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Characteristics and Variations of the East Asian Monsoon System and Its Impacts on Climate Disasters in China

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ABSTRACT

Recent advances in studies of the structural characteristics and temporal-spatial variations of the East Asian monsoon (EAM) system and the impact of this system on severe climate disasters in China are reviewed. Previous studies have improved our understanding of the basic characteristics of horizontal and vertical structures and the annual cycle of the EAM system and the water vapor transports in the EAM region. Many studies have shown that the EAM system is a relatively independent subsystem of the Asian-Australian monsoon system, and that there exists an obvious quasi-biennial oscillation with a meridional tripole pattern distribution in the interannual variations of the EAM system. Further analyses of the basic physical processes, both internal and external, that influence the variability of the EAM system indicate that the EAM system may be viewed as an atmosphere-ocean-land coupled system, referred to the EAM climate system in this paper. Further, the paper discusses how the interaction and relationships among various components of this system can be described through the East Asia Pacific (EAP) teleconnection pattern and the teleconnection pattern of meridional upper-tropospheric wind anomalies along the westerly jet over East Asia. Such reasoning suggests that the occurrence of severe floods in the Yangtze and Huaihe River valleys and prolonged droughts in North China are linked, respectively, to the background interannual and interdecadal variability of the EAM climate system. Besides, outstanding scientific issues related to the EAM system and its impact on climate disasters in China are also discussed.

Key words: East Asian monsoon system, climate disaster, persistent drought, severe flood, EAP pattern teleconnection

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1. Introduction

China is located in the East Asian monsoon region, thus, the climate of China is influenced mainly by the East Asian monsoon (EAM) (e.g., Zhu, 1934; Tu and Huang, 1944). The significant interannual and interdecadal variabilities of the EAM are related to frequent climate disasters (e.g., Huang and Zhou, 2002; Huang et al., 2006a). Especially since the 1980s, severe climate disasters over large areas have caused major damage to agricultural and industrial production in China. Each year, the economic losses due to droughts and floods can reach over 200 billon yuan (i.e., about US$24 billion), accounting for 3%–6% of China's GDP in the early 1990s (e.g., Huang et al., 1999a; Huang and Zhou, 2002). In the summer of 1998, for example, particularly severe floods occurred in the Yangtze River basin and the Songhua and Nen River valley, causing losses as high as 260 billion yuan (i.e., about US$ 31 billion) (e.g., Huang et al., 1998a). In addition, persistent droughts in North China since the late 1970s brought not only huge losses to agriculture and industry, but also seriously affected the region's water resources and ecology resulting in a large increase in the frequency sand-dust storms. To reduce the losses due to climate disasters, research is necessary to increase understanding and the ability to predict climate disasters in China. As a result, such research was one among the first batch of projects supported by the National Key Program for Developing Basic Sciences (e.g., Huang et al., 1999a; Huang, 2001a, 2004) and was a major project supported by the National Natu-

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The occurrence of climate disasters such as droughts and floods in China, especially the severe flooding disaster in the Yangtze River basin in the summer of 1998 and the persistent droughts in North China since the late 1970s, is closely associated with the variability and anomalies associated with the EAM system. Just as monsoons generically may be viewed as atmosphere-ocean-land coupled systems (Webster et al., 1998), the variability and anomaly of the EAM system are affected not only by internal dynamical and thermodynamical processes in the atmosphere, but also by the interactions among various components of a coupled atmosphere-ocean-land system. To study the recurrence and causes of severe climate disasters in China, the variability in various components of the EAM climate system has been analyzed in detail in recent years. These components include the circulation of the EAM, western Pacific subtropical high, atmospheric disturbances in mid-and high latitudes, thermal states of the Pacific warm pool, convective activity around the Philippines, ENSO cycle in the tropical Pacific, dynamical and thermal effects over the Tibetan Plateau, land surface process in the arid and semi-arid areas of Northwest China, and snow cover on the Tibetan Plateau (e.g., Huang et al., 1998a; Huang et al., 2001; Huang et al., 2004a). In addition to descriptive aspects of these features, the nature of the internal and external physical processes that influence the variabilities in the EAM system have been addressed recently.

This paper attempts to summarize the advances in recent studies on the characteristics and variabilities of the EAM system and its impacts on climate disasters in China. The review focuses on the progress achieved by research in China during the recent decades.

2. Characteristic of the EAM system

The Asian-Australian monsoon system is an important circulation system in the global climate system. Many studies have shown that the Asian and Australian monsoons play an important role in global climate variability (e.g., Tao and Chen, 1987; Ding, 1994; Huang and Fu, 1996; Webster et al., 1998; Huang et al., 2003; Huang et al., 2004a). Since there is a close association between the South Asian monsoon (SAM), the East Asian monsoon (EAM) and the North Australian monsoon (NAM), some scholars consider them three subsystems of the Asian-Australian monsoon system (e.g., Webster et al., 1998). However, there are some differences among these monsoon subsystems. For example, the East Asian summer monsoon (EASM) is not only a part of the tropical monsoon, it also has properties of disturbances in middle latitudes (e.g., Tao and Chen, 1987). But, the South Asian summer monsoon (SASM) and the North Australian summer monsoon (NASM) are only tropical. Therefore, the EASM differs from the SASM and the NASM in aspects described in the following sub sections.

2.1 *A relatively independent component of the Asian-Australian monsoon system*

According to Krishnamurti and Ramanathan (1982) study, the principal components of the SASM include: the Mascarene high, Somali cross-equatorial low-level flow, monsoon trough over North India in the lower troposphere, South Asian high, and the north to south cross-equatorial flow in the upper troposphere. Tao's investigation (e.g., Tao and Chen, 1985) showed the main components of EASM monsoon include: the Indian SW monsoon flow, Australian cold anticyclone, cross-equatorial flow east to 100°E, monsoon trough (or ITCZ) over the South China Sea (SCS), tropical easterly flow around the west Pacific the western Pacific subtropical high, mei-yu (or Baiu in Japan, or Changma in Korea) frontal zone, and disturbances in mid-latitudes. Hence, the EASM is a relatively independent monsoon circulation system.

Recently, Chen and Huang (2006) analyzed the climatological characteristics of the wind structure and seasonal evolution of subsystems of the Asian-Australian monsoon system, specifically the SASM over the area (0°–25°N, 60°–100°E) and the EASM over the area (0°–45°N, 100°–140°E) in boreal summer, and the NASM over the area (0°–15°S, 110°–150°E) in austral summer. Results (Figs. 1a and 1c) show that both the SASM and the NASM are solely tropical strong zonal flow with vertical easterly shear, i.e., low-level westerlies and high-level easterlies. The vertical easterly shear in the SASM region is stronger than that in the NASM region. The vertical structure of zonal flow in the EASM region is complex. It includes vertical easterly shear in the region to the south of 25°N, such as over the South China Sea (SCS) and the tropical western Pacific, and vertical westerly shear in the subtropical monsoon region north of 25°N, such as over mainland China, Korea and Japan (Fig. 1b). Thus, the EASM is composed of both tropical and subtropical summer monsoons with a significant meridional flow and vertical northerly shear, i.e., low-level southerlies and high-level northerlies (Fig. 2). Moreover, compared to the meridional components of wind in the SASM and NASM regions, the low-level southerlies in the EASM region are stronger than those in the SASM and NASM regions.

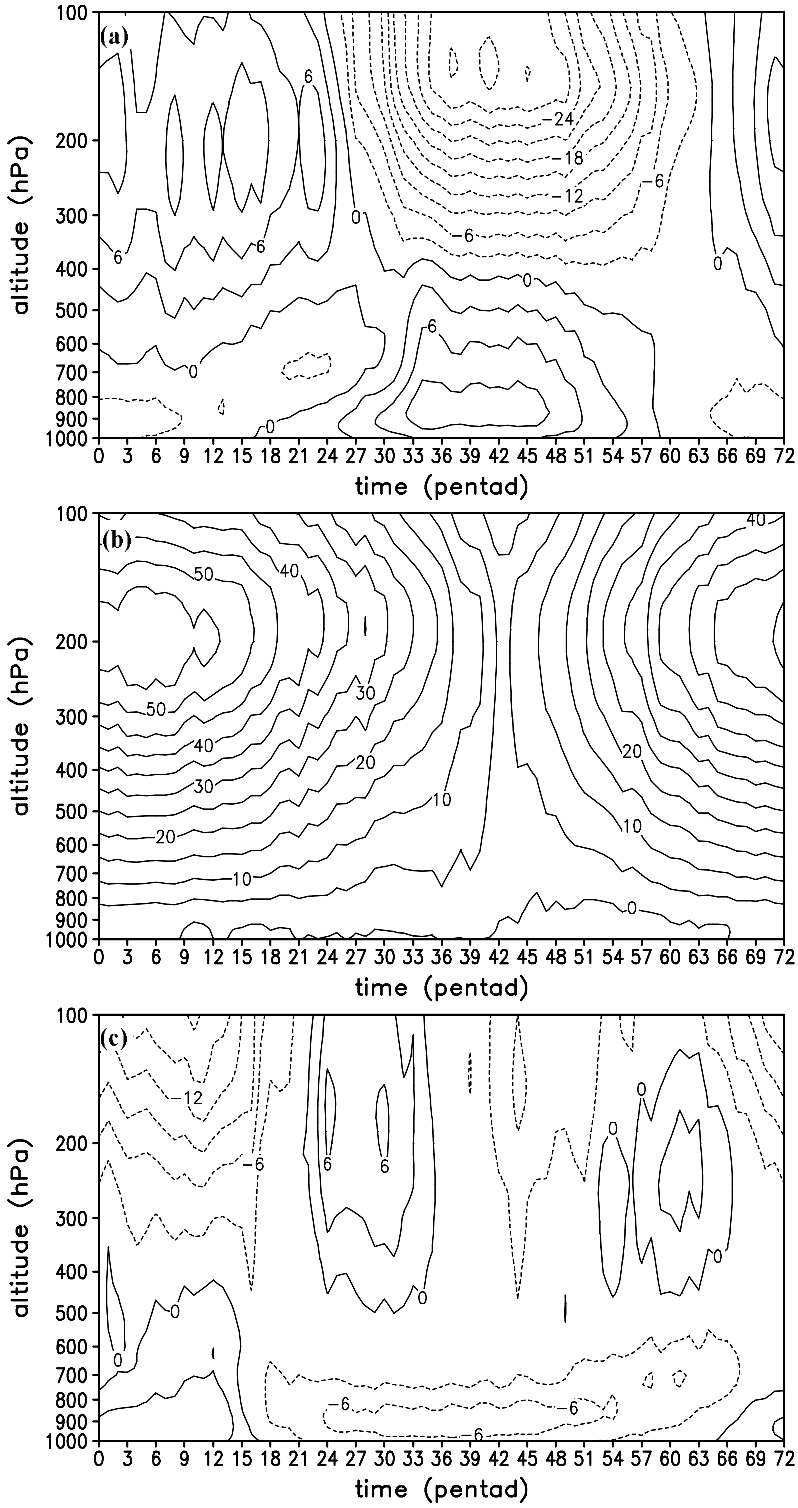

Fig. 1. Altitude-time cross section of zonal wind averaged over (a) South Asia (0°–25°N, 60°–100°E), (b) East Asia (20°–45°N, 100°–140°E) and (c) North Australia (0°–15°N, 110°–150°E). Units: m s^{-1}. Solid and dashed lines indicate westerly and easterly winds, respectively. Shown are 1979–2003 means derived from NCEP/NCAR reanalysis data (e.g., Kalnay et al., 1996).

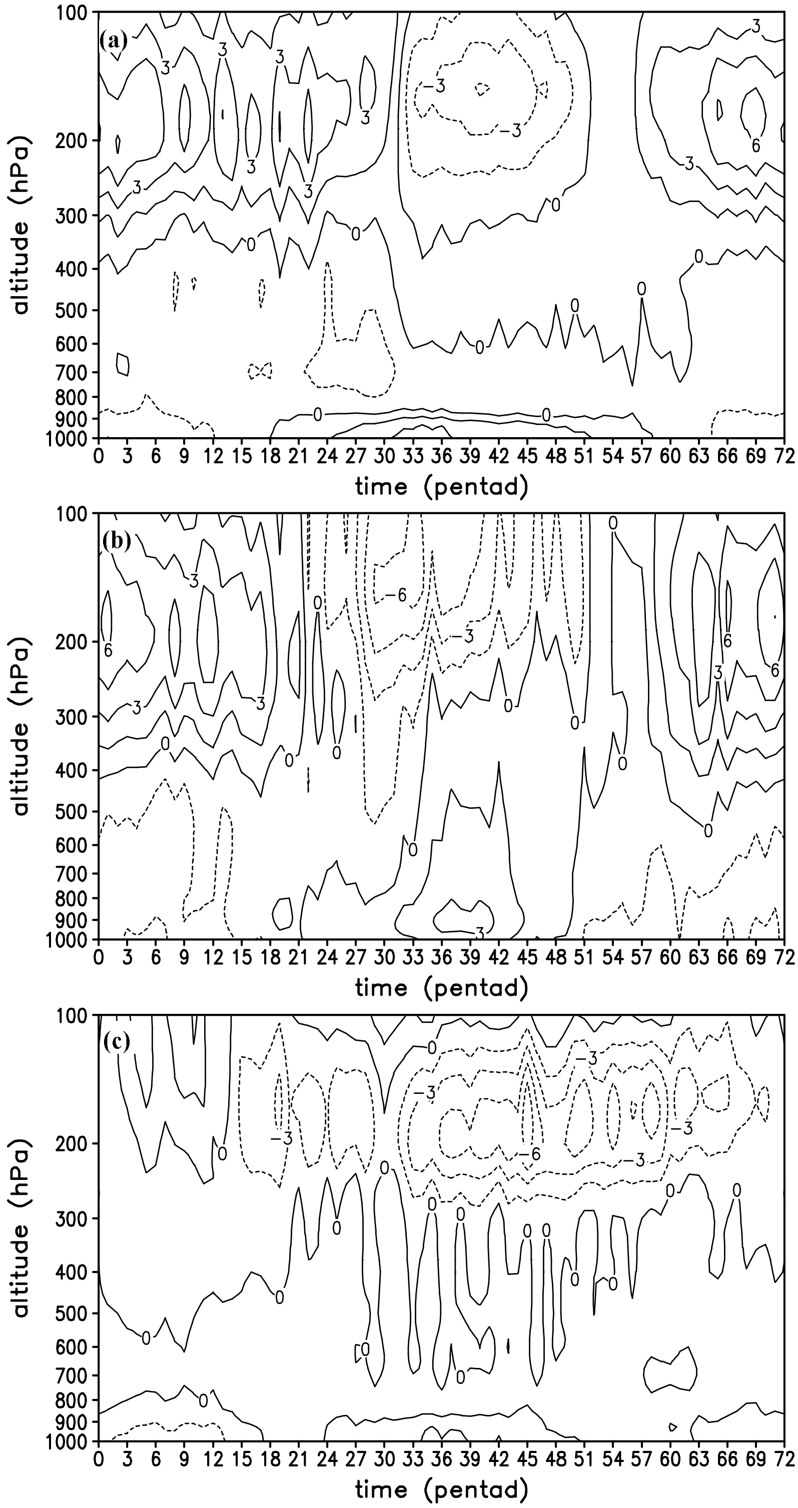

Fig. 2. As in Fig. 1 except for the meridional wind.

2.2 *Annual cycle between summer and winter monsoons in the EAM region*

It is clear from either precipitation and surface winds or tropospheric air temperatures and circulation patterns that the SAM and the NAM are phenomena having an annual cycle (e.g., Li and Yanai, 1996; Tomas and Webster, 1997; Goswami et al., 2006). The annual cycle is more pronounced in the EAM region.

Tao and Chen (1987) pointed out that the earliest onset of the Asian Summer Monsoon (ASM) is found over the SCS. It subsequently moves northward to South China, the Yangtze River and the Huaihe River valleys, Korea and Japan, and reaches North China and Northeast China in early or mid-July. The annual cycle of the EAM is readily apparent from seasonal variations of the monsoon rainband over East Asia (e.g., Huang et al., 2003). Figure 3 is the latitude-time cross section of 5-day precipitation along 115°E (average for 110°–120°E) averaged over the 40 years from 1961 to 2000. Figure 3 clearly shows that the monsoon rainband is located over South China in spring, then moves northward to the south of the Yangtze River during the period from May to the first 10 days of June, and then abruptly moves northward to the Yangtze River and Huaihe River valleys of China, Japan and South Korea. This is the beginning of the mei-yu season in the Yangtze River and Huaihe River valleys and start of the Baiu in Japan. Thereafter, as seen from Fig. 3, the monsoon rainband moves northward to North China and North Korea in early July. As it does so, the mei-yu season ends in the Yangtze River and Huaihe River valleys (i.e., Jianghuai valley in Chinese) and the rainy season begins in North China and Northeast China. The northward movement of the summer monsoon rainband over East Asia agrees well with the onset of EAM in various regions of East Asia (Tao and Chen, 1987).

The northward movement of the rainband is closely associated with the northward shift of the western Pacific subtropical high (e.g., Huang and Sun, 1992; Ding, 1992; Huang et al., 2003; Lu, 2004; Huang et al., 2005). Yeh et al. (1959) were the first to point out the abrupt change in the planetary–scale the circulation over East Asia occurring during early and mid-June that accompanies the onset of the EASM. Later, Krishnamurti and Ramanathan (1982) and McBride (1987) noted the onset of the SASM and the NASM circulations also coincided with abrupt changes of planetary-scale circulations. Additionally, as shown by Huang and Sun (1992), abrupt changes occurred during early or mid-June in the circulation over East Asia are closely associated with convective activity around the Philippines.

The southward retreat of the EASM is very rapid. Generally, the EASM moves rapidly southward to South China during the two weeks following mid-August. Subsequently, the EAWM begins with strong northerly winds prevailing over East Asia. In October strong northeasterly winds reach the area over the SCS and winds become easterly over the Indo-China Peninsula. Thus, the annual cycle of the EASM and EAWM is characterized mainly by migration in the meridional direction, while migration of the SAM and NAM annual cycle between winter and summer is primarily in the zonal direction.

Differences in the annual cycle of wind fields among these three monsoon systems can be seen also from the altitude-time cross sections of zonal (Fig. 1) and meridional winds (Fig. 2) averaged over East Asia, South Asia, and North Australia. From early June over South Asia (Fig. 1a) strong westerly winds prevail in the lower troposphere below 500 hPa and strong easterly winds are found in the upper troposphere above 500 hPa. However, from early October over this region the westerly wind become easterly in the lower troposphere below 700 hPa, while the easterly wind become westerly in the upper troposphere above 500 hPa. Hence, in the SAM region the annual cycle between summer and winter monsoons is clearly evident in the zonal wind fields. The same phenomenon also appears in the NAM region (Fig. 1c), but the reverse of zonal wind occurs in early November as the summer approaches in the Southern Hemisphere. Comparison of Fig. 1b with Figs. 1a and 1c shows the seasonal reverse of zonal winds in the troposphere over East Asia is not significant. Rather, as shown in Fig. 2b, there is an obvious seasonal reverse of meridional winds in the lower and upper troposphere over East Asia in early June and mid-September, respectively.

From the above analysis, it can be seen that in EAM region the annual migration between winter and summer monsoons is primarily in the meridional direction and appears mainly in the meridional component of wind field. It therefore differs markedly from the annual cycle of wind fields in the SAM and NAM regions.

2.3 *The characteristics of water vapor transports in the EASM region*

Huang et al. (1998b) showed that the characteristics of water vapor transports in the EAM region are considerably different from those characterizing the SASM area. In the SASM region the zonal transport of water vapor dominates, while the meridional transport of water vapor is very large in the EASM region. Moreover, the convergence of water vapor over the EASM region, which is closely associated with monsoon rainfall there, is to the combined effects of moisture ad-

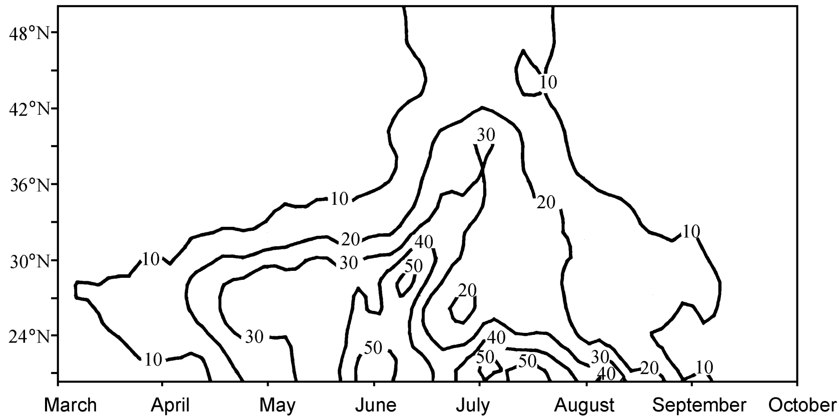

Fig. 3. Latitude-time cross section of 5-day precipitation along 115°E (average over 110°–120°E) for the period 1961–2000. Units: mm.

vection and convergence of the wind fields. Over the SASM region, water vapor convergence results mainly from wind-field convergence. The authors also point out that the anomalous summer monsoon rainfall in East Asia is influenced primarily by three branches of water vapor transport, namely, from the Bay of Bengal, South China Sea and tropical western Pacific. Zhou and Yu (2005) have shown the relationship between summer monsoon rainfall anomaly patterns in China and the water vapor transports. Additionally, they noted that the anomalously strong summer rainfall pattern occurring in the mid- and lower reaches of the Yangtze River valley is closely associated with the convergence of the northward transport of water vapor from the Bay of Bengal and the southward transport of water vapor from mid-latitudes. However, if the anomalous rainfall pattern shifts northward to the Huaihe River valley, it may be supported by the convergence of the water vapor transports from the South China Sea and mid-latitudes.

Recently, Chen and Huang (2007) analyzed the characteristics of water vapor transports over the EASM, the SASM and NASM regions using the ERA-40 reanalysis data for 1979–2002. The result is in good agreement with those by Huang et al. (1998b). The convergence of water vapor transport over the SASM region is mainly due to the convergence of the wind field in the lower troposphere over this region because of the large vertical velocity forced by large vertical shear of the zonal wind, as shown in Fig. 1a. A similar result can be found over the NASM region in the Southern Hemisphere summer (not shown). However, over the EASM region, water vapor transport is due not only to converging wind fields, but also to the moisture advection associated with the southerly monsoon flow in the lower troposphere. This is because there is a smaller vertical velocity corresponding to lesser vertical wind shear (Fig. 1b) than that in the SAM region.

From the above results, it may be concluded that the EAM system is a relatively independent component of the Asian-Australian monsoon system, although the EASM is also influenced by the SASM.

3. Characteristics of temporal and spatial variabilities of the EAM system and their impact on droughts and floods in China

Since the EASM is influenced not only by the SASM and the western Pacific subtropical high (e.g., Tao and Chen, 1987; Huang and Sun, 1992), as well as by mid- and high latitude circulation systems over both Northern Hemispheres (e.g., Tao and Chen, 1987; Gong and Ho, 2003) and Southern Hemisphere (e.g., Nan and Li, 2003; Fan and Wang, 2004; Xue et al., 2004), the interannual and interdecadal variations of EASM system are significant and very complex. In comparison to summertime surface air temperatures, the interannual and interdecadal variabilities of summer monsoon rainfall are more obvious in East Asia and have a large impact on climate disasters in China (e.g., Huang et al., 1999a; Huang and Zhou, 2002). Therefore, the interannual and interdecadal variabilities of summer monsoon rainfall and water vapor transports in East Asia are emphasized in this section.

3.1 *Interannual variations of onset and northward advance of the EASM and their impact on droughts and floods in China*

The interannual variability of summer monsoon rainfall in East Asia is influenced not only by the strength of the EASM, but also by the date of its onset. According to the studies by Tao and Chen (1987), and

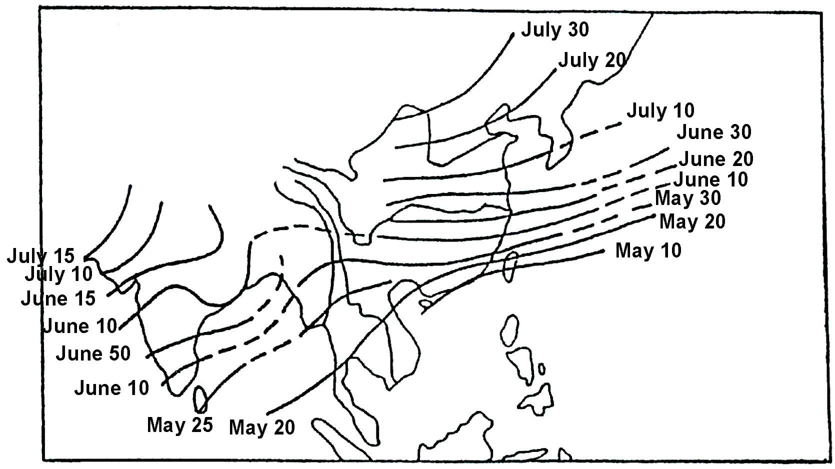

Fig. 4. Climatological-mean onset dates of the EASM (from Tao and Chen, 1987).

He and Luo (1999), the earliest onset of the ASM is found over the SCS and the Indo-China Peninsula, as shown in Fig. 4. Recently, Ding and He (2006) proposed that the earliest onset of the ASM is over the tropical eastern Indian Ocean. Since the onset of the SCSM has a direct impact on the northward advance of the ASM over East Asia, the study of the SCSM onset is emphasized in the review. The appearance of strong convective activity and the southwesterly flow over the SCS signals the onset of the ASM. Generally, the summer monsoon over the SCS is referred to the South China Sea summer monsoon (SCSM) in China. In order to investigate the interannual variability of onset date and progress of the SCSM, it is necessary to define an index for measuring the SCSM onset. However, there are many definitions of the SCSM onset (e.g., Wang et al., 2004) to choose. In comparison with other definitions, the one proposed by Liang and Wu (2002) appears to be more reasonable and used in many studies (e.g., Huang et al., 2005, 2006a).

Huang et al. (2005), and Huang et al. (2006a) analyzed the characteristics of interannual variations of the SCSM onset and its subsequent development. Their results showed that the interannual variability of SCSM onset date is very large and closely associated with the thermal state of the tropical western Pacific in spring. When the tropical western Pacific is warming during spring, the western Pacific subtropical high shifts eastward and twin anomalous cyclones develop early over the Bay of Bengal and Sumatra preceding the onset of the SCSM. In this case, the cyclonic circulation located over the Bay of Bengal can intensify early and develop into a strong trough. As a consequence, the westerly flow and convective activity can intensify over Sumatra, the Indo-China Peninsula and the SCS in mid-May, leading to an early onset of the SCSM (Fig. 5a). On the other hand, when the tropical western Pacific is cooling in spring, the western Pacific subtropical high shifts westward, and the twin anomalous anticyclones are located over the equatorial eastern Indian Ocean and Sumatra from late April to mid-May. Thus, the westerly flow and convective activity does not increase in intensity as early over the Indo-China Peninsula and the SCS. Only when the western Pacific subtropical high moves eastward, the weak trough over the Bay of Bengal can intensify. As a result, the strong southwesterly wind and convective activity over the Indo-China Peninsula and the SCS are delayed generally until late May, thus, the late onset of the SCSM is caused (Fig. 5b).

Following the SCSM onset, the monsoon moves northward over East Asia. Huang and Sun (1992), Huang et al. (2004a), and Huang et al. (2005) also investigated the interannual variations of the northward advance of the EASM. Their results showed the northward advances of the EASM after the onset over the SCS are greatly influenced by the thermal state of the tropical western Pacific in summer. They pointed out 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. 5a, when the SST in the tropical western Pacific is above normal in summer, i.e., warm sea water accumulates in the West Pacific warm pool, and a cold tongue extends westward from the Peruvian coast along the equatorial Pacific, convection intensifies from the Indo-China Peninsula to east of the Philippines, and the western Pacific subtropical high shifts anomalously northward. In this case, the summer monsoon rainfall may be below normal in East Asia, especially in the Yangtze River and

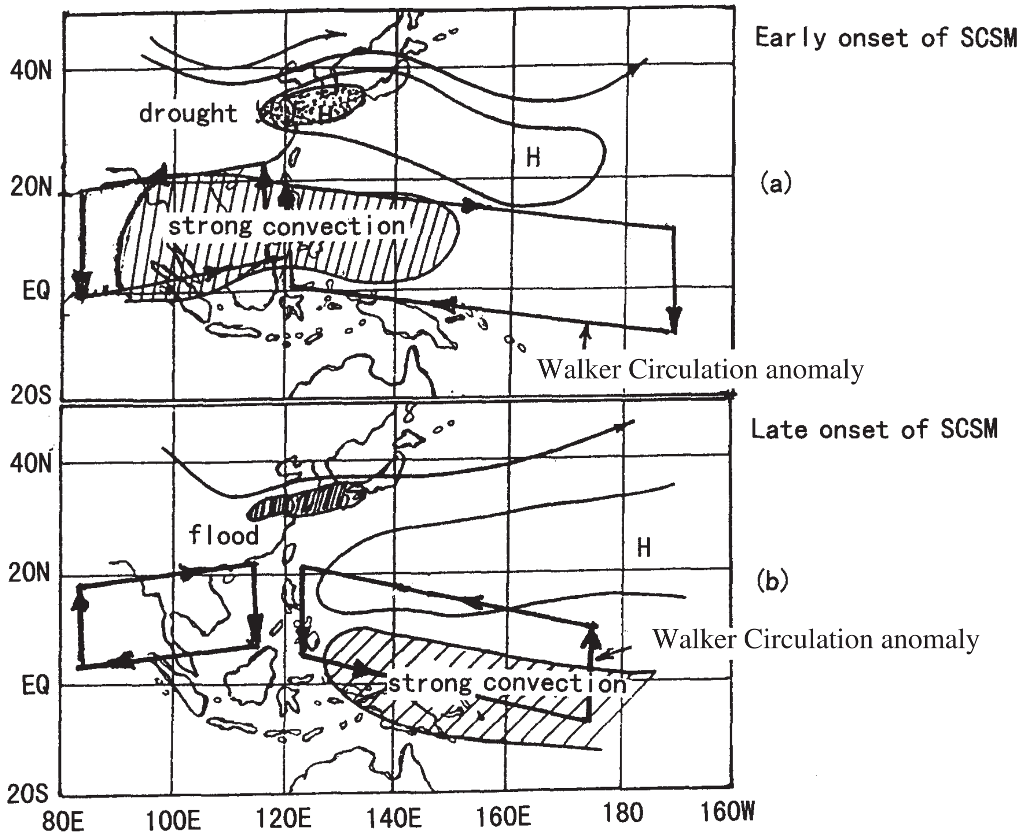

Fig. 5. Schematic map of the relationships among the thermal states of the tropical western Pacific (TWP) (i.e., 0°–14°N, 130°–150°E) in spring, the convective activity around the Philippines, the western Pacific subtropical high, the onset of SCSM and the summer monsoon rainfall in East Asia. (a) warming TWP; (b) cooling TWP.

Huaihe River basins of China, South Korea, and Japan. On the other hand, when the SST in the tropical western Pacific is below normal, i.e., the warm sea water extends eastward from the West Pacific warm pool along the equatorial western Pacific in summer, the convective activity is weak around the Philippines, and the western Pacific subtropical high may shift southward. In this case, the summer monsoon rainfall may be above normal in the Yangtze River and Huaihe River valleys 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 and Huaihe River valleys and droughts in North China in summer.

Therefore, the thermal state of the tropical western Pacific, especially the anomaly of oceanic heat content (OHC) in the area known as NINO West (i.e., 0°–14°N, 130°–150°E) in spring (March–May) can be considered as a physical factor affecting the SCSM onset and summertime droughts and floods in the Yangtze River and the Huaihe River valleys, South Korea, and Japan.

3.2 *The EAP index and interannual variability in the strength of the EASM*

Monsoon indices are criteria for measuring the strength of monsoons and are necessary for studying the interannual variability of the ASM. Thus, two types of indices of Asian monsoon strength are used. One is defined from the thermodynamic elements, such as precipitation or OLR (e.g., Tao and Chen, 1987; Murakami and Matsumoto, 1994). The other is defined from the dynamic elements, such as the difference of zonal wind between lower and upper troposphere (e.g., Webster and Yang, 1992; Zeng et al., 1994) or the difference of sea-level pressure between the Eurasian continent and North Pacific (e.g., Guo, 1983). The former is easily influenced by local thermodynamic conditions, but the latter is only suitable for studying the SAM and the NAM regions where there are the large differences in the zonal wind between lower and upper troposphere, as described in section 2. Since differences in zonal wind are small in the EASM region, the definition based on zonal winds is not suitable for use in there. Rather, the study by

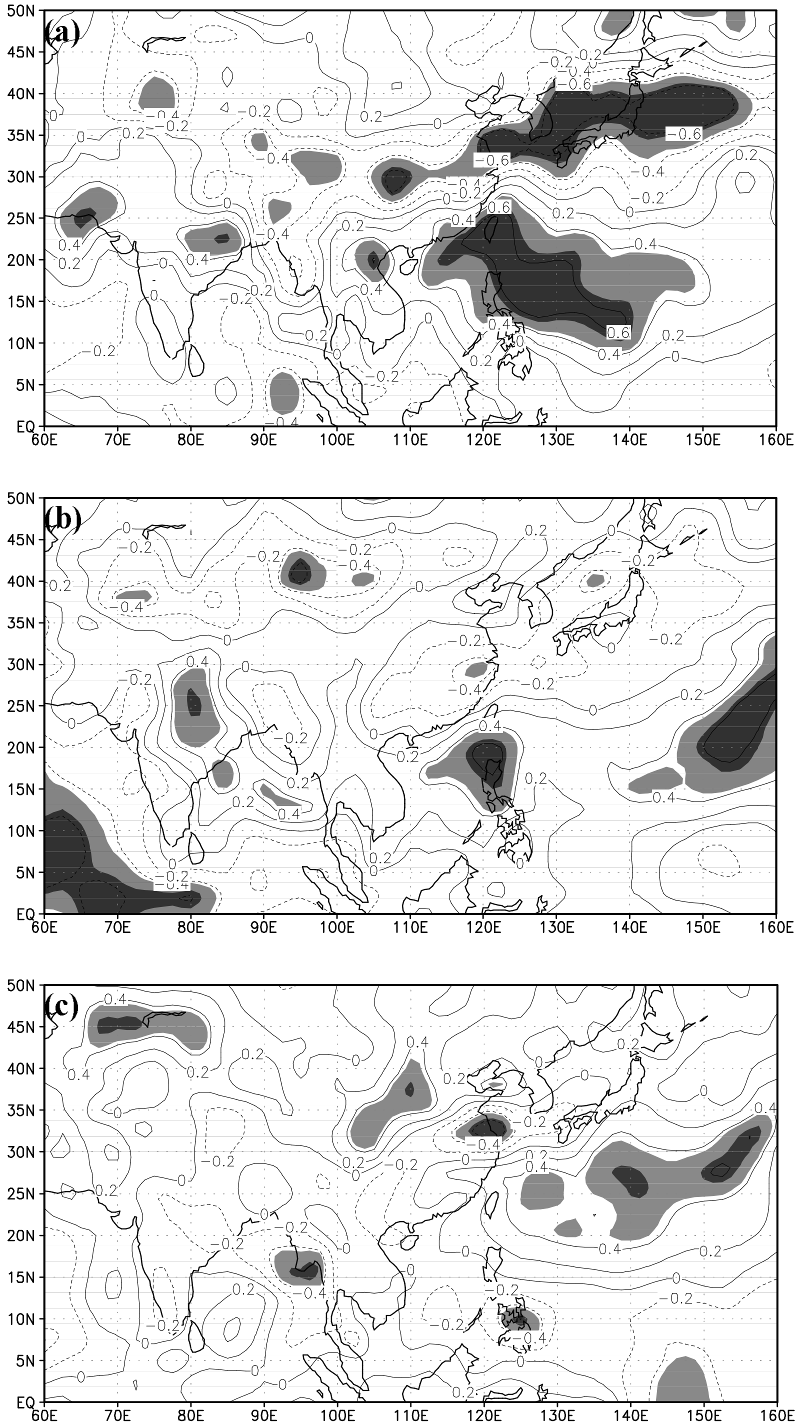

Fig. 6. Distributions of correlation coefficients between summer rainfall anomalies in East Asia with (a) the EAP index, (b) the WY index (e.g., Webster and Yang, 1992), and (c) the SM index (e.g., Guo, 1983). Areas of confidence level over 95% are shaded. Rainfall data is from the Xie-Arkin precipitation data for 1979–1998 (e.g., Xie and Arkin, 1997).

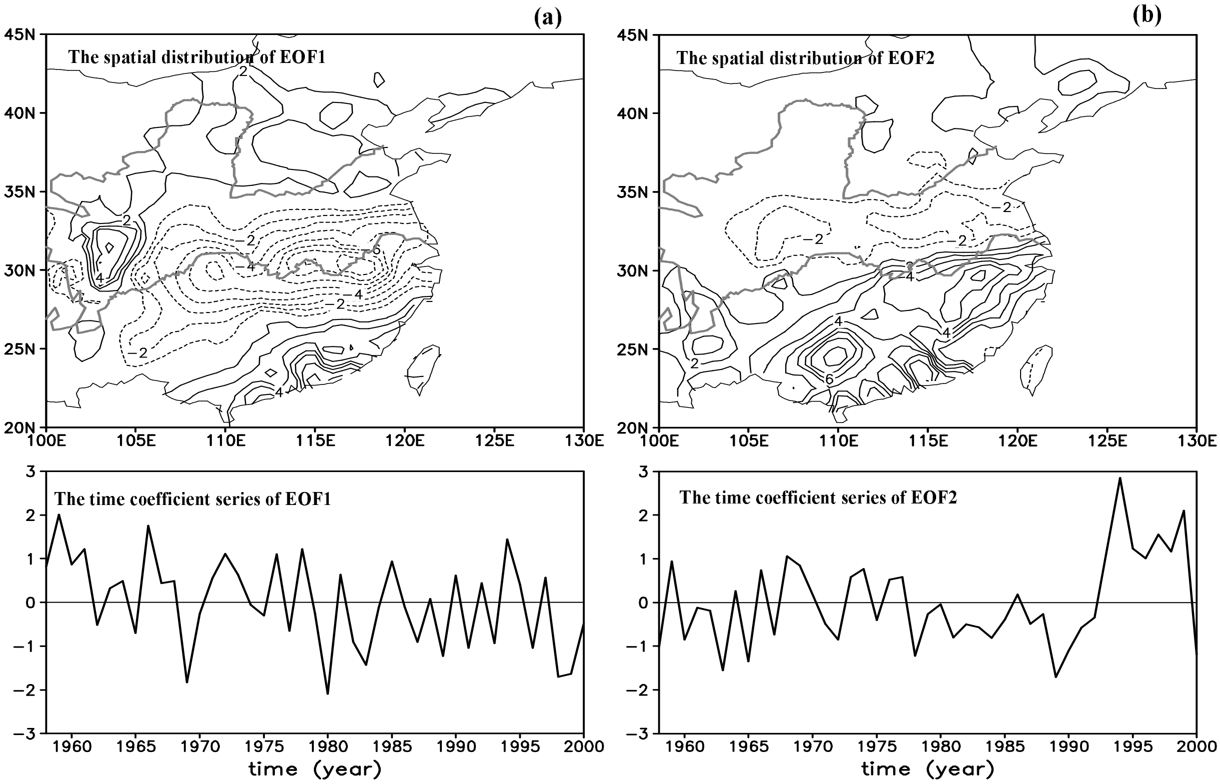

Fig. 7. Spatial distribution and the corresponding time coefficient series of the (a) first and (b) second component of EOF analysis (i.e., EOF1 and EOF2) of summer (JJA) rainfall in China from 1958 to 2000. EOF1 and EOF2 explain 15.6% and 12.7% of the variance, respectively.

Huang (2004) showed that the interannual variability of EASM can be described well by using the East/Pacific teleconnection pattern (EAP) index, which is based upon summer 500 hPa height anomalies corresponding to the EAP teleconnection of summer circulation anomalies (e.g., Nitta, 1987; Huang and Li, 1987, 1988).

Figures 6a–c show correlations between summer rainfall in East Asia and the EAP index, the Webster-Yang (WY) zonal-wind index, and the sea-level pressure based index (SM). Comparison of Fig. 6a with Figs. 6b and 6c clearly shows that the EAP index corresponds well and more so that the WY and SM indices with summer monsoon rainfall in East Asia. Also, from Fig. 6a, it can be seen that, if the EAP index is negative (positive), summer monsoon rainfall tends to be above (below) normal in the Yangtze River and the Huaihe River valleys. For example, in the summers of 1954, 1957, 1980, 1987, 1993, and 1998, the EAP index was largely negative, and severe floods occurred in these regions. Moreover, Fig. 6a shows a meridional tripole pattern in the distribution of correlation coefficients in East and Northeast Asia, which corresponds to interannual variations of summer monsoon rainfall which generally appear as a meridional tripole pattern in rainfall distribution.

3.3 *The quasi-biennial oscillation and tripole pattern distribution of the EASM anomalies over East Asia and their impacts on droughts and floods in China*

The quasi-biennial oscillation of circulation in the tropical troposphere, i.e., the TBO, is a fundamental characteristic of interannual variations in air-sea coupling in the SAM and NAM regions (e.g., Mooley and Parthasarathy, 1984; Yasunari and Suppiah, 1988). Also, Miao and Lau (1990), Lu et al. (1995), Yin et al. (1996), and Chang et al. (2000) proposed that the tropospheric biennial oscillation (TBO) can be found in interannual variations of summer monsoon rainfall in East Asia. Recently, Huang et al. (2006b) showed that there is also an obvious oscillation with a period of two–three years, i.e., the TBO, in the corresponding time-coefficient series of the EOF1 of summer rainfall in China (Fig. 7a), especially from the mid-1970s to the late 1990s. And, as shown by the spatial distribution of EOF1 in Fig. 7a, a strong negative signal occurs in the Yangtze River and the Huaihe River valleys. Moreover, it is also shown that this oscillation is closely associated with the quasi-biennial oscillation in the interannual variations of water vapor transport fluxes by the summer monsoon flow over East Asia (Fig. 8b). Additionally, the spatial distribution of EOF1 of summer rainfall in China (Fig. 7a) and the spatial distribution of the EOF1 of water vapor transports over East and Northeast Asia (Fig. 8a) are similar in exhibiting a meridional tripole pattern.

This meridional tripole pattern is seen clearly in the circulation anomalies at 500 hPa or 700 hPa. Figures 9a and 9b are the composite 500 hPa height anomalies over East Asia for summers with high and low EAP index, respectively. These figures show that with either high or low EAP index summers, which correspond respectively to drought and flood conditions in the Yangtze River and Huaihe River valleys, the summer monsoon circulation anomalies also exhibit the meridional tripole pattern distribution over East and Northeast Asia.

The above results show that the interannual variability of EASM clearly exhibits a quasi-biennial oscillation with a meridional tripole pattern distribution over East Asia and the tropical western Pacific. This may be a significant characteristic of the interannual variability of EASM. The frequency of drought and flood disasters also exhibit a quasi-biennial oscillation in the Yangtze River and the Huaihe River valleys, and the spatial distributions of these disasters often appear in the form of a meridional tripole pattern over East Asia.

3.4 *Interannual variability of the East Asian winter monsoon (EAWM) and its relation to the EASM*

East Asia is also a region of a strong winter monsoon. The East Asian winter monsoon (EAWM) features strong northwesterlies over North China, Northeast China, Korea and Japan and strong northeasterlies along the coast of East China (e.g., Staff members of Academia Sinica, 1957; Chen et al., 1991; Ding, 1994). A strong winter monsoon can bring not only disasters, such as wintertime low temperatures and severe snow storms in Northwest and Northeast China, North Korea, and North Japan, and springtime severe dust-storms in North and Northwest China, but also can cause strong convection over the maritime continent of Borneo and Indonesia. (e.g., Chang et al., 1979; Lau and Chang, 1987). Also, strong and frequent cold waves caused by the strong EAWM can trigger the occurrence of El Niño (e.g., Li, 1988).

Chen and Graf (1998), and Chen et al. (2000) systematically investigated the interannual variability of EAWM and its relation to the EASM with a new definition of the EAWM index. This index is defined by using the normalized meridional wind anomalies at 10 m over the East China Sea (25°–40°N, 120°–140°E) and the South China Sea (10°–25°N, 110°–130°E), averaged over November to March period following winter. Wu and Wang (2002) proposed an intensity index of the EAWM defined as the sum of zonal sea-surface pressure differences (110°E minus 160°E) over 20°–70°N with a $2.5° \times 2.5°$ resolution in latitude and longitude. Results of the above mentioned studies show there is a significant variability in the interannual variations of EAWM.

Recently, Huang et al. (2007) investigated the interannual variations of the EAWM and its anomalies in the winters of 2005 and 2006 using the intensity index of EAWM defined by Wu and Wang (2002). They pointed out that, as shown in Fig. 10, the interannual variability of EAWM is significant and there is a clear difference between the EAWM intensity in the winter of 2005 (December 2005–February 2006) and the winter of 2006 (December 2006–February 2007). This was reflected in the different climate anomalies in the Northern Hemisphere, especially in East Asia, during these two winters.

The EAWM intensity can influence the following EASM intensity. The study by Chen et al. (2000) showed that following a strong (weak) EAWM, a drought (flood) summer may occur in the Yangtze River and the Huaihe River valleys. For example, in the summer of 1998, the severe flood shown in Fig. 17 in section 5.1 occurred in the Yangtze River valley following the weak EAWM in the winter of 1997.

3.5 *Interdecadal variability of the EASM*

3.5.1 *A dipole pattern distribution in the interdecadal variability of EASM over East Asia*

Huang et al. (1999b), and Huang (2001b) analyzed the interdecadal variations of summer monsoon rainfall in East Asia, and Chen et al. (2004) systematically discussed the characteristics of the climate change in China during the last 80 years. These results showed that the interdecadal fluctuations in summer (June–August) monsoon rainfall are more obvious than those in surface air temperature in East Asia. Huang et al. (1999b) pointed out that summer monsoon rainfall began to decrease in North China from the mid-1960s, especially from the late 1970s to the late 1990s. This resulted in prolonged severe droughts in this region, as shown in Fig. 18 of section 5. They also pointed out that the interdecadal variations of summer monsoon rainfall in North China are similar to those in the Sahelian region of Africa. Ren et al. (2004) also discussed the close linkage between the interdecadal variations of summer precipitation in North China and those in the Sahelian region. The opposite phenomenon, namely summer rainfall clearly increasing from the late 1970s

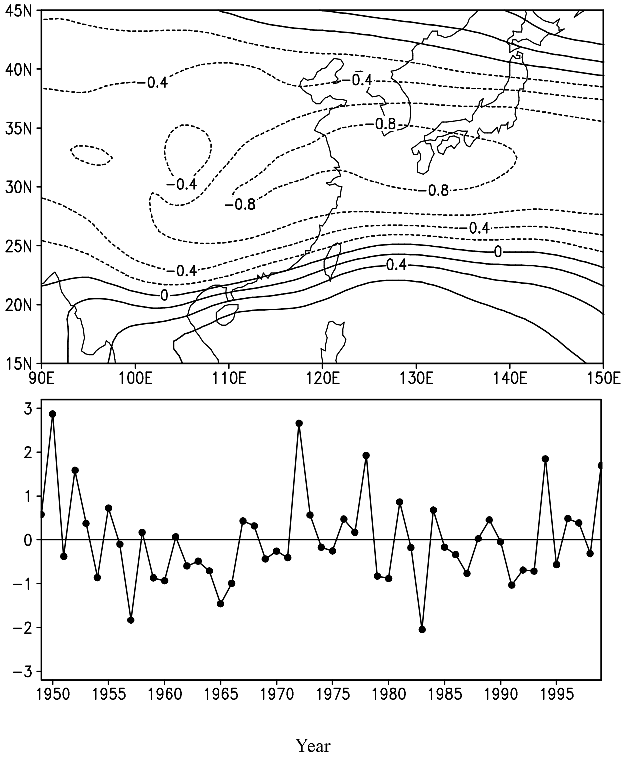

Fig. 8. (a) Spatial distribution and (b) corresponding time coefficient series of the first component of zonal water vapour transports in summer. Moisture and wind fields are taken from NCEP/NCAR reanalysis dataset from 1949 to 1999 (e.g., Kalnay et al., 1996). EOF1 explains 27.0% of the variance.

appears in the Yangtze River and the Huaihe River valleys and Northwest China. This interdecadal oscillation can be seen also in the dipole pattern in the spatial distribution of the EOF2 of summer rainfall in China and corresponding EOF2 time-coefficient series (Fig. 7b). This interdecadal variability of summer monsoon rainfall also appears in the frequency of heavy rainfall. As shown by Bao and Huang (2006), more heavy rainfall occurred in the 1980s than the 1970s in the middle and lower reaches of the Yangtze River and Huaihe River valleys and was followed by a further increase in the 1990s. In conjunction with this, however, a decrease of heavy rainfall occurred in the eastern part of North China since the late 1970s and has continued to the present.

3.5.2 *Possible impact of the African summer monsoon on the EASM on an interdecadal timescale*

The decrease of summer monsoon rainfall in North China from 1965, especially from the late 1970s, is closely associated with the weakening of the EASM. As pointed out by Huang and Zhou (2004), and Huang et al. (2004b), southerly winds over North China clearly weakened. Recently, Huang et al. (2006c) analyzed the interdecadal variations of drought and flood disasters in China and their association with the EAM system. As shown in Fig. 11, an interdecadal meridional tripole circulation anomaly distribution, similar to the EAP pattern teleconnection, appeared over the West Pacific in the late 1970s. This was influenced by the interdecadal El Niño-like SST anomaly pattern which became apparent in the tropical central and eastern Pacific from the late 1970s and has continued to the present. Comparison of Fig. 11b with Fig. 11a shows the anticyclonic anomaly located over the Mongolian Plateau during 1961–1976 clearly shifted southward to North China, and a cyclonic anomaly appeared over the Yangtze River and the Huaihe River valleys from the late 1970s. Thus, the circulation anomalies exhibited a meridional dipole pattern distribution over East Asia during this period. This led to the weakening of the EASM in North China and the southward and westward shift of the western Pacific subtropical high to south of the Yangtze River. On the other hand, the results also showed that the interdecadal variability of the Walker circulation from the late 1970s to the present resulted in intensification of the descending branch over North Africa, which led to intensification of the anticyclonic anomaly circulation over the Sahelian region and eastern North Africa (Fig. 11b). Due to propagation of quasi-stationary planetary waves, the intensification of the anticyclonic anomaly over the Sahelian region led to the appearance of an anticyclonic anomaly over South China and the Indo-China Peninsula beginning in the mid-late 1970s. Also, as shown in Figs. 11a and 11b, the distribution of interdecadal anomalies in the circulation in the lower troposphere over mid- and high latitudes appeared in a Eurasian (EU) pattern-like teleconnection. Additionally, anticyclonic anomalies over North China appeared after 1976. These led to weakening of the southerly monsoon flow in North China and water vapor convergence in the Yangtze River and the Huaihe River valleys. The net result was an interdecadal variation of droughts and floods in China beginning in the late 1970s.

3.6 *Interdecadal variability of the EAWM*

The EAWM also has a significant interdecadal variability. As shown in Fig. 10, the EAWM was stronger from the mid-1970s to the late 1980s but tended to be weaker from the late 1980s to late 1990s. This latter period was associated with continuously warm winters in China and an increase of spring rainfall in North and Northwest China (e.g., Huang and Wang, 2006;

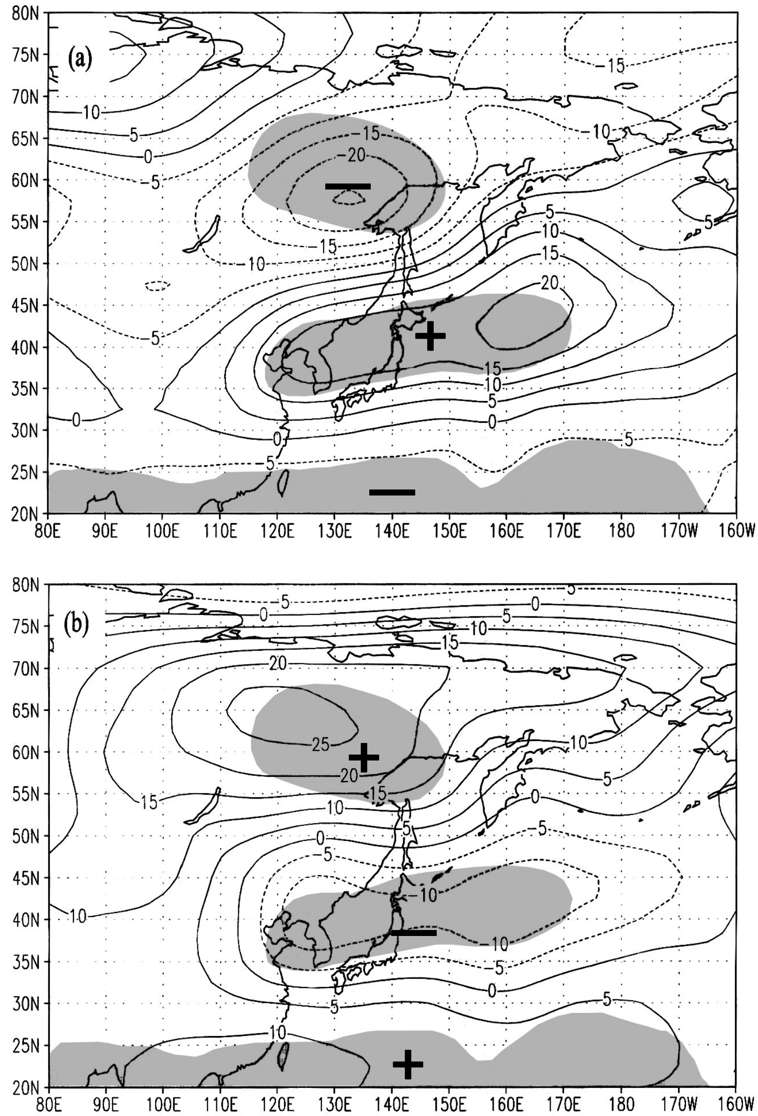

Fig. 9. Composite anomaly distributions of the 500 hPa height anomalies over East Asia and the tropical western Pacific for the summers with (a) high and (b) low EAP index. Units: gpm. Areas of confidence level over 95% are shaded. Height fields are taken from NCEP/NCAR reanalysis (e.g., Kalnay et al., 1996).

Kang et al., 2006).

The interdecadal variations of the EASM and EAWM have a significant impacts not only on drought and flood disasters in China, but also on the marine environment offshore of the Chinese mainland, including the Bohai Sea, Yellow Sea, East China Sea, and South China Sea. According to the study by Cai et al. (2006), since the winter and summer monsoon flows became weak offshore of China from 1976 to the present, winter and summer sea-surface wind stresses, especially the meridional component, have weakened, and SSTs have noticeably increased. These events can provide a favorable marine environment for the frequent occurrence of red tide in oceanic regions offshore of China.

4. The EAM climate system and its variabilities

As shown by Webster et al. (1998), the monsoon is not just an atmospheric circulation system, but rather an atmosphere-ocean-land coupled system. The interannual and interdecadal variabilities of the EASM and EAWM are influenced by many atmospheric circulation systems, such as the SAM, western Pacific

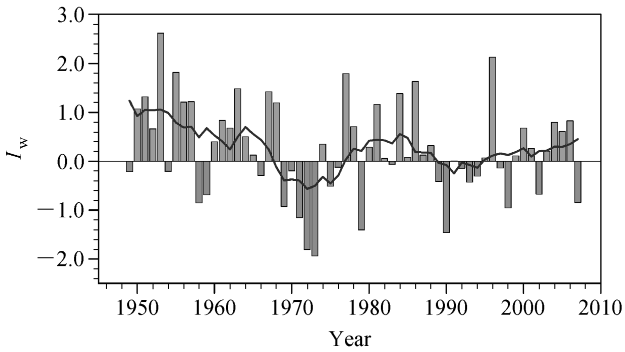

Fig. 10. The interannual variations of EAWM index based upon the definition of EAWM index by Wu and Wang (2002), based upon the NCEP/NCAR reanalysis data (e.g., Kalnay et al., 1996).

subtropical high, atmospheric disturbances in mid-and high latitudes. Additionally, the variability of the EASM and EAWM are affected by features such as the thermal state of the West Pacific warm pool, convection around the Philippines, ENSO cycle in the tropical Pacific, dynamical and thermal influences of the Tibetan Plateau, including cold season snow cover, and land surface process in the arid and semi-arid areas of Northwest China. The components of an atmosphere-ocean-land coupled system associated with the EAM are shown schematically in Fig. 12. This coupled system can be referred to as the East Asian monsoon climate system (e.g., Huang et al., 2004a), which then may be considered a subsystem of the Asian-Australian monsoon coupled system (e.g., Webster et al., 1998).

In order to understand the causes of variabilities in the EAM climate system, it is necessary to assess the interactive processes between the atmosphere and oceans and between the atmosphere and land surfaces. However, because of the complexity of these interactions, only the effects of atmosphere-ocean and atmosphere-land coupling are discussed.

4.1 *Thermal effect of the tropical western Pacific on the EAM variability*

Oceans have a significant thermal-effect on the Asian monsoon systems. Yang and Lau (1998) studied the influences of SST and ground wetness (GW) on Asian monsoons using a GCM and showed that ocean basin-scale SST anomalies have a stronger impact on the interannual variability of the Asian monsoon systems than GW anomalies. Lu et al. (2002a) discussed the associations between the western North Pacific (WNP) monsoon and the South China Sea monsoon (SCSM). They found that weak (strong) convective activity, which has a large impact on the SCSM onset, is related to El Niño (La Niña) pattern SST anomalies in the preceding winter and in spring.

Studies by many scholars (e.g., Nitta, 1987; Huang and Li, 1987; Kurihara, 1989; Huang and Sun, 1992) showed that the thermal state of the tropical western Pacific and convective activity around the Philippines play important roles in the interannual variability of EASM, as shown in Fig. 5. Nitta (1987), Huang and Li (1987), and Huang and Sun (1992, 1994) made systematic investigations of the thermal influence of the tropical western Pacific and convection around the Philippines on the interannual variability of the EASM circulation based upon observational data and dynamical theory. They proposed the P-J oscillation or the EAP pattern teleconnection of summer circulation anomalies over the Northern Hemisphere. As described in section 3, their results showed that the thermal state of the tropical western Pacific and convective activity around the Philippines have an obvious effect on the meridional shifts of the western Pacific subtropical high in summer. Lu (2001), and Lu and Dong (2001) also showed convective activity over the tropical western Pacific has a significant impact on the zonal shifts of the western Pacific subtropical high. Moreover, Huang et al. (2005) pointed out that the onset date of SCSM is closely associated with the thermal states of the tropical western Pacific and convective activity around the Philippines in spring.

Recently, Huang et al. (2005), and Huang et al. (2006b) investigated the interannual variability in the thermal state of subsurface waters of the tropical west Pacific. It can be seen from Fig. 13 that there is a significant quasi-biennial oscillation in the interannual variations of thermal structure. As shown by Huang et al. (2005), the oscillation has a large impact on the interannual variability of the northward advance of EASM and the water vapor transports driven by the monsoon flow. As shown in Fig. 14a, the composite distribution of water vapor transport anomalies for the summers when the tropical west Pacific is warming is opposite to that for the summers with cooling (Fig. 14b). Also, the anomalies in the water vapor transports shown in Figs. 14a and 14b exhibit a meridional tripole pattern. Thus, the influence of the thermal state of the tropical western Pacific on water vapor transport over East Asia explain well the TBO contribution to the summer monsoon rainfall in China or East Asia (e.g., Huang et al., 2006b).

4.2 *ENSO cycle and its impact on the EAM system*

It is well known that the ENSO cycle is one of the most striking phenomena of the tropical Pacific and

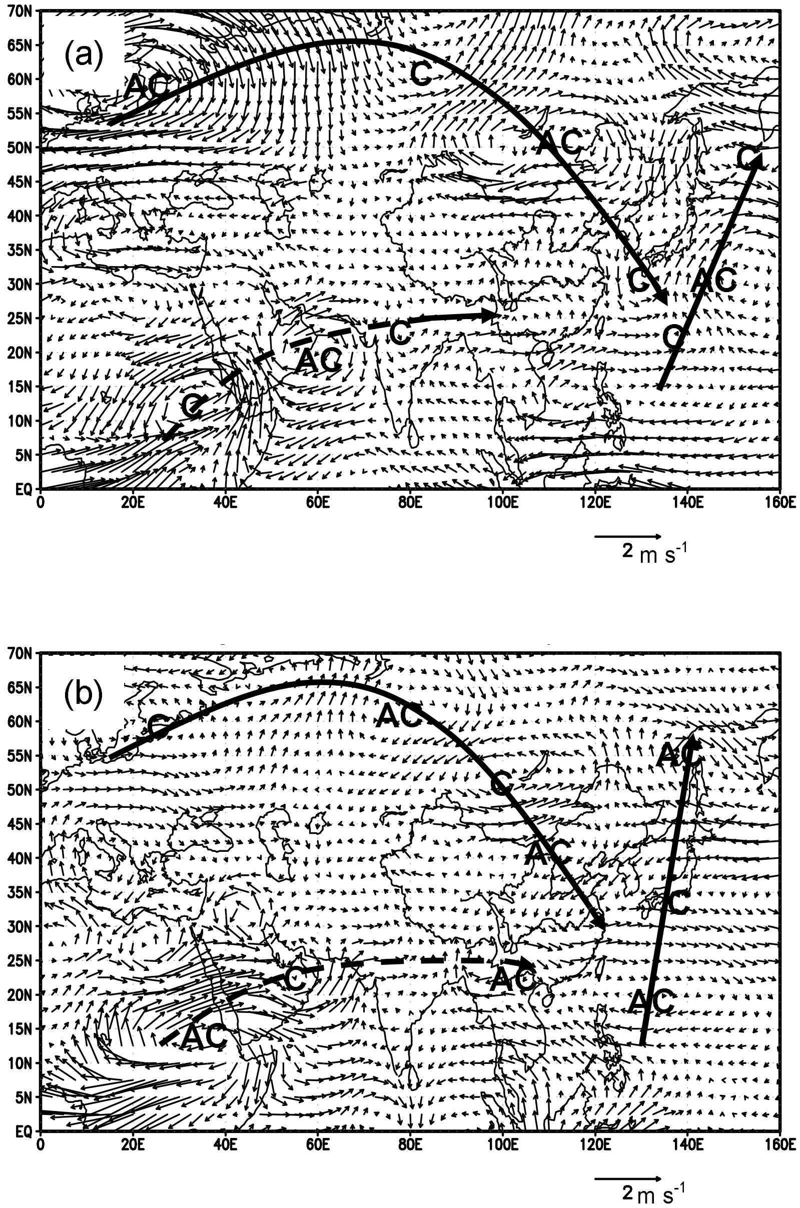

Fig. 11. Interdecadal variations of the summer (JJA) circulation anomalies at 700 hPa over East Asia and tropical western Pacific: (a) 1966–1976; (b) 1977–2000. Normals based upon the climatological monthly mean circulation for 1961–1990. Wind fields obtained from the ERA-40 reanalysis data (e.g., Uppala et al., 2005).

has a great influence on the Asian-Australian monsoon system. Weak SASMs tend to occur in El Niño years (e.g., Webster et al., 1998). Huang and Wu's study (1989) was the first to show that summer monsoon rainfall anomalies in East Asia depend on the stage of ENSO cycle, and these anomalies are closely related to the position of the western Pacific subtropical high. Recently, Huang and Zhou (2002) pointed out from composite analyses of summer monsoon rainfall anomalies for different stages of the ENSO cycle during the period of 1951–2000 that droughts in North China tend to occur in the developing stage (Fig. 15a). During the decaying stage of El Niño events, floods tend to occur in the Yangtze River valley of China, especially in the regions south of the Yangtze River (Fig. 15b). Zhang et al. (1996), Huang et al. (2001), and Zhang (2001) also pointed out that southerly wind anomalies can appear in the lower troposphere over the SCS and the southeastern coast of China during the mature and decaying stages of ENSO. In this case, since an anticyclonic anomaly tends to appear over the Philippine Sea, the corresponding intensification of southerly

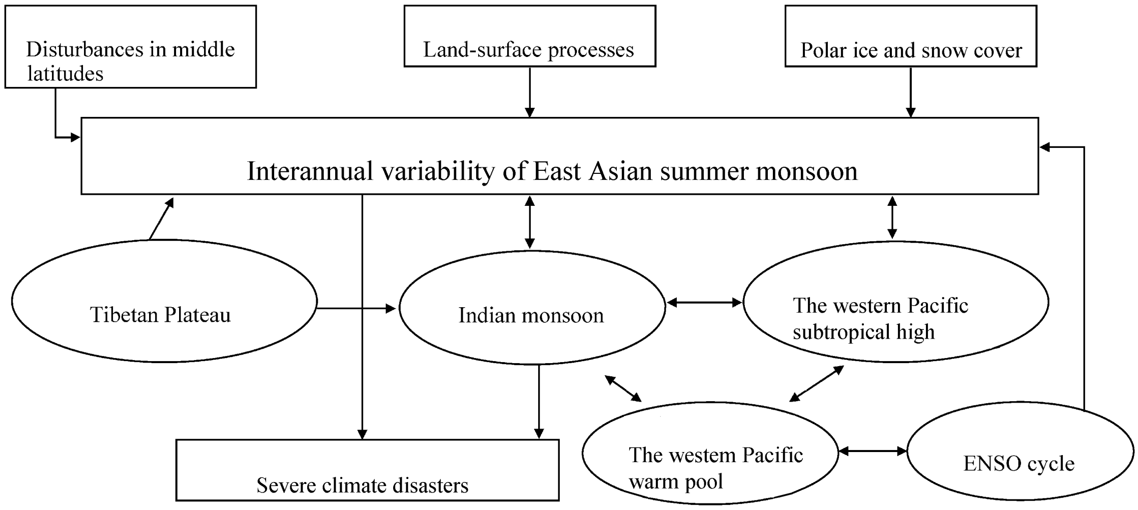

Fig. 12. Schematic map of various components of the EAM climate system.

winds is favorable for the transport of water vapor from the Bay of Bengal and the tropical western Pacific to South China. Thus, during the mature phase of El Niño events, rainfall generally is stronger in South China.

The ENSO cycle also has a significant influence on the annual cycle between the EAWM and the EASM. Chen et al. (2002), and Huang et al. (2004b) proposed that the interannual variations of the EAWM are closely associated with the ENSO cycle. Chen (2002) analyzed the composite distribution of the meridional wind anomalies at 850 hPa for winters preceding El Niño events. He showed that that there are anomalous northerly winds from the coastal area of China to the SCS and, thus, the EAWM is strong. He also pointed out that there is an anomalous cyclonic circulation over the West Pacific and anomalous northeasterly winds over the Yangtze River and Huaihe River valleys and the southeastern coast of China These features indicate a weak western Pacific subtropical high and a weak EASM in a summer when an El Niño is developing. Moreover, following the development stage, an El Niño event generally reaches its maturity, and anomalous southerly winds prevail in the southeastern coast of China and SCS. This points generally to a weak EAWM. In the following summer, the El Niño event may decay, and there is an anomalous anticyclonic circulation over the West Pacific about a strong western Pacific subtropical high. In this case, anomalous southwesterly winds occur over the region from South China to the Yangtze River valley and, therefore, indicate that a strong EASM may appear in when an El Niño event is in its decaying phase.

Since El Niño events can cause severe climate anomalies in many regions of the world, especially in the Asian-Australian monsoon region (e.g., Webster et al., 1998), many meteorologists and oceanographers focus upon studies of the recurrent nature and associated physical mechanisms of the ENSO cycle (e.g., Bjerknes, 1969; Philander, 1981; McCreary, 1983; McCreary and Anderson, 1984; Yamagata and Matsumoto, 1989; Anderson and McCreary, 1985; Cane and Zebiak, 1985; Schopf and Suarez, 1988; Chao and Zhang, 1988; McCreary and Anderson, 1991). Especially because of the interaction between the Asian-Australian monsoon system and ENSO, the relevant physical processes of ENSO cycles are very complex. The tropical western Pacific provides the necessary thermal conditions for ENSO (e.g. Huang and Wu, 1992; Li and Mu, 1999; Li and Mu, 2000; Chao et al., 2002, 2003), and the atmospheric circulation and zonal wind anomalies over this region can provide the necessary dynamical conditions. Li (1988, 1990) pointed out the triggering effect of the anomalous wind fields associated with EAWM on El Niño events. Huang and Fu (1996), Huang et al. (1998c), Huang et al. (2001) analyzed the atmospheric circulation and zonal wind anomalies in the lower troposphere over the tropical western Pacific and their roles in the development and decay processes of El Niño events in the 1980s and 1990s. Figures 16a–d show the distributions of the seasonal-mean circulation anomaly fields at 850 hPa over the tropical western Pacific before the development stage of El Niño evolution. From these figures it can be seen that before the development, there are cyclonic circulation anomalies in the lower troposphere over the tropical western Pacific that were responsible for the westerly wind anomalies over the tropical western Pacific around Indonesia. The westerly wind anomalies in turn were favorable for the formation of the eastward-

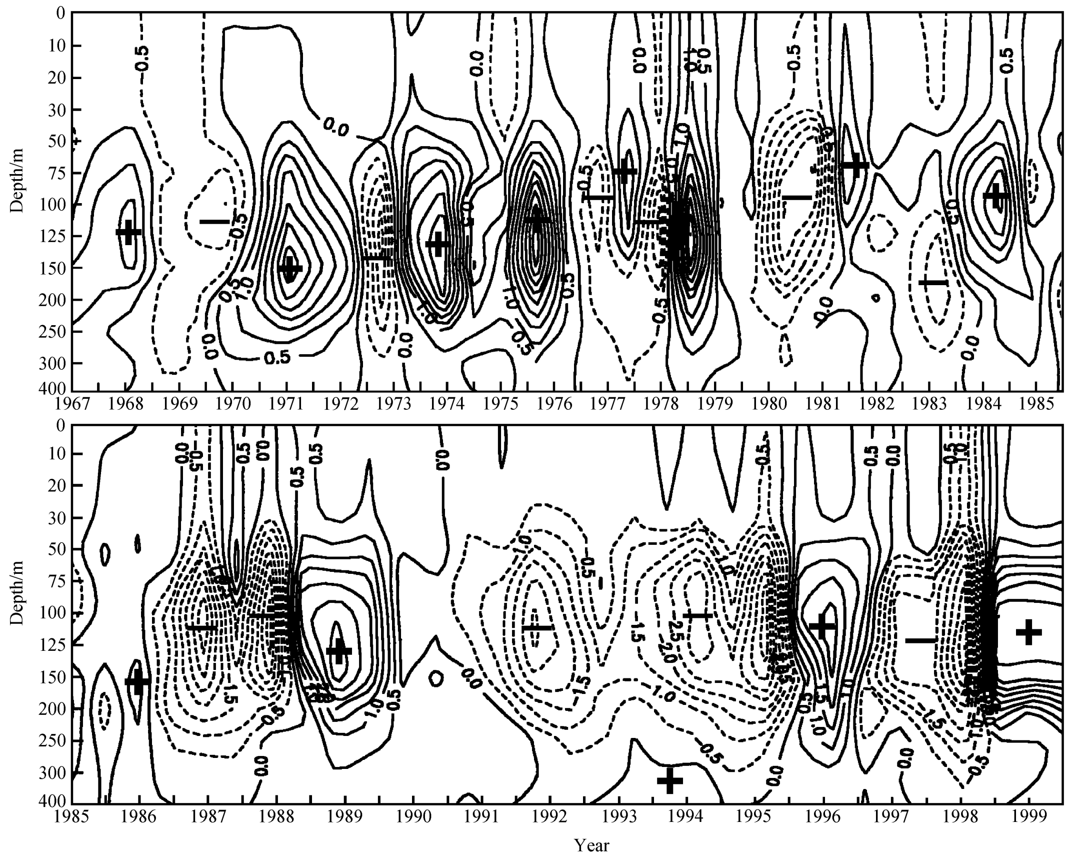

Fig. 13. Time-depth cross section of sea temperature anomalies averaged form 5°N to 10°N along 137°E. Units: °C. Solid and dashed lines indicate positive and negative anomalies, respectively. Data obtained from the Oceanographic Research Vessel "Ryofu-Maru", JMA.

propagating warm Kelvin wave along the equatorial Pacific that gives rise to the El Niño events. Zhang et al. (1996), and Huang et al. (2001) also analyzed the distributions of the seasonal mean circulation anomalies at 850 hPa over the tropical western Pacific for the mature phase of the El Niño events (not shown). The results showed that in the mature phase of El Niño there are also obvious anticyclonic circulation anomalies in the lower troposphere over the tropical western Pacific. These resulted in the easterly wind anomalies over the region from Papua-New Guinea to Sumatra Island along Indonesia conducive to development of an eastward-propagating cold Kelvin wave along the equatorial Pacific that results in the decay and ultimate demise of El Niño events.

Huang et al. (2001), and Huang et al. (2004b) further discussed theoretically the dynamical influence of the westerly wind anomalies over the tropical Pacific on the development and decay of the 1997/98 El Niño event using a simple tropical air-sea coupled model and observed anomalous near sea-surface wind stress of the tropical Pacific during 1997 and 1998. The results identified the triggering effect of zonal wind anomalies over the tropical western Pacific on the equatorial oceanic Kelvin and Rossby waves in the tropical Pacific.

From the above studies it can be seen that the thermal and dynamical influences within and over the tropical western Pacific play an important role in ENSO cycles. Additionally, the coastal boundary of the West Pacific has an important effect on El Niño by reflecting equatorial oceanic Rossby waves, as shown in the theory of the delayed oscillator proposed by Cane and Zebiak (1985), and Schopf and Suarez (1988).

4.3 *Thermal effects of the Tibetan Plateau on the EAM System*

The Tibetan Plateau has important thermal and dynamical effects on the interannual variability of the EASM. Ye and Gao (1979) first described the thermal effect of the Tibetan Plateau on the ASM. Later, many investigators noted that the heating anomaly over the Tibetan Plateau has a large impact on the ASM anomalies (e.g., Nitta, 1983; Luo and Yanai, 1984; Huang, 1984, 1985). Wu and Zhang (1997) explained how the heating over the Tibetan Plateau acts

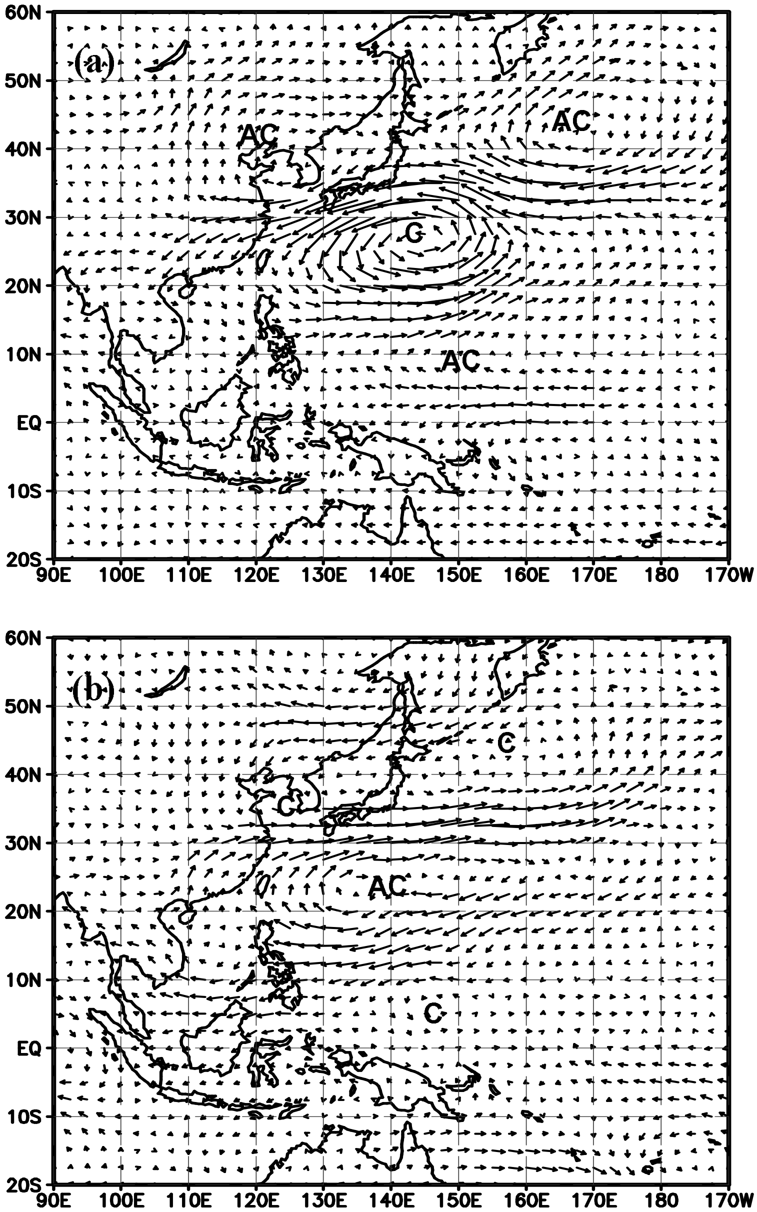

Fig. 14. Composite distributions of water vapor transport anomalies over East Asia and Northeast Asia for summers with (a) warming and (b) cooling of the tropical western Pacific in summer. Units: 10^3 g s^{-1} cm^{-1}. Moisture and wind fields obtained from the ERA-40 reanalysis dataset. (e.g., Uppala et al., 2005)

as an air pump and plays a triggering role in ASM onset. Recently, Zhang et al. (2002) pointed out heating over the Tibetan Plateau has an important effect on the east-west oscillation of the South Asian high, which has a significant influence on the EAM system. Wei and Luo (1996) noted that snow cover significantly influences the heating over the Tibetan Plateau, and there is a large positive correlation between snow cover in the Tibetan Plateau and summer monsoon rainfall in the upper and middle reaches of the Yangtze River.

Recently, Wei et al. (2002, 2003) analyzed the interannual and interdecadal variations of the number of days and depth of snow cover on the Tibetan Plateau based upon the observed daily snow cover at 72 observational stations located in the Tibetan Plateau during 1960–1999. They discovered that there are obvious variations in the number of days and depth of snow cover in the Tibetan Plateau on interannual and inter-

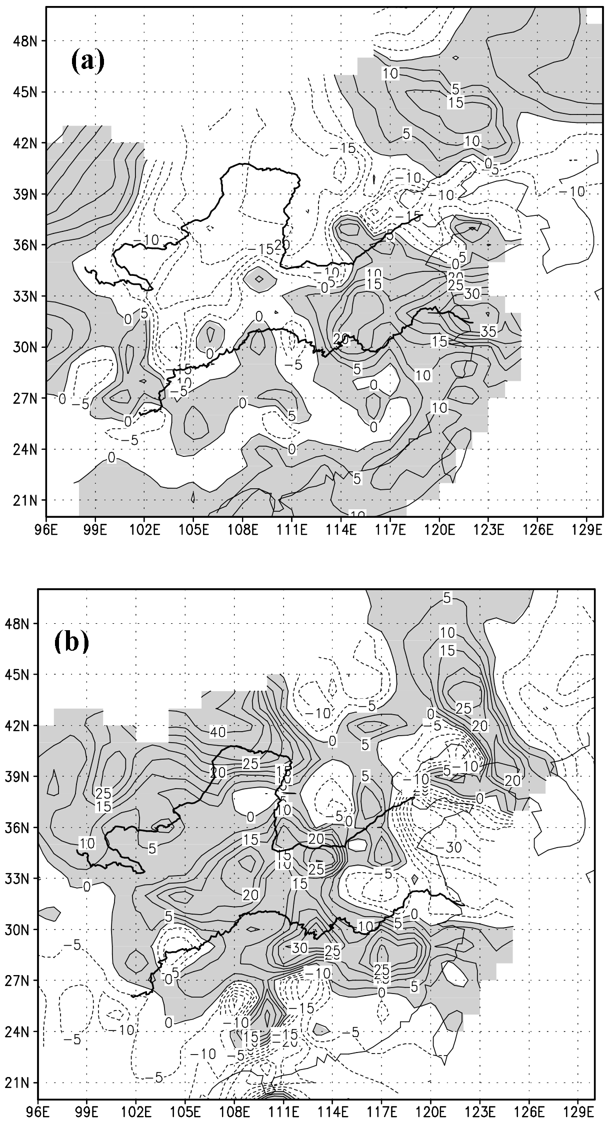

Fig. 15. Composite distributions of summer (June–August) rainfall anomalies (in percentage) in China for (a) the summers in the developing stage and (b) the summers in the decaying stage of El Niño events during the period from 1951 to 2000. Solid and dashed contours indicate positive and negative rainfall anomalies, respectively, and positive values are shaded.

decadal time scales. Moreover, their results showed that there are large positive correlations in the middle and upper reaches of the Yangtze River and negative correlations in South China and Northeast China between the depth of snow cover in the previous winter and spring and the following summer rainfall. This may explain why, if the snowfall in the Tibetan Plateau is heavy in the previous winter and spring of a given year, the following summer rainfall is heavy in the upper and middle reaches of the Yangtze River. For example, in the winter of 1997 and the spring of 1998, the particularly heavy snowfall on the Tibetan Plateau was followed by the severe flood disaster in the Yangtze River valley in the summer of 1998. Also, comparison of the days and depth of snow cover in the Tibetan Plateau during the period from the late 1970s to the late 1990s with those during the period from the early 1960s to the mid-1970s shows clearly that the days with snow cover have increased and the snow depth has become deeper during the former period. The interdecadal variation of snow cover on the Tibetan Plateau has an important impact on the summer monsoon rainfall in the middle and upper reaches of the Yangtze River (e.g., Wei et al., 2002, 2003; Huang et al., 2004a).

Huang and Zhou (2004) investigated the variability of the northerly wind circulation over the west side of the Tibetan Plateau and its impact on the EASM circulation. Their result showed that after 1965, especially from 1977, northerly winds have become weak, the southerly component of the EASM has become weaker, and the water vapor transported into North China was greatly weakened. This resulted in the decrease of summer rainfall and the severe droughts in North China.

4.4 *Thermal effect of sensible heating in the arid and semi-arid regions of Northwest China on the EAM System*

Since monsoon circulations result fundamentally from the land-sea thermal contrast, the variability of the EAM system is influenced not only by the thermal states of the tropical western Pacific, but also by the thermal states of the Eurasian continent. Zhou and Huang (2003, 2006) analyzed the interannual and interdecadal variations of the differences between land surface and the surface air temperatures ($T_s - T_a$) and sensible heating in spring in the arid and semi-arid regions of Northwest China and Central Asia and their impact on summer monsoon rainfall in China. Their results show that the strongest sensible heating in the Eurasian continent is located in Northwest China and Central Asia. Thus, this region may be seen as a “Warm lying surface”. They also pointed out that the $T_s - T_a$ and sensible heating in this region have an obvious interdecadal variability. Before the late 1970s, the sensible heat anomalies in spring were negative, but the anomalies became largely positive in the late 1970s. Moreover, from correlation analyses it is evident that when $T_s - T_a$ or sensible heating anomalies become positive in Northwest China in spring, rainfall can be heavy in the lower reaches of the Yangtze River and light in North China during the following summer. Therefore, the interdecadal variation of the spring sen-

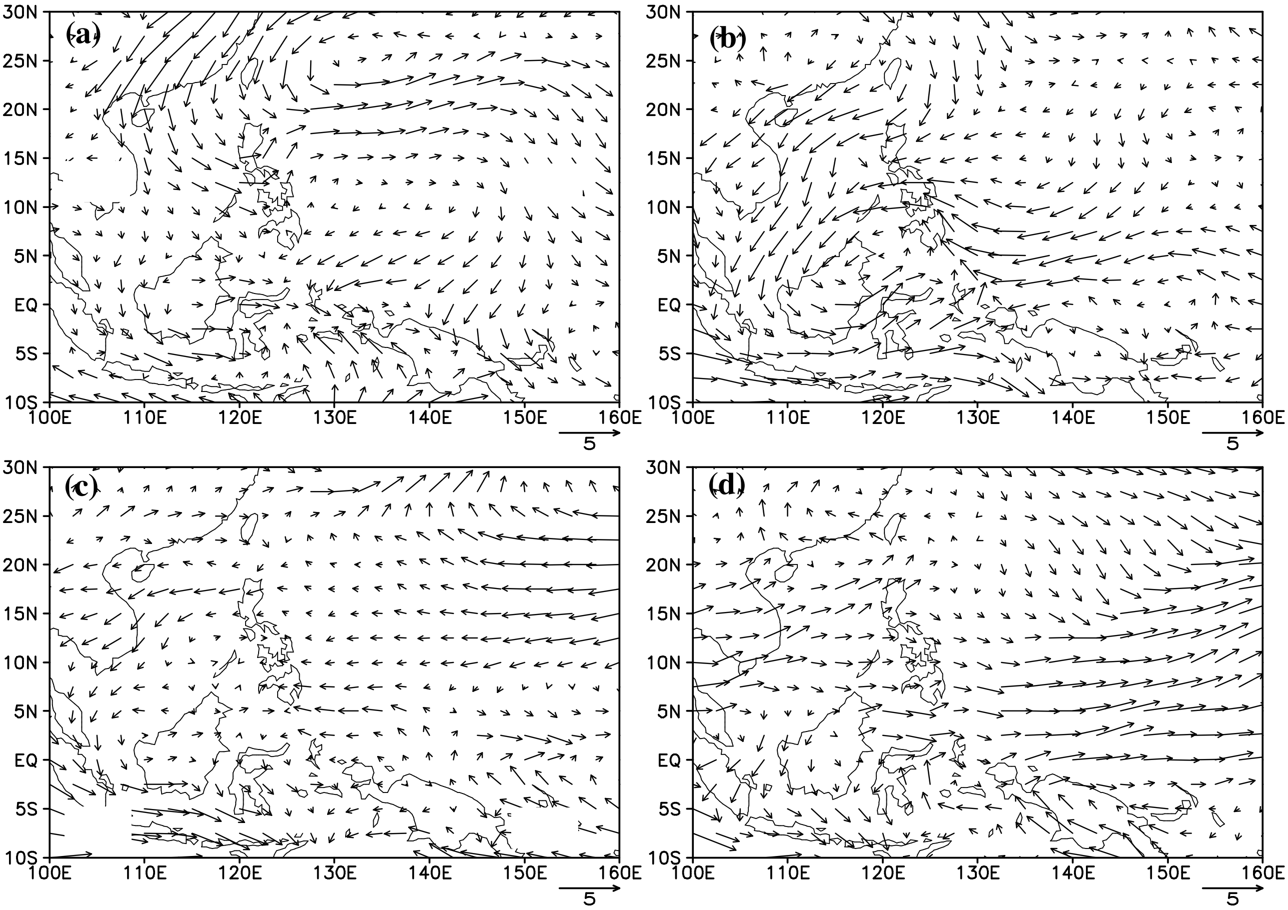

Fig. 16. Distributions of the circulation anomalies at 850 hPa over the tropical western Pacific before the development stage of the El Niño events during the period 1980–1998. Units: m s^{-1}. (a) spring of 1982, (b) winter the 1985, (c) spring of 1991, (d) winter of 1996. Analyses based upon ERA-40 reanalysis data. (e.g., Uppala et al., 2005)

sible heating in Northwest China and Central Asia can be one of the contributors to the interdecadal variability of the EASM that occurred since the late 1970s.

Additionally, the interdecadal cooling at the upper troposphere over the Mongolian Plateau, North China and Northwest China from the late 1970s have an impact on the weakening trend of the summer monsoon over East Asia (e.g., Yu et al., 2004), but the physical mechanism of this impact needs further study.

5. Climate background of the occurrence of climate disasters in China

Due to the severity of climate disasters in China, the causes of floods in the Yangtze River valley and the persistent droughts in North China from the late 1970s have been studied from the perspective of the interannual and interdecadal variabilities of the EAM climate system.

5.1 *Climate background of the severe floods in the Yangtze River and Huaihe River valleys*

The causes of severe floods in the Yangtze River valley, especially the particularly severe flood in the summer of 1998, as shown in Fig. 17, have been systematically studied from the perspective of interannual variabilities in the anomalies associated with the atmosphere, ocean and land surface components of the EAM climate system (Fig. 12) (e.g., Huang et al., 1998a; e.g., Huang and Zhou, 2002: Huang et al., 2003). Furthermore, the influence of the variability of the EAM climate system on severe flooding disasters in China has been analyzed by assessing the processes associated with the severe flood event in the Yangtze River valley during the summer of 1998 (e.g., Huang et al., 2003, 2004a). The configuration of anomalies associated with various component of the EAM climate system causing the severe floods in the Yangtze River

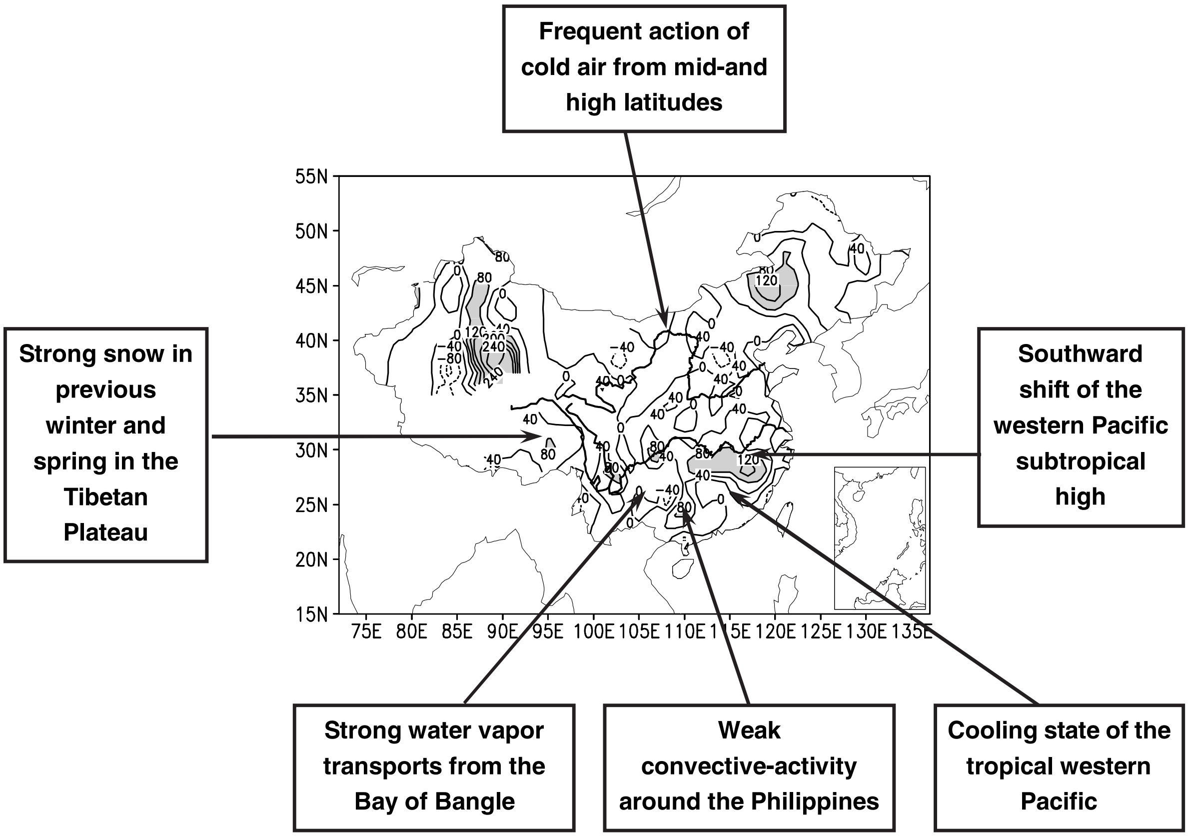

Fig. 17. Schematic diagram of various component anomalies of the EAM climate system associated with the occurrence of severe floods in the Yangtze River and Huaihe River valleys. The distribution of precipitation anomaly percentages shown is for the summer of 1998. Precipitation anomaly percentages over 80% are shaded.

and Huaihe River valleys are summarized in Fig. 17. As shown in Fig. 17, when the tropical western Pacific is cooling, the convection around the Philippines is weak and the western Pacific subtropical high shifts anomalously westward and southward. These conditions are favorable for lengthening the period over. which the summer monsoon rain belt remains over the Yangtze River valley. Also, if the number of days and depth of snow cover on the Tibetan Plateau is anomalously large during the winter and spring, conditions are favorable in the following summer for maintenance of the summer monsoon rain belt, and hence heavy rainfall in the upper and middle reaches of the Yangtze River. In addition, when a low-level trough is located over Inner-Mongolia and Northeast China, cold air can be continuously transported from the trough region to the Yangtze River valley, which is necessary for the maintenance of the mei-yu front over the Yangtze River and Huaihe River valleys. The strong northeastward propagating 30–60 day oscillation from the Bay of Bengal to the Yangtze River valley is also an important factor for severe flooding in the Yangtze and Huaihe River valleys, because it can bring large amounts of water vapor from the Bay of Bengal and the SCS into these valleys. In the summer of 1998, as shown in Fig. 17, large anomalies appeared in all the components of the EAM climate system resulting in the particularly severe flooding and huge economic losses to China.

5.2 *Climate background of the persistent droughts in North China*

Similarly, the occurring causes of the persistent droughts in North China from the late 1970s have been systematically investigated in terms of the interdecadal variability and anomalies of the various components of the EAM climate system (e.g., Huang et al., 1999b; Huang et al., 2001; Huang and Zhou, 2002; Huang, 2004; Huang et al., 2004a; Huang, 2006; Huang et al., 2006c). The seasonal droughts in summer are emphasized in this paper. Their results clearly show that the interdecadal anomalies of circulation over the tropical western Pacific, which have a large impact on the EASM and the summer monsoon rainfall in China, especially in North China, were influenced by the interdecadal variability of the tropical eastern Pacific SSTs.

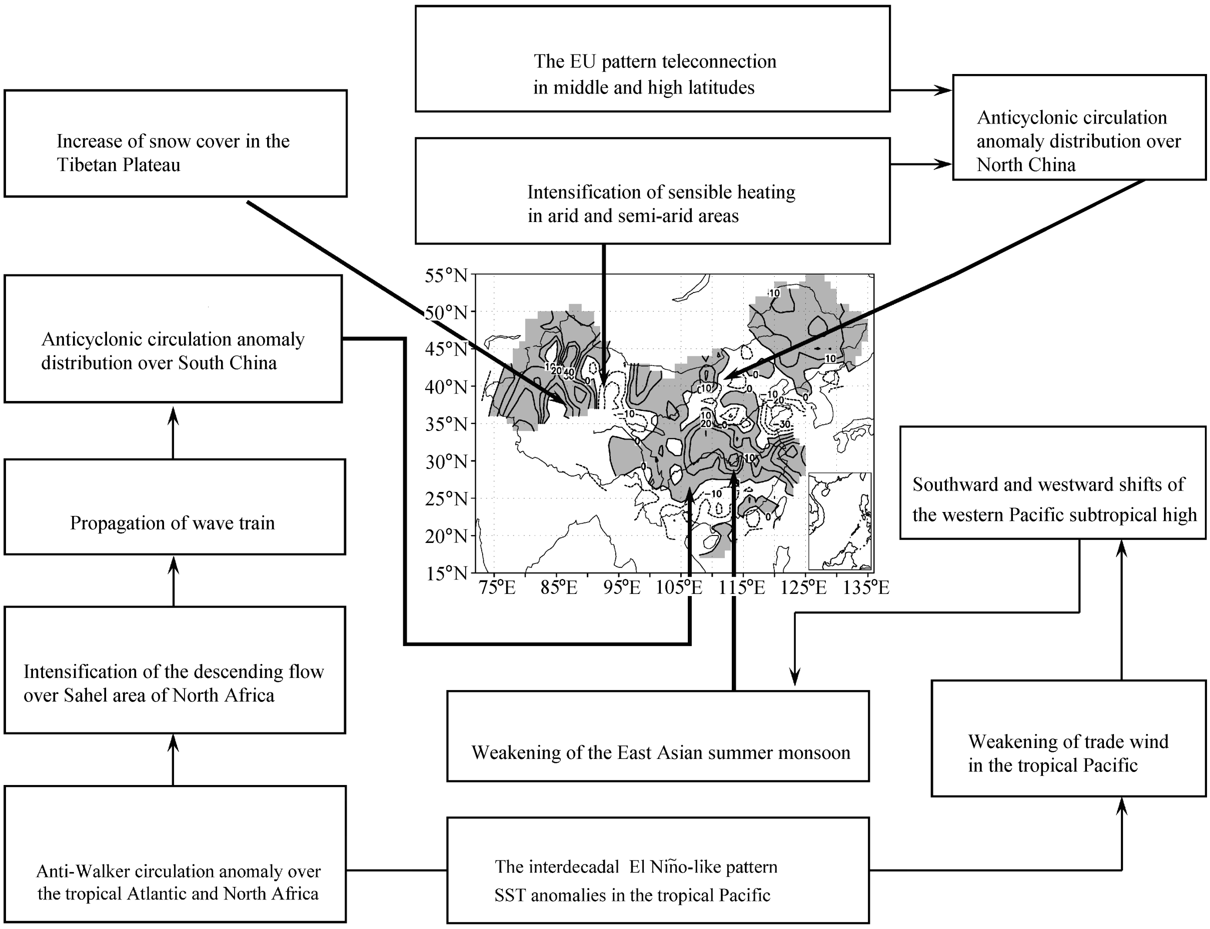

Fig. 18. Schematic diagram of the climate background causing the persistent droughts in North China. The summer precipitation anomaly percentages in China are the difference between summer rainfall anomalies averaged over 1977–2000 and 1966–1976 at 160 observational stations in China. Areas of positive values are shaded.

Due to the obvious warming of the tropical eastern and central Pacific from the late 1970s, the Walker circulation became weak over the tropical Pacific, which caused weakening of the trade winds over the tropical western Pacific and the EASM. The weakening of the EASM led to the persistent droughts in North China from the late 1970s.

On the other hand, the warming of the tropical eastern and central Pacific from the late 1970s also caused the Walker circulation anomaly over the tropical Atlantic and North Africa (e.g., Huang et al., 2006c). Anomalous ascent and descent were clearly located over the tropical eastern Pacific and North Africa, respectively. The intensification of the anomalous descent over the Sahelian region of North Africa led to a strong anticyclonic anomaly over this region from the late 1970s. Moreover, their results showed that there appears to be a teleconnection pattern of circulation anomalies from the Sahelian region of North Africa to South China near the Arabian Peninsula. This results from propagation of an atmospheric Rossby wave-train and the fact that circulation anomalies over South China can be associated with those over North China in the context of the EAP pattern teleconnection. Because this anticyclonic anomaly over North China suppresses the northward progression of southerly winds to North China, only light monsoon rainfall occurs in this region. As shown by Rodwell and Hoskins (1996), diabatic descent of the Asian summer monsoon can have a significant effect on the circulation anomalies over the desert regions of North Africa, again through propagation of a Rossby wave-train. However, as shown by the study of Huang et al. (2006c), variability in the circulation over the desert regions of North Africa can influence the ASM variability on the interdecadal time-scale.

In addition the interdecadal variation of land surface processes have an impact on ASM variability on the interdecadal time scale. The results analyzed by Wei et al. (2002, 2003) have indicated that the num-

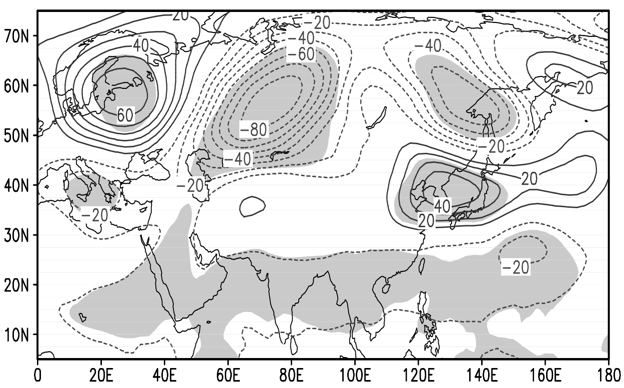

Fig. 19. Distribution of 500-hPa height anomalies regressed by the time coefficients of EOF1. Solid and dashed contours indicate positive and negative height anomalies, respectively. Contour interval is 20 m. Areas of confidence level over 95% are shaded. Analysis based on ERA-40 reanalysis data (e.g., Uppala et al., 2005)

ber of days and thickness of winter and spring snow cover on the Tibetan Plateau increased from the late 1970s. And the $T_{\rm s}-T_{\rm a}$ and sensible heating in spring became large in the arid and semi-arid areas of Northwest China from the late 1970s (e.g., Zhou and Huang, 2003, 2006). These factors are conducive to increasing the summer monsoon rainfall in the Yangtze River and the Huaihe River valleys and the decreasing summer rainfall in North China.

From the above-mentioned studies, the climate background of the persistent droughts in North China associated with the interdecadal variations of various components of the EAM climate system may be summarized as shown in Fig. 18.

6. Dynamic processes in the EAM climate system

As shown in section 5, the occurrence of climate disasters in China are closely associated not only with the variability and anomalies of ocean and land, but also with internal dynamical processes in the EAM climate system. Because of these dynamical processes, there are close relationships amongst the variabilities of various components of this system. Therefore, it is necessary to assess how the EAM climate system influences the occurrence of climate disasters in China.

6.1 *The East Asia/Pacific (EAP) pattern teleconnection*

As described in sections 2 and 3, there is an obvious tripole pattern either in the distributions of summer monsoon rainfall anomalies in China and summer water vapor transports over East Asia or in the distributions of summer monsoon circulation anomalies over East Asia. As a result, the distributions of droughts and floods in China are closely associated with this meridional tripole pattern. Huang et al. (2004a), and Huang et al. (2006b) 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. From analyses of observational data, dynamic theory and numerical simulations, they noted that the distribution of atmospheric circulation anomalies with the meridional tripole pattern over East Asia and the West Pacific in summer can be due to the thermal anomalies of the tropical western Pacific or anomalies in convective activity around the Philippines via propagation of a Rossby wave-train. Of course, as shown in Fig. 19, this meridional tripole pattern of circulation anomalies is also associated with the EU pattern teleconnection proposed by Wallace and Gutzler (1981).

Lu and Huang (1996a,b, 1998) investigated the variability of a blocking high over Northeast Asia and its impact on summer monsoon rainfall in the Yangtze River and Huaihe River valleys. They pointed out that there is a good relationship between variations in the blocking high, especially over the Sea of Okhotzk, and summer monsoon rainfall variability in the Yangtze River and Huaihe River valleys. Also, they proposed that this relationship is related to the EAP teleconnection of circulation anomalies over the Northern Hemisphere. When the tropical western Pacific is cooling in summer, the convective activity is weakened around the Philippines and the western Pacific subtropical high shifts southward and westward. In establishing the EAP pattern teleconnection via Rossby wave-train propagation, an anticyclonic anomalous circulation appears over Northeast Asia, and the blocking high is maintained over Northeast Asia for a lengthy period of time. In this case, the mei-yu front is also maintained in the Yangtze River and the Huaihe River valleys for a longer period of time, resulting in severe flooding in these regions.

6.2 *The North Africa/East Asia teleconnection of meridional circulation anomalies in the upper troposphere*

Yang et al. (2002) analyzed the association of Asian-Pacific-American winter climate with the East Asian jet stream (EAJS) on interannual time scales. 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 the boreal winter. Moreover, Lu et al. (2002b), and Lin and Lu (2005) analyzed the variability of meridional circulation anomalies for the boreal summers of 1986–2000 using the HadAM3 data from the Hadley Center. Their results showed that there is an obvious teleconnection pattern in the meridional circulation anomalies in the upper troposphere over the regions from North Africa to East Asia. They also pointed out that this teleconnection may be due to the eastward propagation of a Rossby wave-train along the westerly jet stream at 200 hPa (e.g., Lu and Kim, 2004). Recently, Tao and Wei (2006) demonstrated from the analysis of isentropic potential vorticity that the northward advance (southward retreat) of the western Pacific subtropical high may reflect formation of a ridge (trough) along the eastern coast of China associated with the propagation of a Rossby wave-train along the Asian jet in the upper troposphere. From an 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) showed that the meridional tripole structure of summertime monsoon rainfall anomalies over East Asia is related to the propagation of a Rossby wave-train along the Asian jet in the upper troposphere, in addition to the EAP pattern teleconnection over East Asia and the western North Pacific. Thus, the abovementioned meridional tripole structure of circulation anomalies over East Asia may be also associated with the teleconnection pattern along the Asian jet in the upper troposphere.

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

Huang and Gambo (1982, 1983a,b), and Huang (1984) 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. The study utilized a 34-level model in addition to theoretical consideration based upon the refractive index square and E-P wave fluxes. They pointed out that there are two wave guides in the three-dimensional propagation of quasi-stationary planetary waves. One is the so-called polar waveguide, by which quasi-stationary planetary waves can propagate from the troposphere to the stratosphere at high latitudes. The other is the so-called low-latitude waveguide in which waves can propagate from the lower troposphere over mid- and low latitudes to the upper troposphere over low latitudes. Based on these studies of Chen et al. (2002, 2003, 2005), Chen and Huang (2005) recently examined the interannual variation of propagating wave guides for quasi-stationary waves with E-P wave fluxes using NCEP/NCAR and ERA-40 reanalysis data and an AGCM simulation. Their results showed that these two wave guides for quasi-stationary planetary waves evidently have an interannual oscillation. When the polar wave guide is strong (weak) in winter, the low-latitude wave guide may be weak (strong). Moreover, it was also found that due to wave-flow interaction, the interannual oscillation of these two wave guides has a significant influence on the Arctic Oscillation (AO), which is closely related to the EAWM (e.g., Gong et al., 2001; Gong and Ho, 2003) through NAM proposed by Thompson and Wallace (1998, 2000). When the equatorward propagation of quasi-stationary planetary waves from the lower troposphere over middle latitudes toward the upper troposphere over low latitudes is strong during a winter, the upward propagation of quasi-stationary planetary waves from the troposphere into the stratosphere becomes weak in winter. This can lead to the weakening of the East Asian westerly jet stream because of the convergence of wave activity fluxes for quasi-stationary planetary waves over this region. Thus, the East Asian trough, the Siberian high and the Aleutian low can become weak during winter, which can decrease the northwesterly winds over East Asia and, therefore warming in winter over East Asia.

Recently, Huang and Wang (2006) also investigated the interdecadal variation of quasi-stationary planetary waves and its impact on the EAWM. Their results showed that an obvious interdecadal variability of the EAWM has occurred in East Asia and the EAWM became weak beginning in the late 1980s to late 1990s. As shown by Gong et al. (2001), the weakening of the EAWM may be affected by the AO. Moreover, Huang and Wang (2006) pointed out that there was an obvious interdecadal variation of planetary wave activity in the late 1980s. As shown in Figs. 20b and 20c, the low-latitude wave guide for quasi-stationary planetary waves intensified beginning in 1987, which resulted in intensification of E-P flux convergence of quasi-stationary planetary waves in the upper troposphere over low latitudes. Their result also showed that the intensification of quasi-stationary wave propagation from mid- and high latitudes to low latitudes led to deceleration of zonal-mean zonal winds in the upper troposphere over the latitudes around 35°N. This caused the intensification of the AO, the weakening of EAWM and the prolonged warm winters in China from 1987. Thus, the interdecadal variation of planetary wave activity from the late 1980s to the late 1990s has had an important impact on the interdecadal variation of EAWM.

The interdecadal variation of the AO also has a large impact on the spring climate over the Eurasian continent, especially over East Asia. Yu and Zhou (2004) pointed out that the unique cooling over the

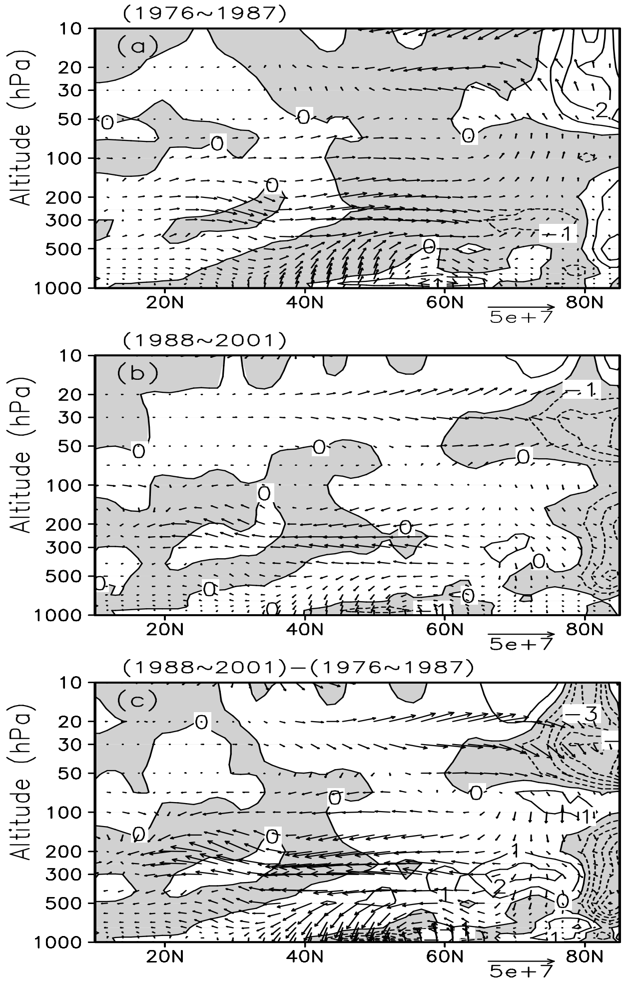

Fig. 20. Composite anomaly distributions of the E-P fluxes ($\times\rho^{-1}$) and their divergence (Units: m s^{-1} d^{-1}) for the quasi-stationary planetary waves 1–3 averaged for (a) the Northern Hemisphere winters of 1976–1987, for (b) the winters of 1988–2001, and (c) difference between them. Normals are the climatological mean E-P fluxes for 30 winters from 1971 to 2000. Solid and dashed contours indicate positive and negative anomalies of the divergence of E-P fluxes respectively. Areas of negative anomalies are shaded. Analyses are derived from the ERA-40 reanalysis data (e.g., Uppala et al., 2005)

subtropical Eurasian continent in spring over the last half century may be related to the interdecadal variation of the NAO. Li et al. (2005) also pointed out that the March–April cooling shift on the lee side of the Tibetan Plateau may not be a local phenomenon. Instead, it is associated with an eastward extension of the cooling signal originating from North Africa, which is related to the NAO of the previous winter. Moreover, Xin et al. (2006) revealed that precipitation in late spring in South China experienced a significant decrease from the late 1970s, and pointed out that this decrease may be associated with the spring cooling in the upper troposphere over Central China, which is strongly related to the NAO during the previous winter.

7. Conclusions and remarks for future studies

From the above review, it can be seen that there have been significant advances in the describing the basic characteristics and properties of the EAM system and the spatial and the temporal variabilities which are closely associated with the occurrence of climate disasters in China. The basic physical processes underlying these variabilities, both internal and external, have also been studied. The advances are summarized as follows:

(1) The EAM system is a relatively independent monsoon subsystem of the Asian-Australian monsoon system. Both the horizontal and vertical structure of wind fields and water vapor transports and the annual cycle of this system differ from the SAM and the NAM systems.

(2) The EAM system has significant interannual and interdecadal variabilities. The interannual variability of this system exhibits an obvious quasi-biennial oscillation, i.e., the TBO, with a meridional tripole pattern in spatial distribution, which can cause a tripole pattern in the spatial distribution of drought and flood disasters in East Asia .

(3) The EAM system variabilities are closely associated with coupling of atmosphere, ocean, and land processes and, hence, the EAM can be referred to as the EAM climate system. The EAM climate system then is a system that includes various components of atmosphere, ocean and land surface processes that influence variability of the EAM.

(4) The occurrence of climate disasters in China is closely associated with the variability and anomalies of various components of the EAM climate system. The climate backgrounds of occurrences of severe floods in the Yangtze River and the Huaihe River valleys and the prolonged droughts in North China from the late 1970s have been tied preliminarily to the interannual and interdecadal variations of the EAM climate system, respectively, and these results have been now applied to the seasonal and annual predictions of climate anomalies in China.

(5) The EAP teleconnection pattern of summertime circulation anomalies and the teleconnection of meridional wind anomalies along the westerly jet stream in the upper troposphere over East Asia can explain well the physical mechanism for the meridional tripole pattern in spatial distributions of the summer

monsoon rainfall, water vapor transports and monsoon circulation anomalies over East Asia.

Nevertheless, many problems on the basic physical-processes of the EAM climate system variability and their impacts on climate disasters in China still remain unclear:

(1) The EAM system is largely independent in its horizontal and vertical wind field structures relative to the SAM and NAM systems. These differences are significant in the annual cycle, monsoon onset, active phase and break periods. However, these monsoon systems are interactively to each other. The associations among the onset, active, break, and annual cycle processes of these monsoon systems requires further study.

(2) Many investigations have shown that the interdecadal variability of the EAM system has a significant impact on its interannual variability, which in turn influences its intraseasonal variations. However, the physical processes involved in the interactions amongst different time-scale features of this system are not yet clear and, thus, important issues for future investigation.

(3) There are complex dynamic and thermal processes in the interannual variability of the EAM climate system. These processes strongly influence the EAM variabilities. The dynamic processes of the quasi-biennial oscillation, i.e., the TBO, with the meridional tripole pattern distribution and the thermal effect of tropical heating on the TBO have been emphasized in recent studies. However, as shown by Yang et al. (2004), extratropical processes also have an important effect on the EAM. Therefore, the effect of extratropical process in the EAM climate system on the EAM variabilities should be considered in future study.

(4) The EAM system has a large interdecadal variability. However, the physical processes of this variability, for example, the dipole pattern distribution of this system, are not yet clear, and studies on this problem to date are not sufficient. These issues here need further study with focus on interactions between various components of the EAM climate system on an interdecadal time-scale.

The above review shows that the EAM system variabilities on interannual and interdecadal time scales and their physical mechanisms remain important research issues for future study. If the physical processes of these variabilities are not revealed further, improvements in seasonal and annual predication of climate disasters in China may be difficult. Therefore, understanding of the internal and external dynamic processes affecting the interannual and interdecadal variabilities of the EAM system remains a main objective of future investigation. We believe that through implementation of some National Research Programs, it is possible to further understand the physical mechanisms of the interannual and interdecadal variabilities of the EAM system.

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