solid and dashed contours indicate positive and negative anomalies, respectively. Positive values are shaded.

when an El Niño event is in its mature phase. When El Niño begins to decay, the anomalous anticyclonic circulation is intensified over the tropical western Pacific, strengthening the western Pacific subtropical high. In this case, anomalous southwesterly winds are distributed over the region from South China to the Yangtze River valley, which shows that a strong EASM may appear over the Yangtze-Huaihe River valley in the summer when El Niño is in its decaying phase. The recent study by Wang and Wu (2012) further suggests that the role of ENSO is particularly evident during the transitions from weak EAWM to weak EASM.

Recently, several studies on the leading modes of the tropical Pacific SST variability have been published (e.g., Ashok et al., 2007; Weng et al., 2007; Zhang and Huang, 2008; Huang and Huang, 2009). They reveal two leading modes in the tropical Pacific SST anomalies. These two leading modes are characterized by positive SST anomalies in the tropical eastern Pacific and the tropical central Pacific, i.e, the eastern Pacific warming pattern and the central Pacific warming pattern (i.e., El Niño Modoki), respectively. Huang and Huang (2009) analyzed the impact of El Niño Modoki on EAM system variability, especially on summertime rainfall over eastern China. Their results show that summertime rainfall anomaly distributions during the developing and decaying stages of an El Niño Modoki are very different from those shown in Fig. 17. In the summer, with the developing stage of El Niño Modoki, summer monsoon rainfall may be below normal in the Huaihe River valley and above normal in South China (Fig. 18b). In contrast, in the summer with the decaying stage of El Niño Modoki, summer rainfall may be above normal in the Huaihe River valley and below normal in North China and the region south of the Yangtze River (Fig. 18b). In addition, Feng et al. (2010) described the two types of Pacific warming that have distinct impacts on the wintertime rainfall over southeast China and Southeast Asia. In El Niño winters, wet conditions occur over South China, and dry conditions occur over the Philippines, Borneo, Celebes, and Sulawesi. In contrast, for El Niño Modoki winters, the negative rainfall anomalies around the Philippines are weaker and are located more northward compared to their El Niño counterpart.

5.3 *Impact of PDO on the EAM system variability*

Studies have shown significant decadal oscillations in the North Pacific SST, i.e., the Pacific Decadal Oscillation (PDO); this oscillation has an important impact on the atmospheric circulation over the North Pacific (e.g., Trenberth and Hurrell, 1994; Bond and Harrison, 2000). The interannual and interdecadal variabilities of EASM system mentioned previously are closely associated with not only atmospheric but also oceanic anomalous patterns. Specifically, the PDO has a significant impact on EAM system variability on an interdecadal time scale. As mentioned above, the mature phase of El Niño is usually accompanied by a weaker EAWM system and the mature phase of La Niña is usually accompanied by a stronger EAWM

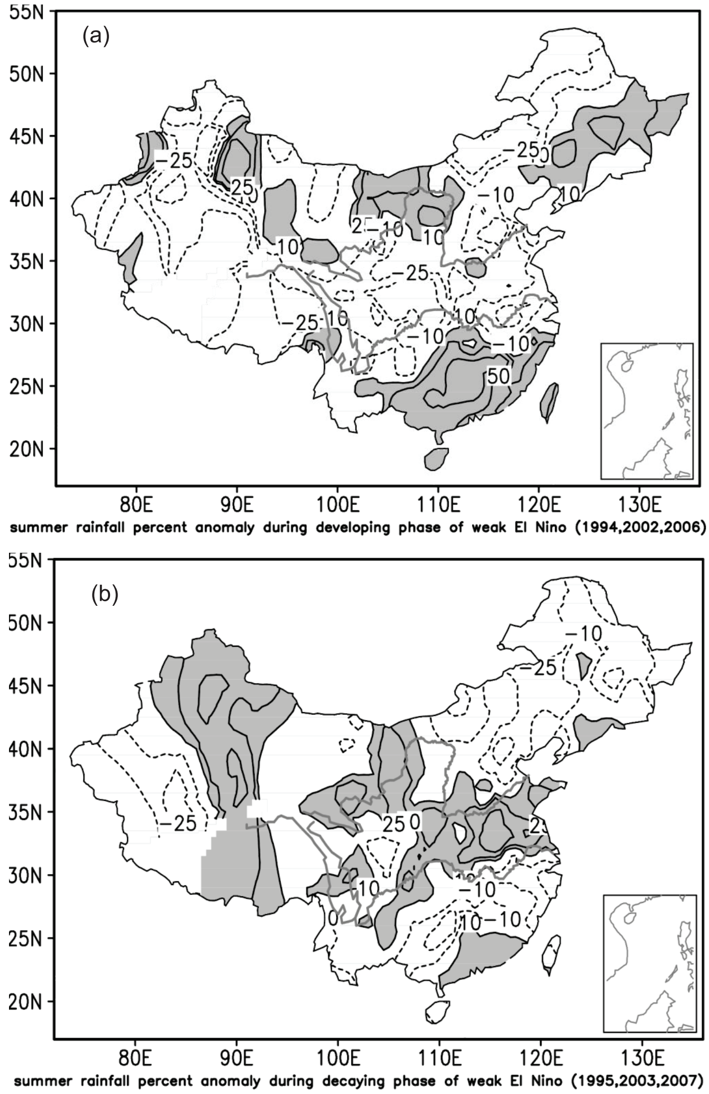

Fig. 18. Composite distributions of summer rainfall anomalies (percentage) in China for (a) the summers of 1994, 2002, and 2006 (i.e., the developing stage of El Niño Modoki) and (b) the summer of 1995, 2003, and 2007 (i.e. the decaying stage of El Niño Modoki). The solid and dashed contours indicate positive and negative anomalies, respectively. Positive values are shaded.

system. However, according to Wang et al. (2008), the impact of the ENSO cycle on the EAWM system variability is modulated by the PDO. When the PDO is in its high phase, there is no significant relationship between the ENSO and EAWM systems on the interannual time scale because the ENSO–EAWM teleconnection is not significant. When the PDO is in its low phase, however, the ENSO cycle has strong impact on the EAWM system, causing significantly low temperatures over East Asia. The PDO was in its high phase after the mid-1970s; therefore, the impact of ENSO cycles on the EAWM system became weak during the following decades. However, in the winters before the mid-1970s, the ENSO cycle had a significant influence on the North Pacific Oscillation (NPO) and on EAWM system variability (Wang et al., 2007).

The PDO also has an important influence on EASM system variability. Previous studies have elucidated the close relationship between PDO and interdecadal variability of climate in China (e.g., Zhu and Yang, 2003; Yang et al., 2005; Xu et al., 2005; Yang and Zhu, 2008). Recently, Zhang et al. (2007) analyzed the interdecadal variations of summertime rainfall in eastern China and their association with the temporal evolution of the PDO. Their results show that the interdecadal variations of summertime rainfall pattern in eastern China and the EASM circulation are closely related to the PDO in the North Pacific. Moreover, Deng et al. (2009) concluded that the first interdecadal variation of summertime rainfall pattern over eastern China occurred in the mid-and late 1970s may have been influenced by the transition of the PDO from a negative to a positive phase, and that the second interdecadal variation of the rainfall pattern that occurred in the late 1980s and the early 1990s may have been association with the warming of the western North Pacific to the south of Japan, especially the warming around the Philippines.

5.4 *Impact of the North Indian Ocean on the EASM system variability*

The tropical Indian Ocean also has an important thermal effect on EASM system variability. The studies by Annamalai et al. (2005) and Yang et al. (2007) suggest that the SST anomalies in the Indian Ocean have an important effect on EASM system variability and climate anomalies over East Asia. Xie et al. (2009) proposed that the Indian Ocean has a capacitor-like effect on the climate variability over the Indo-Western Pacific during the summer following El Niño.

Recently, many studies have focused the thermal role of the tropical northern Indian Ocean in the delayed impact of El Niño on the EASM system. For example, Li et al. (2008), Huang and Hu (2008), and Huang et al. (2010) systematically studied the thermal effect of the tropical northern Indian Ocean on the anomalous anticyclonic circulation in the low troposphere over the western North Pacific in summer, which causes the delayed impact of El Niño on the EASM system. Huang and Hu (2008) further reported that the interannual variation of the western North Pacific anomalous anticyclone is closely associated with SST anomalies in the tropical and northern Indian Ocean in summer, but that it does not have an obvious correlation with the SST anomalies in the western South Indian Ocean. The low-level anomalous anticyclonic circulation over the Northwest Pacific caused by the summertime warming SSTs in the tropical northern Indian Ocean was well simulated by Huang and Hu (2008) using the ECHAM 5.0 climate model. Using five AGCMs, Li et al. (2008) demonstrated that Indian Ocean warming can trigger an anticyclonic anomaly circulation in the lower troposphere over the subtropical western Pacific, intensifying the southwesterly flow to East China; it can also trigger a Gill-type response with the intensified South Asian high in the upper troposphere. The two circulation systems are favorable to the enhancement of the EASM system.

Moreover, Huang et al. (2010) also investigated the interdecadal variation of the relationship between the SST in the tropical northern Indian Ocean and the Northwest Pacific low-level anticyclonic anomaly circulation in boreal summer using both observation data and AGCM simulations. Their results show that the low-level anticyclonic anomaly circulation over the Northwest Pacific is positively correlated with the summertime SST in the tropical northern Indian Ocean after the mid-1970s, but the correlation between them was weak for the period 1958–1976. Their numerical simulations with a 21-member ensemble AGCM (ECHAM5.0) also showed an interdecadal variation in the relationship between the low-level anticyclonic anomaly circulation over the Northwest Pacific and the summertime SST in the tropical Indian Ocean after the mid-1970s.

These studies show that a basin-scale warming trend occurred in the tropical Indian Ocean from the mid-1970s, which caused the intensification of the low-level anticyclonic anomaly circulation and the strong southwesterly flow over East Asia from the mid-1970s. However, according to the results of Huang et al. (2004a, 2006a, 2010), the EASM system has become substantially weaker since the mid-1970s, especially from the late 1990s, although it was stronger during the period 1993–1998. Thus, these results cannot confirm a causal relationship between the tropical Indian Ocean warming and the interdecadal weakening of the EASM system from the mid-1970s (e.g., Li et al., 2008; Huang et al., 2010).

The tropical Indian Ocean has not only a significant impact on the low-level anomaly circulation over the Northwest Pacific but also an important thermal effect on the South Asian High. The variations of the South Asian High (SAH) are closely associated with precipitation and circulation over Asia (e.g., Tao and Zhu, 1964). According to the result of Zhang et al. (2002), in the summer when the SAH shifts eastward, the summer monsoon rainfall may be above normal in Southern Japan, the Korea Peninsula and the Yangtze River valley of China. On the other hand, in the summer when the SAH shifts westward, the summer monsoon rainfall may be below normal in these regions. Zhang et al. (2005) pointed out that the SAH is also linked to global circulation and precipitation in summer. A strengthened SAH is generally accompanied by strengthened and westward western Pacific subtropical high, weakened mid-Pacific trough, and intensified Mexican high, Moreover, increasing precipitation may appear in South Asia, Central America, Australia, and Central Africa, and decreasing precipitation may be caused over the Pacific and the Mediterranean Sea. Additionally, a strengthened SAH can lead to the intensification of the subtropical high over the extratropical North Pacific (Zhao et al., 2009). Therefore, SAH variability is also a factor affecting the EASM system.

From their numerical simulations with five AGCMs, Li et al. (2008) stated that the tropical Indian Ocean warming can trigger the intensification of the SAH in the upper troposphere over South Asia. Recently, the simulation results of Huang et al. (2011a), using the ECHAM 5.0 AGCM also showed that when the tropical Indian Ocean is in a warming state, the SAH is strengthened and its center shifts southward over South Asia. Furthermore, they proposed a possible mechanism of the connection between the thermal state of the tropical Indian Ocean and the SAH variability: The warming SST in the tropical Indian Ocean causes the increase of the equivalent potential temperature in the atmospheric boundary layer and can alter the temperature profile of the moist atmosphere over the tropical Indian Ocean. This induces significant positive geopotential height anomalies over South Asia, and the SAH is thus intensified.

5.5 *The Impact of land surface processes on the EASM system variability*

Because monsoon circulations result fundamentally from the ocean–land thermal contrast, EAM system variability is influenced not only by the thermal state of the tropical Pacific and tropical Indian Ocean but also by the thermal state of the Eurasian continent.

The spring Eurasian snow cover greatly influences the thermal state of the Eurasian continent; thus, it has an important impact on the following summer climate over East Asia. Recently, Wu et al. (2009), and Zhang et al. (2008) analyzed the cause of the significant decadal shift of the summer climate over eastern China that occurred in the late 1980s, which was proposed from the interdecadal variability of the summer monsoon index defined by Wang et al. (2001). This decadal shift of the summer climate over eastern China in the late 1980s, proposed by Wu et al. (2009) and Zhang et al. (2008), may be similar to the decadal shift of the summer rainfall to South China in the early 1990s reported in previous studies (e.g., Ding et al., 2008; Deng et al., 2009; Huang et al., 2011c). As mentioned in subsection 3.3, Wu et al. (2009) and Zhang et al. (2008) revealed that the decadal climate shift of the summer monsoon rainfall belt to South China is closely associated with the decadal variability of the spring snow cover over the Eurasian continent. Their studies also showed a strong negative correlation between these two aspects. They also investigated the physical processes of this correlation; their results show that the snow cover variability in spring Eurasian continent can excite a Rossby wave train over high latitudes from spring to summer, leading to an anomalous high over North China and a weak low over South China. Under these conditions, more monsoon rainfall can be caused in South China.

The snow cover over the Tibetan Plateau is a part of the snow cover over the Eurasian continent. Ye and Gao (1979) first reported that the Tibetan Plateau has important thermal and dynamic effects on the interannual variability of the EASM system. Since then, many investigators have also emphasized the thermal effect of the Tibetan Plateau on the EASM system variability (e.g., Huang, 1984, 1985; Wu and Zhang, 1998).

In the past 10 years, some studies have focused the thermal effect of snow cover over the Tibetan Plateau on the EASM system variability. Wei et al. (2002, 2003) analyzed the interannual and interdecadal variations of the days and depth of snow cover over the Tibetan Plateau using the observation data of daily snow cover at 72 observation stations in the Tibetan Plateau for the period 1960–1999. They discovered obvious interannual and interdecadal variations of the days and depth of snow cover on the Tibetan Plateau. Moreover, these variations of snow cover over the Tibetan Plateau also have an important impact on the summer monsoon rainfall in the middle and upper reaches of the Yangtze River valley (e.g., Wei et al., 2002, 2003; Huang et al., 2004a).

5.6 *Thermal effect of the sensible heating in the arid and semiarid regions of Northwest China on the EASM system variability*

EAM system variability is greatly influenced by the thermal states of the Eurasian continent, especially the thermal states in the arid and semiarid regions of Northeast China and Central Asia, because the sensible heating in these regions is larger than that in the EASM region in spring and summer (Fig. 19). Zhou and Huang (2006, 2010) and Zhou (2010) analyzed the interannual and interdecadal variations of the difference between the surface temperature and the surface air temperature, i.e, $T_{\mathrm{s}} - T_{\mathrm{a}}$, and sensible heating in spring in the arid and semiarid regions of Northwest China and Central Asia and their impact on summer monsoon rainfall in China. Their results show that the strongest sensible heating over the Eurasian continent is located at Northwest China and Central Asia in spring, thus, this region may be seen as a "warm lying surface" in the Eurasian continent. The $T_{\mathrm{s}} - T_{\mathrm{a}}$ and sensible heating over this region exhibit obvious interdecadal variability. Before the late 1970s, the sensible hearting anomalies in spring were negative, but

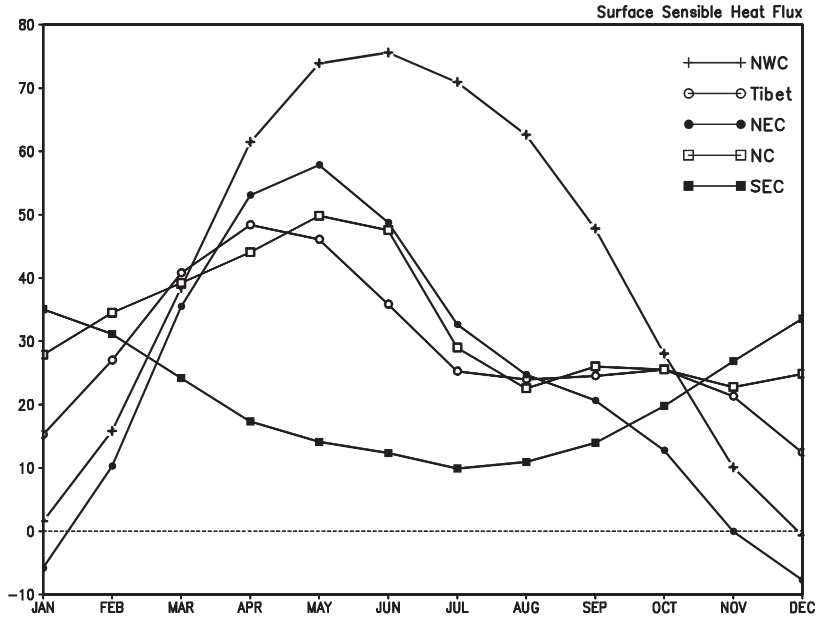

Fig. 19. Climatological mean monthly sensible heating flux in Northwest China (NWC), Tibetian Plateau (Tibet), Northeast China (NEC), North China (NC) and Southeast China (SEC) based on ERA-40 reanalysis data. Units: W m^{-2}.

the sensible heating anomalies became largely positive from the late 1970s onward. Zhou and Huang (2008, 2010) discussed a possible physical process of the thermal effect of the sensible heating anomalies in the arid and semiarid regions of Northwest China on EASM system variability. Their analyses showed that since the sensible heating became strong during the period 1978–2000, the cyclonic circulation anomaly intensified over Northwest China. This was closely associated with the anomalous ascending motion over Northwest China, which could contribute to anomalous descending motion over North China. Moreover, their results also showed that during the period 1978–2000, the air temperature at 300 hPa decreased obviously, but it increase near the surface over Northwest China in the summer. This caused the enhancement of vertical convective instability, which contributed to the strengthening of ascending motion and the increase of rainfall in Northwest China after 1978. Moreover, influenced by the anomalous ascending motion over Northwest China, an opposite phenomenon occurred over North China, anomalous descending motion occurred over North China and the vertical convective instability became weak over North China. This contributed to the decrease of summer rainfall in North China after the late 1970s. Therefore, the intensification of spring sensible heating over Northwest China and Central Asia may have been one of the causes of the interdecadal variability of the EASM system occurred in the late 1970s.

6. The internal dynamic processes in the EAM climate system

As shown in section 5, EAM system variability is closely associated not only with the variabilities of various component of the EAM climate system, including atmosphere–ocean–land interactions but also with the internal dynamical and thermo-dynamical processes in the EAM climate system. Because of the dynamical and thermo-dynamical processes in this system, there are close relationships among the variabilities of its various components. Therefore, it is necessary to discuss the internal dynamical and thermo-dynamical processes in the EAM climate system.

6.1 *The property of the East Asia/Pacific (EAP) teleconnection and its role in the EASM system variability*

The interannual and interdecadal variabilities of the EASM system are dominated by the meridional teleconnection. The meridional teleconnection is generally referred to as the Pacific-Japan (PJ) pattern (Nitta, 1987) or the EAP pattern (Huang and Li, 1987, 1988). Studies on the role of the EAP pattern teleconnection in the processes of the EASM system variability, its characteristics and properties have advanced our understanding in recent years.

During recent years, many studies on the role of the EAP pattern teleconnection in the meridional tripole pattern distribution of the EASM system variability have used reanalysis data and observational data (e.g., Huang et al., 2006b, 2007b, 2011c). As described in section 3, an obvious meridional tripole pattern occurs either in the anomaly distributions of summer monsoon rainfall in eastern China or in the anomaly distributions of the summertime water vapor transport fluxes over East Asia on interannual and interdecadal time scales (e.g., Huang et al., 2006b, 2011c). As a result, the distributions of droughts and floods in eastern China also exhibit a characteristic of the meridional tripole pattern. Huang et al. (2006b, 2007b) used the EAP pattern teleconnection proposed by Nitta (1987), and Huang and Li (1987, 1988) to interpret the physical mechanism of the meridional tripole pattern of the spatio-temporal variabilities of the EASM system. Huang et al. (2006b, 2007b, 2011c) explained that the distributions of summertime atmospheric circulation anomalies with the meridional tripole pattern over East Asia and the western North Pacific are caused by the heating anomaly due to thermal anomaly of the tropical western Pacific or convective activity anomaly around the Philippines through the EAP pattern teleconnection. Of course, this meridional tripole pattern of circulation anomalies over East Asia is also associated with thermal anomalies over the North Atlantic through the EU pattern teleconnection over middle and high latitudes, as proposed by Wallace and Gutzler (1981).

An important advance in recent research on the internal dynamical processes is the further understanding of EAP-pattern teleconnection. In the middle 1980s, the EAP-pattern teleconnection was considered a northward-propagating Rossby wave train excited by the anomalous heating due to convective activity around the Philippines (Nitta, 1987; Huang and Li, 1987, 1988). Therefore, the EAP pattern teleconnection can be seen as a thermal mode of summertime circulation variability over East Asia and the Northwest Pacific. However, Kosaka and Nakamura (2006) proposed that this meridional teleconnection could efficiently gain kinetic energy and available potential energy from the basic flow over East Asia and the western North Pacific. Thus, the meridional teleconnection can be also considered as a dynamical mode of summertime circulation variability over these regions. Lu et al. (2006) reported two leading modes in the atmospheric circulation anomalies over East Asia and the western North Pacific. The first mode is associated with the circulation variation over the tropical region, which is mainly attributed to external SST forcing. The second mode is a meridional teleconnection mode, which mainly results from internal atmospheric variability. Therefore, the EAP pattern teleconnection may be considered as a combination of the thermal mode and the dynamical mode of summertime circulation variability over East Asia and the western North Pacific.

Moreover, Kosaka and Nakamura (2006) also presented the three-dimensional structure of the EAP pattern teleconnection and described its meridional and vertical coupled characteristics. Lu and Lin (2009) proposed that this vertical and meridional coupled teleconnection can be depicted by zonal shift of the western Pacific subtropical high in the subtropical lower troposphere and the meridional displacement of the East Asian jet stream (EAJS) in the upper troposphere over Asia. Actually, the meridional displacement of the EAJS is the leading mode of interannual variation of upper-tropospheric zonal wind anomalies over East Asia and the western North Pacific.

On the other hand, Lu and Lin (2009) suggested that the precipitation anomaly in the EASM system plays a crucial role in maintaining this meridional teleconnection. The climatological mean of the subtropical precipitation over East Asia is $\sim$7.0 mm d^{-1} and the interannual standard deviation is 1.0 mm d^{-1}, which are comparable to their counterparts over the tropical western Pacific. Thus, as a strong heating source, the strong precipitation in the EASM system can significantly feedback to the meridional teleconnection. This explains further that the meridional teleconnection is more properly viewed as a thermal-dynamical mode.

6.2 *The "Silk Road pattern" teleconnection along the Asian jet in the upper troposphere and its role in EASM system variability*

Yang et al. (2002) analyzed the association of Asian–Pacific–American winter climate with the East Asian jet stream (EAJS) on an interannual time scale. They proposed that the EAJS is coupled to a teleconnection pattern extending from the Asian continent to North America with the strongest signals over East Asia and the West Pacific in boreal winter. Moreover, Lu et al. (2002), Lu and Kim (2004), and Lin and Lu (2005) analyzed the variability of meridional circulation anomalies in the upper troposphere over the Northern Hemisphere for the boreal summers of 1986–2000 using HadAM3 data. Their results showed that there is an obvious teleconnection pattern in the meridional circulation anomalies along the Asian jet in the upper troposphere over the region from West Asia to East Asia. At the same time, Enomoto et al. (2003) further analyzed the formation of the high ridge near Japan (i.e., the Bonin high) resulting from the propagation of stationary Rossby waves along the Asian jet in the upper troposphere. This teleconnection is called the "Silk Road pattern" in their study. Lu and Kim (2004) also explained that this teleconnection may be due to the eastward propagation of the Rossby wave-train along the westerly jet stream at 200 hPa.

Recently, from the analysis of isentropic potential vorticity, Tao and Wei (2006) demonstrated that the northward advance or southward retreat of the western Pacific subtropical high may be associated with the propagation of the Rossby wave train along the Asian jet in the upper troposphere because it may form a high ridge or a low trough along the eastern coast of China. From the analysis of the relationship between the summer monsoon rainfall anomalies in East Asia and the circulation anomalies in the upper troposphere over the Eurasian continent, Hsu and Lin (2007) also concluded that the meridional triple structure of summertime monsoon rainfall anomalies over East Asia is related to the propagation of the Rossby wave-train along the Asian jet at the upper troposphere in addition to the EAP pattern teleconnection over East Asia and the western North Pacific.

According to the study by Lu (2004), the EAP pattern teleconnection exhibits an intraseasonal difference between early summer and late summer in addition to its interannual variability. Generally, it is weak in June but strong in July and August. Lu (2004) attributed this intraseasonal difference to two reasons. First, June is a transition month from spring with a strong vertical westerly shear over the western North Pacific to late summer (July and August) with a strong vertical easterly shear; therefore, the vertical shear over the western North Pacific is near zero in June. The near-zero vertical shear is unfavorable for the coupling of external mode and internal mode excited by the precipitation anomaly in the western North Pacific, so it weakens the meridional teleconnection (e.g., Lu, 2004; Lin and Lu, 2008). Second, the EAJS abruptly jumps northward from 40°N in mid-July to 45°N in late July (e.g., Lin and Lu, 2008). When the jet axis is located more northward, the vertical shear is favorable for the coupling of external mode and internal mode. Both the lower- and the upper-level responses are significantly stronger, so the meridional teleconnection becomes stronger (e.g., Kosaka and Nakamura, 2010; Ye and Lu, 2011). This result suggests that the EAP pattern teleconnection can be modulated by the "Silk Road pattern" teleconnection.

From the studies mentioned here, it can be concluded that the meridional tripole structure of summertime circulation anomalies over East Asia are also associated not only with the EAP teleconnection but also with the "Silk Road pattern" teleconnection along the Asian jet in the upper troposphere. Furthermore, the "Silk Road pattern" teleconnection can modulate the EAP teleconnection.

6.3 *Impact of quasi-stationary planetary wave activity on the EAWM system variability*

As discussed in subsections 6.1 and 6.2, both the EAP teleconnection and the "Silk Road pattern" teleconnection are closely associated with the propagations of quasi-stationary planetary waves over the Northern Hemisphere in summer. Thus, quasi-stationary planetary wave activity has a significant impact on EASM system variability. Similarly, quasi-stationary planetary wave activity also has an important effect on EAWM system variability.

Early in the 1980s, Huang and Gambo (1982a,b) investigated the three-dimensional propagation of quasi-stationary planetary waves responding to forcing by topography and stationary heat sources in the troposphere in boreal winter with a 34-level model in addition E-P flux of waves. Two wave guides were discernible in the three-dimensional propagations of quasi-stationary planetary waves in the Northern Hemisphere winter. That is, in addition to the polar wave guide by which the quasi-stationary planetary waves propagate from the troposphere to the stratosphere over high latitudes (e.g., Dickinson, 1968), there is a second wave guide, namely, the low-latitude wave guide. The waves can propagate from the lower troposphere over middle and high latitudes to the upper troposphere over low latitudes along this low-latitude wave guide. Based on these studies, Chen et al. (2002, 2003, 2005) and Chen and Huang (2005) systematically studied the interannual variations of propagating wave guides for quasi-stationary waves with E-P fluxes using the NCEP/NCAR and ERA-40 reanalysis data and AGCM simulation data. Their results suggest an out-of-phase oscillation between these two wave guides for quasi-stationary planetary waves. When the polar wave guide is strong in a winter, the low-latitude wave guide is weak; when the polar wave guide is weak, the low-latitude wave guide is strong. Moreover, the anomalous propagation of quasi-stationary planetary waves characterized as the convergence/divergence of the wave E-P fluxes can induce a dipole mode in the anomaly distribution of zonal mean zonal wind anomalies. This shows that, due to the wave-flow interaction, the interannual oscillation of these two wave guides of quasi-stationary planetary waves has a significant influence on Arctic Oscillation (AO), which is closely related to EAWM system variability (e.g., Gong et al., 2001; Gong and Ho, 2003) through the Northern Annular Mode (NAM, Thompson and Wallace, 1998, 2000).

Recently, some studies have shown that the stratospheric circulation anomalies can influence the EAWM system variability. Along with the anomalous cold event that occurred over South China in January 2008, a downward propagation of stratospheric zonal wind anomalies was observed in the polar region of the Northern Hemisphere (Gu et al., 2008; Yi et al., 2009). In December 2009, the anomalous cold events over East Asia were also accompanied by significant downward propagations of stratospheric signals (Wang and Chen, 2010b). Therefore, the preceding upward propagation of anomalous planetary waves from the troposphere into the stratosphere and the succeeding downward propagation of anomalous zonal flow and low temperatures in the stratosphere and their impact on the troposphere may have key roles in the mechanisms of these cold events.

The activity of planetary waves also undergoes obvious interdecadal variation, which is well related to EAWM system variability (e.g., Huang and Wang, 2006; Wang et al., 2009b). Compared to the period 1976–1987, the southward propagation of quasi-stationary planetary waves after 1988 was enhanced along the low-latitude wave guide in the troposphere, and the upward propagation of waves into the stratosphere was reduced along the polar wave guide (Fig. 20). This can cause a weakened subtropical jet around 35°N due to the convergence of the wave E-P fluxes. The East Asian jet stream was then weakened, which led to the weakening of the EAWM system from 1988. In addition, the amplitude of quasi-stationary planetary waves was significantly decreased around 45°N, which was related to the reduced upward propagation of waves from the lower troposphere after 1988. The decreased amplitude of planetary waves weakened both the Siberian High and the Aleutian Low and led to a decrease in the pressure gradient between them; then, the EAWM system was weakened. Further analyses indicate that the planetary wave zonal wavenumber 2 played the dominant role in this process of the interdecadal variability (Wang et al., 2009b).

7. Conclusions and remarks for future studies

In recent years, many significant advances have taken place in understanding the characteristics and causes of the spatio-temporal variabilities of the EAM system associated with climate disasters in China. The basic physical processes, both internal and external, that influence these variabilities have also been studied further.

However, it should be pointed out that many problems regarding the basic physical processes of the EAM climate system variability and their impacts on climate disasters in China remain unclear. These problems include the association among the onset, activity, and decline of the EASM and the EAWM systems over East Asia as well as cycle processes between them, the association of the EAM system with the SAM and the NAM systems, the interactions and their physical processes among different time-scale variabilities of various components of the EAM system, the effect of extratropical process on the EAM variabilities, the physical mechanism of the second leading mode (i.e., the meridional dipole pattern distribution) of the EASM system variability, the evolution trend of the EAM system under the background of the global warming, and so on. These important issues must be investigated further. Specifically, the EAM climate system vari-

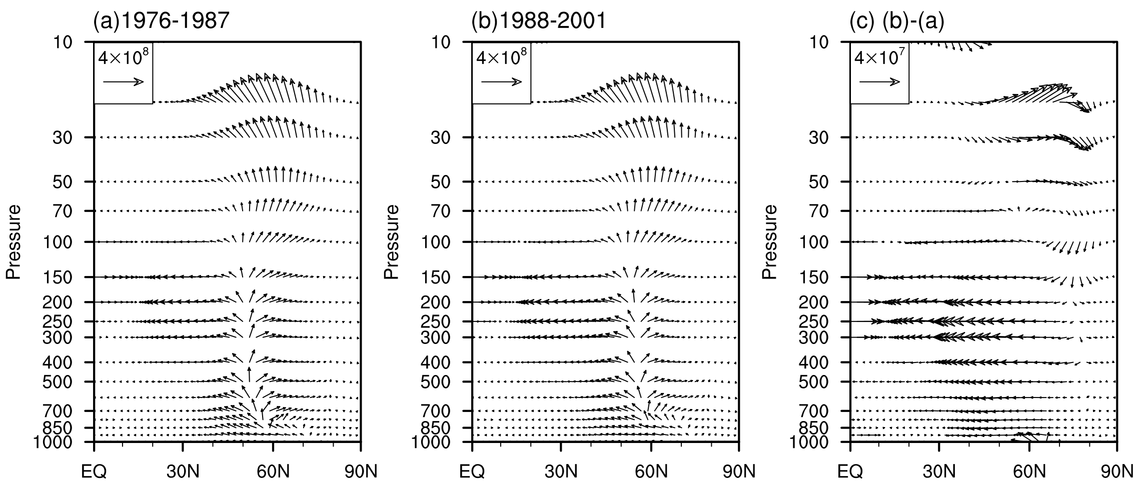

Fig. 20. Composite distribution of the E-P fluxes ($\times\rho^{-1}$) for the quasi-stationary planetary waves 1–3 averaged for the boreal winters of (a) 1976–1987, and (b) 1988–2001, and (c) their difference based on ERA-40 reanalysis data.

abilities on interannual and interdecadal time scales and their physical mechanisms should be emphasized in future studies. If the physical processes of these variabilities can be revealed further, the seasonal and annual prediction of climate disasters in China, such as droughts, floods, cold winter and hot summer, can be improved. Therefore, future studies must aim to understand the dynamical and thermodynamical processes affecting the spatio-temporal variabilities of the EAM climate system. Through the implementation of National Research Programs, it will be possible to more completely understand the physical mechanisms of the spatio-temporal variabilities of the EAM system.

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REFERENCES

Annamalai, H., P. Liu, and S. P. Xie, 2005: Southwest Indian Ocean SST variability: Its local effect and remote influence on Asian monsoons. *J. Climate*, **18**, 4150–4167.

Ashok, K., S. K. Behera, S. A. Rao, H. Y. Weng, and T. Yamagata, 2007: El Niño Modoki and its possible teleconnection. *J. Geophys. Res.*, **112**, doi: 10.1029/2006JC003798.

Barriopedro, D., C. M. Gouveia, R. M. Trigo, and L. Wang, 2012: The 2009–2010 drought in China: Possible causes and impacts on vegetation. *J. Hydrometeorology*, doi: 10.1175/JHM-D-11-074.1. (in press)

Bond, N. A., and D. E. Harrison, 2000: The Pacific decadal oscillation, air-sea interaction and central north Pacific winter atmospheric regimes. *Geophys. Res. Lett.*, **27**, 731–734.

Cai, R. S., J. L. Chen, and R. H. Huang, 2006: The response of marine environment in the offshore area of China and its adjacent ocean to recent global climate change. *Chinese J. Atmos. Sci.*, **30**, 1019–1033. (in Chinese)

Cai, R. S., J. L. Chen, and H. J. Tan, 2011: Variations of the sea surface temperature in the offshore area of China and its relationship with the East Asian monsoon under the global warming. *Climatic and Environmental Research*, **16**, 94–104. (in Chinese)

Chang, C. P., J. E. Erickson, and K. M. Lau, 1979: Northeasterly Cold Surges and near-Equatorial Disturbances over the Winter Monex Area during December 1974 .1. Synoptic Aspects. *Mon. Wea. Rev.*, **107**, 812–829.

Chang, C. P., Y. S. Zhang, and T. Li, 2000a: Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part I: Roles of the subtropical ridge. *J. Climate*, **13**, 4310–4325.

Chang, C. P., Y. S. Zhang, and T. Li, 2000b: Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part II: Meridional structure of the monsoon. *J. Climate*, **13**, 4326–4340.

Chen, J. L., and R. H. Huang, 2006: The comparison of climotological characteristics among Asian and Australian monsoon subsystem. Part I. The wind structure of summer monsoon. *Chinese J. Atmos. Sci.*, **30**, 1091–1102. (in Chinese)

Chen, J. L., and R. H. Huang, 2007: The comparison of climotological characteristics among Asian and Australian monsoon subsystem. Part II. Water vapor transport by summer monsoon. *Chinese J. Atmos. Sci.*, **31**, 766–778. (in Chinese)

Chen, L. X., Q. G. Zhu, H. B. Luo, and J. H. He, 1991: *East Asian Monsoon*. China Meteorological Press, Beijing, 362pp. (in Chinese)

Chen, L. X., X. J. Zhou, W. L. Li, Y. F. Luo, and W. Q. Zhu, 2004: Characteristics of the climate change and its formation mechanism in China during the last 80 years. *Acta Meteorolologica Sinica*, **62**, 634–646. (in Chinese)

Chen, W., 2002: Impacts of El Niño and La Niña on the cycle of the East Asian winter and summer monsoon. *Chinese J. Atmos. Sci.*, **26**, 595–610. (in Chinese)

Chen, W., and H.-F. Graf, 1998: The interannual variability of East Asian winter monsoon and its relation to global circulation. Report No. 250.

Chen, W., and R. H. Huang, 2005: The three-dimensional propagation of quasi-stationary planetary waves in the Northern Hemisphere winter and its interannual variations. *Chinese J. Atmos. Sci.*, **29**, 137–146. (in Chinese)

Chen, W., H. F. Graf, and R. H. Huang, 2000: The interannual variability of East Asian winter monsoon and its relation to the summer monsoon. *Adv. Atmos. Sci.*, **17**, 48–60.

Chen, W., H. F. Graf, and M. Takahashi, 2002: Observed interannual oscillations of planetary wave forcing in the Northern Hemisphere winter. *Geophys. Res. Lett.*, **29**, doi: 10.1029/2002gl016062.

Chen, W., M. Takahashi, and H. F. Graf, 2003: Interannual variations of stationary planetary wave activity in the northern winter troposphere and stratosphere and their relations to NAM and SST. *J. Geophys. Res.*, **108**, doi: 10.1029/2003jd003834.

Chen, W., S. Yang, and R. H. Huang, 2005: Relationship between stationary planetary wave activity and the East Asian winter monsoon. *J. Geophys. Res.*, **110**, doi: 10.1029/2004JD005669.

Chen, W., L. Wang, Y. Xue, and S. Sun, 2009: Variabilities of the spring river runoff system in East China and their relations to precipitation and sea surface temperature. *Int. J. Climatol.*, **29**, 1381–1394.

Cheng, A., W. Chen, and R. Huang, 1998: The Sensitivity of Numerical Simulation of the East Asian Monsoon to Different Cumulus Parameterization Schemes. *Adv. Atmos. Sci.*, **15**, 204–220.

Cornejo-Garrido, A. G., and P. H. Stone, 1977: On the Heat Balance of the Walker Circulation. *J. Atmos. Sci.*, **34**, 1155–1162.

Deng, W. T., Z. B. Sun, G. Zeng, and D. H. Ni, 2009: Interdecadal variation of summer precipitation pattern over eastern China and its relationship with the North Pacific SST. *Chinese J. Atmos. Sci.*, **33**, 835–846. (in Chinese)

Dickinson, R. E., 1968: Planetary Rossby Waves Propagating Vertically through Weak Westerly Wind Wave Guides. *J. Atmos. Sci.*, **25**, 984–1002.

Ding, Q. H., and B. Wang, 2005: Circumglobal teleconnection in the Northern Hemisphere summer. *J. Climate*, **18**, 3483–3505.

Ding, Y. H., 1994: Monsoons over China. Dordrecht/Voston/London: Springer/Kluwer Academic Publishers, 432pp.

Ding, Y. H., 2007: The variability of the Asian summer monsoon. *J. Meteor. Soc. Japan*, **85**, 21–54.

Ding, Y. H., and C. He, 2006: The summer monsoon onset over the tropical eastern Indian Ocean: The earliest onset process of the Asian summer monsoon. *Adv. Atmos. Sci.*, **23**, 940–950.

Ding, Y. H., and X. Q. Ma, 2007: Analysis of isentropic potential vorticity for a strong cold wave in 2004/2005 winter. *Acta Meteorologica Sinica*, **65**, 695–707. (in Chinese)

Ding, Y. H., Z. Y. Wang, and Y. Sun, 2008: Inter-decadal 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.

Du, Z. C., R. H. Huang, G. Huang, and J. L. Chen, 2011: The characteristics of spatial and temporal distributions of convective rainfall and stratiform rainfall in the Asian monsoon region and their possible mechanisms. *Chinese J. Atmos. Sci.*, **35**, 993–1008. (in Chinese)

Enomoto, T., B. J. Hoskins, and Y. Matsuda, 2003: The formation mechanism of the Bonin high in August. *Quart. J. Roy. Meteor. Soc.*, **129**, 157–178.

Feng, J., L. Wang, W. Chen, S. Fong, and K. Leong, 2010: Different impacts of two types of Pacific Ocean warming on the Southeast Asian rainfall during boreal winter. *J. Geophys. Res.*, **115**, D24122, doi: 10.1029/2010JD014761.

Fu, Y. F., Y. H. Lin, G. S. Liu, and Q. Wang, 2003: Seasonal characteristics of precipitation in 1998 over East Asia as derived from TRMM PR. *Adv. Atmos. Sci.*, **20**, 511–529.

Gong, D. Y., S. W. Wang, and J. H. Zhu, 2001: East Asian winter monsoon and Arctic Oscillation. *Geophys. Res. Lett.*, **28**, 2073–2076.

Gong, D. Y., and C. H. Ho, 2003: Arctic oscillation signals in the East Asian summer monsoon. *J. Geophys. Res.*, **108**, doi: 10.1029/2002JD002193.

Gu, L., K. Wei, and R. H. Huang, 2008: Severe disaster of blizzard, freezing rain and low temperature in January 2008 in China and its association with the anomalies of East Asian monsoon system. *Climatic and Environmental Research*, **13**, 405–418. (in Chinese)

Hartmann, D. L., H. H. Hendon, and R. A. Houze, 1984: Some implications of the mesoscale circulations in tropical cloud clusters for large-scale dynamics and climate. *J. Atmos. Sci.*, **41**, 113–121.

He, H. Y., C. H. Sui, M. Q. Jian, Z. P. Wen, and G. D. Lan, 2003: The evolution of tropospheric temperature field and its relationship with the onset of Asian summer monsoon. *J. Meteor. Soc. Japan*, **81**, 1201–1223.

Hong, C. C., and T. Li, 2009: The extreme cold anomaly over Southeast Asia in February 2008: Roles of ISO and ENSO. *J. Climate*, **22**, 3786–3801.

Hsu, H. H., and S. M. Lin, 2007: Asymmetry of the tripole rainfall pattern during the east Asian summer. *J. Climate*, **20**, 4443–4458.

Huang, G., and K. M. Hu, 2008: Impact of North Indian Ocean SSTA on Northwest Pacific lower layer anomalous anticyclone in summer. *Journal of Nanjing Institute of Meteorology*, **31**, 749–757. (in Chinese)

Huang, G., K. M. Hu, and S. P. Xie, 2010: Strengthening of tropical Indian Ocean teleconnection to the Northwest Pacific since the mid-1970s: An atmospheric GCM study. *J. Climate*, **23**, 5294–5304.

Huang, G., X. Qu, and K. M. Hu, 2011a: The impact of the tropical Indian Ocean on South Asian high in boreal summer. *Adv. Atmos. Sci.*, **28**, 421–432.

Huang, G., Y. Liu, and R. H. Huang, 2011b: The interannual variability of summer rainfall in the arid and semiarid regions of northern China and its association with the Northern Hemisphere circumglobal teleconnection. *Adv. Atmos. Sci.*, **28**, 257–268.

Huang, P., and R. Huang, 2009: Relationship between the modes of winter tropical Pacific SSTAs and the intraseasonal variations of the following summer rainfall anomalies in China. *Atmospheric and Oceanic Science Letters*, **2**, 295–300.

Huang, R. H., 1984: The characteristics of the forced stationary planetary wave propagations in summer Northern Hemisphere. *Adv. Atmos. Sci.*, **1**, 84–94.

Huang, R. H., 1985: The numerical simulation of the three-dimensional teleconnections in the summer circulation over the Northern Hemisphere. *Adv. Atmos. Sci.*, **2**, 81–92.

Huang, R. H., 2006: Progresses in research on the formation mechanism and prediction theory of severe climatic disasters in China. *Advances in Earth Science*, **21**, 564–575. (in Chinese)

Huang, R. H., 2009: Recent progresses in studies of variations and anomalies of East Asian monsoon (EAM) climate system and formation mechanism of severe climate disasters in China. *Bulletin of the Chinese Academy of Sciences*, **23**, 222–225. (in Chinese)

Huang, R. H., and K. Gambo, 1982a: The response of a hemispheric multilevel model atmosphere to forcing by topography and stationary heat-sources. 1. Forcing by topography. *J. Meteor. Soc. Japan*, **60**, 78–92.

Huang, R. H., and K. Gambo, 1982b: The response of a hemispheric multilevel model atmosphere to forcing by topography and stationary heat-sources. 2. Forcing by stationary heat-sources and forcing by topography and stationary heat-sources. *J. Meteor. Soc. Japan*, **60**, 93–108.

Huang, R. H., and W. J. Li, 1987: Influence of the heat source anomaly over the tropical western Pacific on the subtropical high over East Asia. *Proc. Int. Conf. on the General Circulation of East Asia,* Chengdu, 40–51.

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

Huang, R. H., and Y. F. Wu, 1989: The influence of ENSO on the summer climate change in China and its mechanism. *Adv. Atmos. Sci.*, **6**, 21–32.

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

Huang, R. H., and L. T. Zhou, 2002: Research on the characteristics, formation mechanism and prediction of severe climatic disasters in China. *Journal of Natural Disasters*, **1**, 1–9. (in Chinese)

Huang, R. H., and L. Wang, 2006: Interdecadal variation of Asian winter monsoon and its association with the planetary wave activity. *Proc. Symposium on Asian Monsoon,* Kuala Lumpur, Malaysia, 126.

Huang, R. H., and J. L. Chen, 2010: Characteristics of the summertime water vapor transports over the eastern part of China and those over the western part of China and their difference. *Chinese J. Atmos. Sci.*, **34**, 1035–1045. (in Chinese)

Huang, R. H., Z. Z. Zhang, G. Huang, and B. H. Ren, 1998a: Characteristics of the water vapor transport in East Asian monsoon region and its difference from that in South Asian monsoon region in summer *Chinese J. Atmos. Sci.*, **22**, 460–469. (in Chinese)

Huang, R. H., Y. H. Xu, P. F. Wang, and L. T. Zhou, 1998b: 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., Y. H. Xu, and L. T. Zhou, 1999: The interdecadal variation of summer precipitations in China and the drought trend in North China. *Plateau Meteorology*, **18**, 465–476. (in Chinese)

Huang, R. H., L. T. Zhou, and W. Chen, 2003: The progresses of recent studies on the variabilities of the East Asian monsoon and their causes. *Adv. Atmos. Sci.*, **20**, 55–69.

Huang, R. H., G. Huang, and Z. G. Wei, 2004a: Climate variations of the summer monsoon over China. *East Asian Monsoon,* Chang, Ed., World Scientific Publishing Co. Pte. Ltd., Singapore, 213–270.

Huang, R. H., W. Chen, B. L. Yang, and R. H. Zhang, 2004b: Recent advances in studies of the interaction between the East Asian winter and summer monsoons and ENSO cycle. *Adv. Atmos. Sci.*, **21**, 407–424.

Huang, R. H., L. Gu, Y. H. Xu, Q. L. Zhang, S. S. Wu, and J. Cao, 2005: Characteristics of the interannual variations of onset and advance of the East Asian summer monsoon and their associations with thermal states of the tropical western Pacific. *Chinese J. Atmos. Sci.*, **29**, 20–36. (in Chinese)

Huang, R. H., R. S. Cai, J. L. Chen, and L. T. Zhou, 2006a: Interdecaldal 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, R. H., J. L. Chen, G. Huang, and Q. L. Zhang, 2006b: 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., L. Gu, L. T. Zhou, and S. S. Wu, 2006c: Impact of the thermal state of the tropical western Pacific on onset date and process of the South China Sea summer monsoon. *Adv. Atmos. Sci.*, **23**, 909–924, doi: 10.1007/s00376-006-0909-1.

Huang, R. H., J. L. Chen, and G. Huang, 2007a: Characteristics and variations of the East Asian monsoon system and its impacts on climate disasters in China. *Adv. Atmos. Sci.*, **24**, 993–1023, doi: 10.1007/s00376-007-0993-x.

Huang, R. H., K. Wei, J. L. Chen, and W. Chen, 2007b: The East Asian winter monsoon anomalies in the winters of 2005 and 2006 and their relations to the quasi-stationary planetary wave activity in the northern hemisphere. *Chinese J. Atmos. Sci.*, **31**, 1033–1048. (in Chinese)

Huang, R. H., L. Gu, J. L. Chen, and G. Huang, 2008: Recent progresses in studies of the temporal-spatial variations of the East Asian monsoon system and their impacts on climate anomalies in China. *Chinese J. Atmos. Sci.*, **32**, 691–719. (in Chinese)

Huang, R. H., J. L. Chen, and Y. Liu, 2011c: Interdecadal variation of the leading modes of summertime precipitation anomalies over Eastern China and its association with water vapor transport over East Asia. *Chinese J. Atmos. Sci.*, **35**, 589–606. (in Chinese)

Huang, R. H., Y. Liu, and T. Feng, 2012a: Characteristics and causes of the interecadal jump of summertime monsoon rainfall and circulation in eastern China occurred in the late 1990s. *Chinese Sci. Bull.*. (in press)

Huang, R. H., Y. Liu, L. Wang, and L. Wang, 2012b: Analyses of the causes of severe drought occurred in Southwest China from the fall of 2009 to the spring to 2010. *Chinese J. Atmos. Sci.*, **36**, 443–457. (in

Chinese)

Iguchi, T., T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto, 2000: Rain-profiling algorithm for the TRMM precipitation radar. *J. Appl. Meteor.*, **39**, 2038–2052.

Jhun, J. G., and E. J. Lee, 2004: A new East Asian winter monsoon index and associated characteristics of the winter monsoon. *J. Climate*, **17**, 711–726.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Kang, L. H., W. Chen, and K. Wei, 2006: The Interdecadal Variation of Winter Temperature in China and Its Relation to the Anomalies in Atmospheric General Circulation. *Climatic and Environmental Research*, **11**, 330–339. (in Chinese)

Kang, L. H., W. Chen, L. Wang, and L. J. Chen, 2009: Interannual variations of winter temperature in China and their relationship with the atmospheric circulation and sea surface temperature. *Climatic and Environmental Research*, **14**, 45–53. (in Chinese)

Kosaka, Y., and H. Nakamura, 2006: Structure and dynamics of the summertime Pacific-Japan teleconnection pattern. *Quart. J. Roy. Meteor. Soc.*, **132**, 2009–2030.

Kosaka, Y., and H. Nakamura, 2010: Mechanisms of Meridional Teleconnection Observed between a Summer Monsoon System and a Subtropical Anticyclone. Part I: The Pacific-Japan Pattern. *J. Climate*, **23**, 5085–5108.

Kurihara, K., 1989: A climatological study on the relationship between the Japanese summer weather and the subtropical high in the western northern Pacific. *Geophys. Mag.*, **43**, 45–104.

Kwon, M., J. G. Jhun, and K. J. Ha, 2007: Decadal change in east Asian summer monsoon circulation in the mid-1990s. *Geophys. Res. Lett.*, **34**, L21706, doi: 21710.21029/22007GL031977.

Lau, K. M., and C. P. Chang, 1987: Planetary scale aspects of the winter monsoon and atmospheric teleconnections. *Monsoon Meteorology,* Chang and Krishnamurti, Eds., Oxford University Press, Oxford, 161–201.

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

Li, X. Z., Z. P. Wen, and W. Zhou, 2011: Long-term Change in Summer Water Vapor Transport over South China in Recent Decades. *J. Meteor. Soc. Japan*, **89A**, 271–282.

Li, Y. Q., and S. Yang, 2010: A dynamical index for the East Asian winter monsoon. *J. Climate*, **23**, 4255–4262.

Liang, J. Y., and S. S. Wu, 2002: A study of southwest monsoon onset date over the South China Sea and its impact factors. *Chinese J. Atmos. Sci.*, **26**, 829–844. (in Chinese)

Lin, Z. D., and R. Y. Lu, 2005: Interannual meridional displacement of the east Asian upper-tropospheric jet stream in summer. *Adv. Atmos. Sci.*, **22**, 199–211.

Lin, Z. D., and R. Y. Lu, 2008: Abrupt northward jump of the East Asian upper-tropospheric jet stream in mid-summer. *J. Meteor. Soc. Japan*, **86**, 857–866.

Liu, P., and Y. F. Fu, 2010: Climatic characteristics of summer convective and stratiform precipitation in Southern China based on measurements by TRMM precipitation radar. *Chinese J. Atmos. Sci.*, **34**, 802–814. (in Chinese)

Lu, M. M., and C. P. Chang, 2009: Unusual late-season cold surges during the 2005 Asian winter monsoon: Roles of Atlantic blocking and the Central Asian anticyclone. *J. Climate*, **22**, 5205–5217.

Lu, R. Y., 2004: Associations among the components of the east Asian summer monsoon system in the meridional direction. *J. Meteor. Soc. Japan*, **82**, 155–165.

Lu, R. Y., and B. J. Kim, 2004: The climatological Rossby wave source over the STCZs in the summer northern hemisphere. *J. Meteor. Soc. Japan*, **82**, 657–669.

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., J. H. Oh, and B. J. Kim, 2002: A teleconnection pattern in upper-level meridional wind over the North African and Eurasian continent in summer. *Tellus (A)*, **54**, 44–55.

Lu, R. Y., Y. Li, and B. W. Dong, 2006: External and internal summer atmospheric variability in the western North Pacific and East Asia. *J. Meteor. Soc. Japan*, **84**, 447–462.

Ma, X. Q., Y. H. Ding, H. Xu, and J. H. He, 2008: The relation between strong cold waves and low-frequency waves during the winter of 2004/2005. *Chinese J. Atmos. Sci.*, **32**, 380–394. (in Chinese)

Nitta, T., 1987: Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation. *J. Meteor. Soc. Japan*, **65**, 373–390.

Sun, X. G., and X. Q. Yang, 2005: Numerical modeling of interannual anomalous atmospheric circulation patterns over East Asia during different stages of an El Niño event. *Chinese Journal of Geophysics*, **48**, 501–510. (in Chinese)

Tao, S. Y., and F. K. Zhu, 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**, 385–396. (in Chinese)

Tao, S. Y., and L. X. Chen, 1985: The East Asian summer monsoon. *Proc.Int. Conf. on Monsoon in the Far East,* Tokyo, 1–11.

Tao, S. Y., and L. X. Chen, 1987: A review of recent research on the East Asia summer monsoon in China. *Monsoon Meteorology,* Chang and Krishnamurti, Eds., Oxford University Press, Oxford, 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.

Thompson, D. W. J., and J. M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.*, **25**, 1297–1300.

Thompson, D. W. J., and J. M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate*, **13**, 1000–1016.

Trenberth, K. E., and J. W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific. *Climate Dyn.*, **9**, 303–319.

Tu, C. W., and S. S. Huang, 1944: The advance and retreat of the summer monsoon. *Acta Meteorologica Sinica*, **18**, 82–92. (in Chinese)

Uppala, S. M., and Coauthors, 2005: The ERA-40 re-analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter. *Mon. Wea. Rev.*, **109**, 784–812.

Wang, B., R. G. Wu, and K. M. Lau, 2001: Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the western North Pacific-East Asian monsoons, *J. Climate*, **14**, 4073–4090.

Wang, B., R. G. Wu, and T. Li, 2003: Atmosphere-warm ocean interaction and its impacts on Asian-Australian monsoon variation. *J. Climate*, **16**, 1195–1211.

Wang, B., LinHo, Y. S. Zhang, and M. M. Lu, 2004: Definition of South China Sea monsoon onset and commencement of the East Asia summer monsoon. *J. Climate*, **17**, 699–710.

Wang, B., Z. W. Wu, C. P. Chang, J. Liu, J. P. Li, and T. J. Zhou, 2010: Another Look at Interannual-to-Interdecadal Variations of the East Asian Winter Monsoon: The Northern and Southern Temperature Modes. *J. Climate*, **23**, 1495–1512.

Wang, L., W. Chen, and R. H. Huang, 2007: Changes in the variability of North Pacific Oscillation around 1975/1976 and its relationship with East Asian winter climate. *J. Geophys. Res.*, **112**, doi: 10.1029/2006JD008054.

Wang, L., W. Chen, and R. H. Huang, 2008: Interdecadal modulation of PDO on the impact of ENSO on the east Asian winter monsoon. *Geophys. Res. Lett.*, **35**, doi: 10.1029/2008GL035287.

Wang, L., W. Chen, W. Zhou, and R. H. Huang, 2009a: Interannual variations of East Asian trough axis at 500 hPa and its association with the East Asian winter monsoon pathway. *J. Climate*, **22**, 600–614.

Wang, L., R. H. Huang, L. Gu, W. Chen, and L. H. Kang, 2009b: Interdecadal variations of the East Asian winter monsoon and their association with quasi-stationary planetary wave activity. *J. Climate*, **22**, 4860–4872.

Wang, L., and W. Chen, 2010a: How well do existing indices measure the strength of the East Asian winter monsoon? *Adv. Atmos. Sci.*, **27**, 855–870.

Wang, L., and W. Chen, 2010b: Downward Arctic Oscillation signal associated with moderate weak stratospheric polar vortex and the cold December 2009. *Geophys. Res. Lett.*, **37**, doi: 10.1029/2010gl042659.

Wang, L., and J. Feng, 2011: Two major modes of the wintertime precipitation over China. *Chinese J. Atmos. Sci.*, **35**, 1105–1116. (in Chinese)

Wang, L., and R. Wu, 2012: The in-phase transition from the East Asian winter to summer monsoon: Role of the Indian Ocean. *J. Geophys. Res.*, **117**, D11112, doi: 10.1029/2012JD017509.

Wang, Z. Y., and Y. H. Ding, 2006: Climate change of the cold wave frequency of China in the last 53 years and the possible reasons. *Chinese J. Atmos. Sci.*, **30**, 1068–1076. (in Chinese)

Webster, P. J., V. O. Magaña, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.*, **103**, 14451–14510.

Wei, K., W. Chen, and W. Zhou, 2011: Changes in the East Asian Cold Season since 2000. *Adv. Atmos. Sci.*, **28**, 69–79, doi: 10.1007/s00376-010-9232-y.

Wei, Z. G., R. H. Huang, W. Chen, and W. J. Dong, 2002: Spatial distributions and interdecadal variations of the snow at the Tibetan Plateau weather stations. *Chinese J. Atmos. Sci.*, **26**, 496–508. (in Chinese)

Wei, Z. G., R. H. Huang, and W. J. Dong, 2003: Interannual and interdecadal variations of air temperature and precipitation over the Tibetan Plateau. *Chinese J. Atmos. Sci.*, **27**, 157–170. (in Chinese)

Wen, M., S. Yang, A. Kumar, and P. Q. Zhang, 2009: An analysis of the large-scale climate anomalies associated with the snowstorms affecting China in January 2008. *Mon. Wea. Rev.*, **137**, 1111–1131.

Wen, Z. P., R. H. Huang, H. Y. He, and G. D. Lan, 2006: The influences of anomalous atmospheric circulation over mid-high latitudes and the activities of 30-60d low frequency convection over low latitudes on the onset of the South China Sea summer monsoon. *Chinese J. Atmos. Sci.*, **30**, 952–964. (in Chinese)

Weng, H. Y., K. Ashok, S. K. Behera, S. A. Rao, and T. Yamagata, 2007: Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific rim during boreal summer. *Climate Dyn.*, **29**, 113–129.

Wu, B. Y., and J. Wang, 2002: Winter Arctic Oscillation, Siberian High and East Asian winter monsoon. *Geophys. Res. Lett.*, **29**, doi: 10.1029/2002GL015373.

Wu, B. Y., R. H. Zhang, and R. D′Arrigo, 2006: Distinct modes of the East Asian winter monsoon. *Mon. Wea. Rev.*, **134**, 2165–2179.

Wu, B. Y., K. Yang, and R. H. Zhang, 2009: Eurasian snow cover variability and its association with summer rainfall in China. *Adv. Atmos. Sci.*, **26**, 31–44, doi: 10.1007/s00376-009-0031-2.

Wu, G. X., and Y. S. Zhang, 1998: Tibetan Plateau forcing and the timing of the monsoon onset over South Asia and the South China Sea. *Mon. Wea. Rev.*, **126**, 913–927.

Wu, R. G., Z. P. Wen, S. Yang, and Y. Q. Li, 2010: An interdecadal change in Southern China summer rainfall around 1992/93. *J. Climate*, **23**, 2389–2403.

Xie, S. P., K. M. Hu, J. Hafner, H. Tokinaga, Y. Du, G. Huang, and T. Sampe, 2009: Indian Ocean capacitor effect on Indo-Western Pacific climate during the summer following El Niño. *J. Climate*, **22**, 730–747.

Xu, G. Y., X. Q. Yang, and X. G. Sun, 2005: Interdecadal and interannual variation characteristics of rainfall in North China and its relation with the northern hemisphere atmospheric circulations. *Chinese Journal of Geophysics*, **48**, 511–518. (in Chinese)

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**, doi: 10.1029/2006GL028571.

Yang, S., K. M. Lau, and K. M. Kim, 2002: Variations of the East Asian jet stream and Asian-Pacific-American winter climate anomalies. *J. Climate*, **15**, 306–325.

Yang, X. Q., and Y. M. Zhu, 2008: Interdecadal climate variability in China associated with the Pacific Decadal Oscillation. Chapter 3, *Regional Climate Studies in China*, Fu et al., Eds., Springer, 97–118.

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 Journal of Geophysics*, **48**, 789–797. (in Chinese)

Yasunari, T., and R. Suppiah, 1988: Some problems on the interannual variability of Indonesian monsoon rainfall. *Tropical Rainfall Measurements,* Theon and Fugono, Eds., Deepak, Hampton, Va, 113–112.

Ye, D. Z., and Y. X. Gao, 1979: *Tibetan Plateau Meteorology.* Science Press, Beijing, 279pp. (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.

Yi, M. J., Y. J. Chen, R. J. Zhou, and S. M. Deng, 2009: Analysis on isentropic potential vorticity for the snow calamity in South China and the stratospheric polar vortex in 2008. *Plateau Meteorology*, **28**, 880–888. (in Chinese)

Zhang, P. Q., S. Yang, and V. E. Kousky, 2005: South Asian high and Asian-Pacific-American climate teleconnection. *Adv. Atmos. Sci.*, **22**, 915–923.

Zhang, Q., G. X. Wu, and Y. F. Qian, 2002: The bimodality of the 100 hPa South Asia High and its relationship to the climate anomaly over East Asia in summer. *J. Meteor. Soc. Japan*, **80**, 733–744.

Zhang, Q. Y., J. M. Lü, and L. M. Yang, 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, R. H., and R. H. Huang, 1998: Dynamical roles of zonal wind stresses over the tropical Pacific on the occurring and vanishing of El Niño. Part I: Diagnostic and theoretical analyses. *Chinese J. Atmos. Sci.*, **22**, 587–599. (in Chinese)

Zhang, R. H., A. Sumi, and M. Kimoto, 1996: Impact of El Niño on the East Asian monsoon: A diagnostic study of the '86/87 and '91/92 events. *J. Meteor. Soc. Japan*, **74**, 49–62.

Zhang, R. H., B. Y. Wu, P. Zhao, and J. P. Han, 2008: The decadal shift of the summer climate in the late 1980s over Eastern China and its possible causes. *Acta Meteorologica Sinica*, **22**, 435–445.

Zhang, Z. H., and G. Huang, 2008: Different types of El Niño events and their relationships with China summer climate anomaly. *Journal of Nanjing Institute of Meteorology*, **31**, 782–789. (in Chinese)

Zhao, P., X. D. Zhang, Y. F. Li, and J. M. Chen, 2009: Remotely modulated tropical-North Pacific ocean-atmosphere interactions by the South Asian high. *Atmospheric Research*, **94**, 45–60.

Zhou, L. T., 2010: Characteristics of temporal and spatial variations of sensible heat flux in the arid and semi-arid region of Eurasia. *Transactions of Atmospheric Sciences*, **33**, 299–306. (in Chinese)

Zhou, L. T., 2011: Impact of East Asian winter monsoon on rainfall over southeastern China and its dynamical process. *Int. J. Climatol.*, **31**, 677-686.

Zhou, L. T., and R. H. Huang, 2006: Characterisitcs of the interdecadal variability of difference between surface temperature and surface air temperature in spring in the arid and semi-arid region of Northwest China and its impact on summer precipitation in North China. *Climatic and Environmental Research*, **11**, 1–13. (in Chinese)

Zhou, L. T., and R. H. Huang, 2008: Interdecadal variability of sensible heat in arid and semi-arid regions of Northwest China and its relation to summer precipitation in China. *Chinese J. Atmos. Sci.*, **32**, 1276–1288. (in Chinese)

Zhou, L. T., and R. H. Huang, 2010: Interdecadal variability of summer rainfall in Northwest China and its possible causes. *Int. J. Climatol.*, **30**, 549–557.

Zhou, X. X., Y. H. Ding, and P. X. Wang, 2010: Moisture Transport in the Asian Summer Monsoon Region and Its Relationship with Summer Precipitation in China. *Acta Meteorologica Sinica*, **24**, 31–42.

Zhu, K. Z., 1934: The enigma of southeast monsoon in China. *Acta Geographica Sinica*, **1**, 1–28. (in Chinese)

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