ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 24, NO. 6, 2007, 972–992

A Review of Recent Advances in Research on Asian Monsoon in China

HE Jinhai[1] (何金海), JU Jianhua*[2] (琚建华), WEN Zhiping[3] (温之平),
LÜ Junmei[4] (吕俊梅), and JIN Qihua[1,4] (金啟华)

[1] *College of Atmospheric Sciences, Nanjing University of Information Science & Technology, Nanjing* 210044

[2] *China Meteorological Administration Training Centre, Beijing* 100081

[3] *Department of Atmospheric Science, Sun Yat-Sen University, Guangzhou* 510275

[4] *Chinese Academy of Meteorological Sciences, Beijing* 100081

(Received 30 January 2007; revised 8 June 2007)

ABSTRACT

This paper reviews briefly advances in recent research on monsoon by Chinese scholars, including primarily: (1) the establishment of various monsoon indices. In particular, the standardized dynamic seasonal variability index of the monsoon can delimit the geographical distribution of global monsoon systems and determine quantitatively the date of abrupt change in circulation. (2) The provision of three driving forces for the generation of monsoon. (3) The revelation of the heating-pump action of the Tibetan Plateau, which strengthens southerlies in the southern and southeastern periphery of the Plateau and results in a strong rainfall center from the northern Bay of Bengal (BOB) to the Plateau itself. (4) Clarification of the initial onset of the Asian Summer Monsoon (ASM) in the BOB east of 90°E, Indochina Peninsula (ICP) and the South China Sea, of which the rapid northward progression of tropical convection in the Sumatra and the rapid westward movement of the South Asia High to the Indochina Peninsula are the earliest signs. (5) The provision of an integrated mechanism for the onset of the East Asian Summer Monsoon (EASM), which emphasizes the integrated impact of sensible heat over Indian Peninsula, the warm advection of the Tibetan Plateau and the sensible heat and latent heat over the Indochina Peninsula on the one hand, and the seasonal phase-lock effect of the northward propagation of low frequency oscillation on the other. (6) The revelation of the "planetary-scale moisture transport large-value band" from the Southern Hemisphere through to the Asian monsoon region and into the North Pacific, which is converged by several large-scale moisture transport belts in the Asian-Australian monsoon regions and whose variation influences directly the temporal and spatial distribution of summer rainfall in China. (7) Presenting the features of the seasonal advance of the EASM, the propagation of intraseasonal oscillation, and their relationship with rainfall in China; indicating that the intraseasonal oscillation of the EASM propagates in the form of a wave-train along the coast and behaves as monsoon surge propagating northward. (8) Describing the interannual and interdecadal variation of Asian monsoon, revealing the factors affecting it, and possible mechanisms of the variation of Asian monsoon. An elementary outlook on the existing problems and future direction of monsoon research is also provided.

Key words: recent research, monsoon, China, review, advances, existing problems, prospects

DOI: 10.1007/s00376-007-0972-2

1. Introduction

Monsoon is an important component of the global climate system, whose variation plays a critical role in weather and climate in the monsoon regions. China is located in the East Asian monsoon region, and therefore research on monsoon has always been high on the agenda of Chinese meteorologists. Research on monsoon in China has a history of nearly 80 years, and many achievements have been made by Chinese me-

*Corresponding author: JU Jianhua, jujh@cma.gov.cn

teorologists in research on the East Asian Monsoon, producing significant influences in China and abroad. As early as the 1930s, Zhu (1934) studied the advancement and withdrawal of summer monsoon and its relationship with rainfall in China. Following this, Tu et al. (1944) explored the advancement and withdrawal of East Asian monsoon and its impact upon the intraseasonal variation of climate in China. Ye et al. (1959) investigated the seasonal transition of the atmospheric circulation over the Northern Hemisphere. Later, Chen et al. (1991) and Ding (1994) proposed the structure and seasonal variation of the East Asian Summer Monsoon (EASM). Recently, Chinese meteorologists have made important progress in research on the forming mechanisms, onset characteristics, and the multi-scale variability of Asian monsoon. This paper comments briefly on recent advances in related research.

2. Description of monsoon and monsoon indices

The monsoon index is a critical parameter for quantitatively describing and studying monsoon. In order to reflect the essence of monsoon, investigators put forward various monsoon indices.

In order to define the East Asian Winter Monsoon (EAWM) index, some factors—for example, differential heating between land and sea, meridional wind regionally averaged over East Asia, and zonal horizontal wind shear—have been considered in previous research (Chen et al., 2000; Wu and Wang, 2002; Yang et al., 2002; Jhun and Lee, 2004). It is well known that meridional wind is a crucial aspect of the EAWM. However, zonal wind also plays an important role, as strong zonal winds over mid and high latitudes can obstruct cold air outbreaks southward. Considering two-dimensional wind vectors, two distinct modes of the EAWM have been identified (Wu et al., 2006c), resulting in a complete understanding of the EAWM.

Based on the contrary trend between the intensity of the tropical monsoon trough and that of the meiyu Front and the variation of their wind anomalies, Zhang et al. (2003) defined an EASM index as the difference of the zonal wind anomaly at 850 hPa between the tropical area (10°–20°N, 100°–150°E) and the subtropical area (25°–35°N, 100°–150°E) in East Asia. This had synoptic meaning, was easy to calculate, and reflected well the interannual variation of the wind and rainfall in East Asia. Utilizing the method of combining dynamic and thermodynamic factors, Ju et al. (2005a) dealt with the southwesterlies and outgoing longwave radiation (OLR) in the East Asian monsoon region to build synthetically an EASM index which could reflect appropriately not only the interannual variation of the East Asian Subtropical Monsoon, but also the essence of the monsoon system. He et al. (2003) set up a new monsoon index by combining the zonal wind shear between the upper and lower levels with the geopotential height at 850 hPa. They investigated the relationship between temperature in the troposphere and the Asian Summer Monsoon (ASM) and found that the reverse of the meridional temperature gradient in the upper level is generally earlier than or synchronous with the onset of summer monsoon in both the East Asian and Indian monsoon regions.

Li and Zeng (2005) presented a standardized dynamic seasonal variability index which can not only describe the seasonal variation and interannual variation in various monsoon regions, as well as their relationship with precipitation, but also outline the distribution of the global monsoon system (Fig. 1). Therefore, this index was named the "unified monsoon index" (Li and Zeng, 2003a,b) and represents significant progress in the study of monsoon indices.

Zeng et al. (2005) and Zhang et al. (2005) adopted the "normalized finite temporal variation" method to determine quantitatively the critical day of abrupt transition in atmospheric circulation, which is just 2–4 days earlier than the so-called "onset date" of monsoon, i.e. the "presage date" of monsoon onset. Whether in the tropical or subtropical monsoon region, the seasonal adjustment and transition of atmospheric circulation have already finished in the stratosphere before summer monsoon breaks out in the lower level. It then extends suddenly downward to the troposphere to trigger the onset of monsoon in the lower level, which indicates that the seasonal transition of the atmospheric circulation from winter to summer commences initially in the Southern Hemisphere and in the stratosphere.

There are three aspects in the research of monsoon indices so far: (1) the intensity of monsoon as described by winds (zonal or meridional), divergence, vorticity or moisture transport averaged over an area, which derives directly from the monsoon circulation itself; (2) the strength of monsoon as depicted by the combination of circulation and rainfall or convective parameters (e.g., OLR) averaged over an area; and (3) the EASM index defined using the meridional land-sea thermal contrast, the zonal land-sea thermal contrast, or both. Whichever index is employed, it is appropriate as long as it distinguishes floods from droughts and relates significantly to the circulation or parameters of the circulation systems (e.g., the position and area of the subtropical high), and also if the relation can be maintained as the database of observations is prolonged. If such an index can reflect the date of

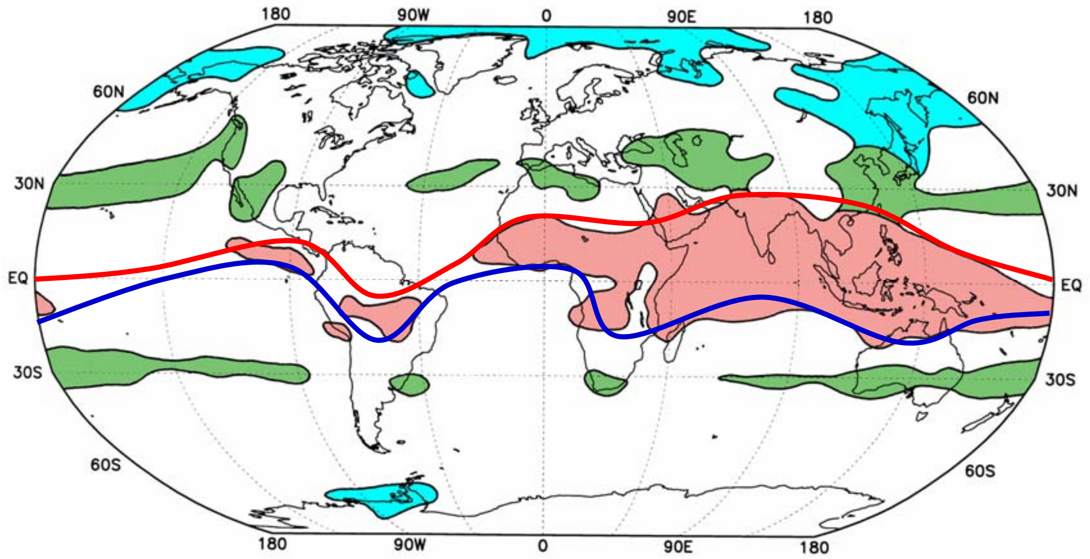

Fig. 1. Distribution of global surface monsoon. Red, green, and blue areas represent the tropical monsoon region, subtropical monsoon region, and extratropical monsoon region, respectively. The red and blue bold solid lines show the positions of the ITCZ in summer and winter respectively (Li and Zeng, 2005).

abrupt seasonal transition of circulation as well, it can be used to determine the onset date of monsoon. Monsoon indices are generalized in a booklet by the research group of the South China Sea Monsoon Experiment (SCSMEX) (He et al., 2001).

3. Mechanisms in forming monsoon

The fundamental mechanism for the formation of monsoon is generally considered to be land-sea thermal contrast. In the meantime, the formation of monsoon is associated with seasonal differences in solar radiation between the Northern and Southern Hemispheres. However, if the surface is covered entirely by oceans, monsoon would maybe still exist. In such an ocean model, the sea surface temperature (SST) may play an important role in the onset and existence of monsoon. When the forcing of seasonal variation in SST was introduced, numerical experiments simulated not only the vivid monsoon circulation, but also the abrupt outbreak and active-break features (Yano and McBride, 1998). Monsoon is probably the outcome of the seasonal movement of the ITCZ (Chao, 2000; Chao and Chen, 2001). The land-sea thermal contrast, like the difference in SST, determines the meridional position of the ITCZ band, but orographic change has more influence on monsoon than land-sea thermal contrast.

The formation of monsoon results from the cooperation between various driving forces. Zeng and Li (2002) suggested two driving forces for monsoon generation: (1) planetary thermal convective circulation (induced by seasonal differences in solar radiation between the Northern and Southern Hemispheres); and (2) the quasi-stationary planetary wave induced by differences in surface characteristics (including land-sea thermal contrast, orographic height etc.). He et al. (2004a,b) considered moist processes as a third driving force of monsoon. The phase-change of moisture in the air and its transporting process can store and redistribute solar energy in the tropics and subtropics, release the energy selectively, and determine the intensity and location of monsoon circulation and rainfall.

Research on the role of the Tibetan Plateau in the ASM has achieved new progress recently. Numerical experiments have shown that in "no-orography experiments" (Fig. 2), monsoon appears in Africa, South Asia and East Asia, and the rough distribution of monsoon regions is similar to the actual situation, indicating that the distribution of land and sea is primary in the formation of Asian monsoon. After introducing an ideal plateau in the experiment, northerlies occur round the west side of the plateau in the lower troposphere, and monsoon on the southwest side of the plateau withdraws southward; thus, the monsoon rainfall in Africa to the west of the plateau is separated from that in Asia. The heating-pump action of the plateau strengthens the southerlies in the southern and southeastern periphery and results in a strong rainfall center from the northern Bay of Bengal (BOB) to the south of the plateau. Seen from the difference of two experiments, the low-level cyclonic circulation triggered by the plateau in summer strengthens signif-

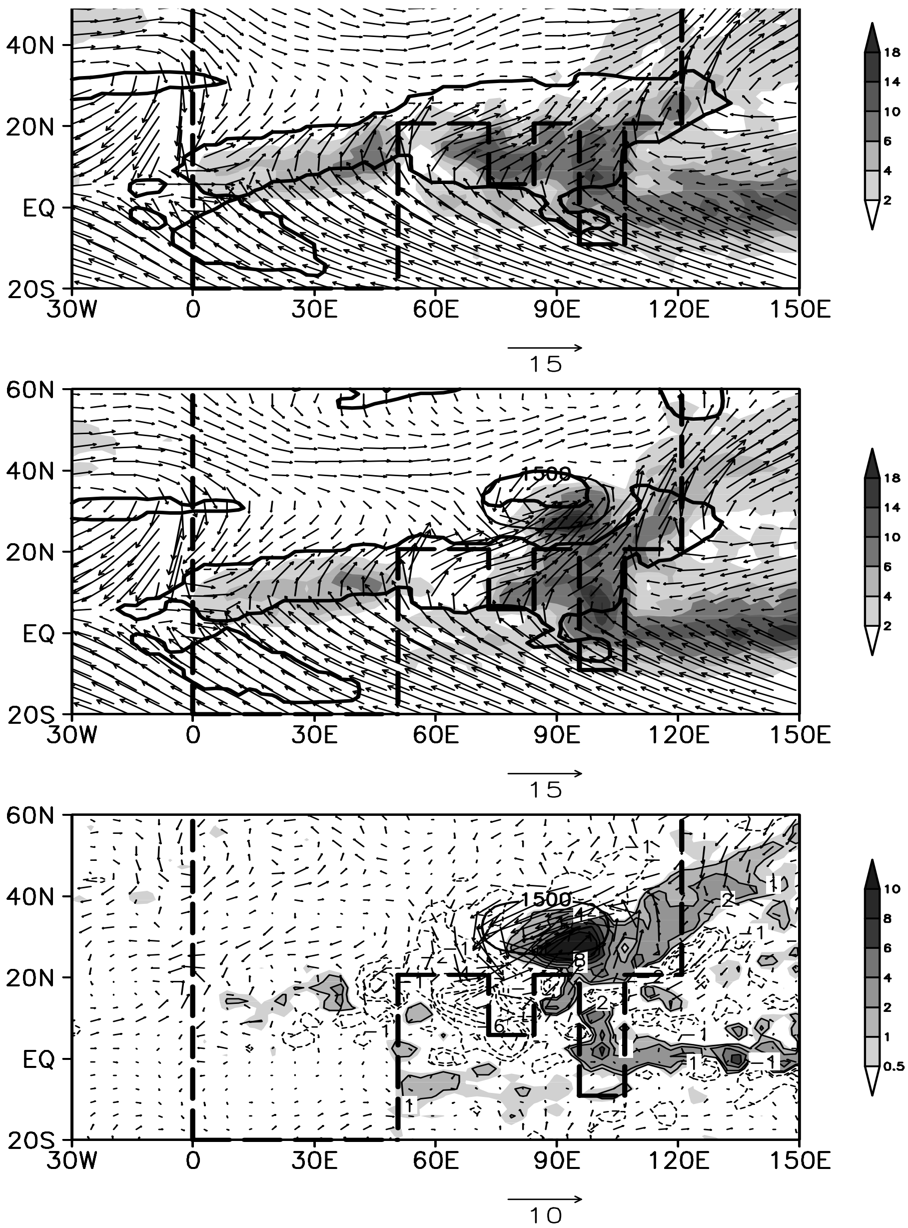

Fig. 2. Distribution of the surface wind vectors (units: m s^{-1}) and rainfall (units: mm d^{-1}) in July in ideal experiments: (a) no-orography experiment; (b) orography experiment; and (c) difference of (b)−(a). The bold dashed line is the land boundary, the curve covers the region where wind diverges more than 120° in Janaury and July, and the ellipse is the contour line of the 1500-m plateau (Wu et al., 2005).

icantly the southwesterlies in the southeast of the Eurasian continent and brings the EASM to Northeast China at 50°N, which greatly strengthens the East Asian monsoon (Wu et al., 2004, 2005).

The thermal contrast between the African continent or Indian subcontinent and the surrounding areas (including the Indian Ocean, Arabian Sea and BOB) might be the main mechanism maintaining the Indian monsoon circulation. In particular, the former has more influence. However, the thermal contrasts between the Indochina Peninsula and the South China Sea (SCS), Australia and the West Pacific play a crucial role in forming the tropical monsoon of the EASM, which indicates it is reasonable to divide the Asian monsoon system into East Asian monsoon and South Asian monsoon (Jin et al., 2006).

4. Onset of the ASM and its mechanisms

4.1 *Onset time and characteristics*

Each year the ASM in the 10°–20°N latitudinal band breaks out initially in the BOB east of 90°E, ICP and SCS, then expands westward and northward, with the EASM and Indian Summer Monsoon establishing themselves one after the other. The Indian Summer Monsoon breaks out later than the EASM (Mooley and Shukla, 1987; Tao and Chen, 1987). The rapid northward progression of tropical convection in the Sumatra in late April and early May is the first sign of such a process (He et al., 1996; Ding et al., 2004; Qian et al., 2004; Liu and Ding, 2005; LÜ et al., 2006).

The Asian tropical summer monsoon is established initially in the equatorial East Indian Ocean and Sumatra in late April (Pentad 24) and then in the east of the BOB and Indochina Peninsula in the 2nd pentad of May (Pentad 26), signifying the outbreak of summer monsoon in these regions. The tropical summer monsoon proceeds northeastward to the central SCS in the 4th pentad of May (Pentad 28), signifying the outbreak of the South China Sea Monsoon (SCSM). It then advances northwestward in late May and early June, with its front arriving at the southern Indian peninsula. Two tropical summer monsoons from the west coast of India and BOB converge in the central Indian Peninsula in the 1st and 2nd pentads of June (Pentads 31 and 32), which signifies the outbreak of the Indian Monsoon. They then arrive in the northwest of India in early July, signifying the establishment of tropical summer monsoon in the whole of India.

The process of summer monsoon onset in East Asia seems complex. It is well known that tropical summer monsoon has proceeded to the Yangtze River and its southern areas in the 1st and 2nd pentads of June after it has initially broken out in the SCS. However, Zhao et al. (2006) pointed out that persistent low-level southwesterly winds occur at their earliest over southeastern China and gradually advance northward, resulting in the onset of large-scale southwesterly winds over eastern China. Moreover, southerly winds extend southward to the SCS. This suggests the EASM breaks out at its earliest over southeastern China.

Accompanied by the northward march of the EASM, summer monsoon rainfall occurs in South China in the first flood period in mid and late May, moves northward rapidly in early June, and brings the mei-yu front to the Yangtze River valley and the mei-yu front to Japan in mid June. The mei-yu front lasts in the Yangtze River valley and then proceeds rapidly northward to North China in early July when the North China rainy season begins. In mid July, the front of summer monsoon arrives in Northeast China, which is the northernmost position of the ASM. The entire process is represented by three still phases and two abrupt jumps, which are closely associated with the activity of the Western Pacific Subtropical High (WPSH) (Ding, 2004). Jiang et al. (2006) distinguished between the mei-yu front in the Huaihe-River and south of the Yangtze River, and pointed out that the rain belt has three jumps northward.

It can be seen from the differences of 500–200-hPa thickness between 20°N and 5°N that the difference turns from negative to positive in early May, first in the longitude of 100°E, i.e., the ICP, and expands eastward to the SCS in the 4th pentad of May (Pentad 28) and westward to the Indian subcontinent in the 1st and 2nd pentads of June (Pentads 31 and 32), which corresponds to the onset of summer monsoon in these regions. In addition, the axis of maximal thermal contrast tilts obviously to the west with time, indicating the maximal thermal gradient moves regularly westward. Therefore, the reverse of the meridional thermal gradient and the westward propagation of the maximal gradient are the manifestation of Asian monsoon advancing from east to west after breaking out in the tropical east Indian Ocean and Indochina Peninsula.

In summarizing the SCSMEX, Ding (2004) revealed a series of important phenomena accompanying the outbreak of monsoon as follows: cross-equatorial flow develops in the equatorial East Indian Ocean and Somali; heat sources in the Indochina Peninsula, South China, Tibetan Plateau and surrounding areas strengthen rapidly in seasonal transition; lower-level westerlies accelerate in the equatorial East Indian Ocean; the Subtropical High belt splits in the BOB and a monsoon low or cyclonic circulation forms; tropical southwesterlies expand eastward from the tropical East Indian Ocean; rainy season arrives in the BOB and Indochina Peninsula; under the influence of mid-latitudinal systems, southwesterlies expand further to the SCS; the main body of the Subtropical High weakens significantly and withdraws eastward; convective cloud, rainfall, low-level southwesterlies and upper-level northeasterlies develop abruptly in the SCS, and so on. These achievements provide favorable references for researching Asian and East Asian monsoon.

4.2 *Onset mechanisms*

4.2.1 *Impact of the Tibetan Plateau on the onset position and intensity of the ASM*

The "heating pulley" action of the Plateau strengthens the southerlies, increases rainfall, and strengthens the latent heat over the land to the southeast of the Plateau; meanwhile, it produces northerlies, decreases rainfall, and strengthens the sensible heat over the land surface to the southwest of the Plateau. The Plateau anchors the location of the ASM onset. In the background of the tropical land-sea distribution, the ASM breaks out initially on the east side of the ocean and west side of the continent to the southeast of the Plateau, and thus the monsoon rainfall in Asia is redistributed. The initial outbreak of the ASM in the east of the BOB is associated with obvious heating in the south side of the Plateau in spring. It has been proven, after analyzing the evolution of the common boundary of easterlies and westerlies, that in the lower troposphere in the Asian monsoon region the transition from the prevalence of easterlies in winter to southwesterlies in summer occurs firstly in the east of the BOB due to heating of the Plateau in spring, accompanied by drastic convective rainfall in its east. Therefore, the region of "east of the BOB-west of the Indochina Peninsula" may be where Asian monsoon initially breaks out (Wu et al., 2004, 2005; Liang et al., 2005).

4.2.2 *Impact of the onset of the BOB Monsoon on the onset of the SCSM*

The introduction of convective latent heating over the BOB results in vigorous ascending motion and onset of the BOB Monsoon, as well as the development of westerlies and vertical ascent over the northern SCS due to an asymmetric Rossby-wave response. Together with low-level moisture advection, convection is induced over the northern SCS. It is the condensation heating over the northern SCS that causes the overturning of the meridional gradient of temperature. Consequently, the vertical slope of the ridge of the subtropical high over the SCS turns from a winter pattern to a summer pattern according to the relation of the thermal wind, i.e., the subtropical high in the low level weakens and moves southward. Eventually, as convection develops over the entire SCS domain, the subtropical high moves out of the region and the SCSM breaks out (Liu et al., 2003a,b).

4.2.3 *The antecedent effect of the "Asian-Australian land bridge" on the onset of the ASM*

Within the South Asian region (10°–20°N), convection flares up initially in the ICP, then in the BOB and SCS, and lastly in India. The convection activity in the ICP is related to sensible heating of the Earth's surface there, but more importantly, it is the result of the northward progression of the tropical convection in Sumatra and the arrival of the South Asia High in this region. The latent heating in the ICP is favorable for triggering a cyclonic circulation on its west side, while the sensible heating in the Indian Peninsula favors triggering of a cyclonic circulation or trough on its east side. The effective match of these two, along with the around-flow and thermodynamic effects of the Plateau and the thermodynamic effect in the middle and high latitudes in East Asia, helps the subtropical high belt in South Asia to split first in the BOB. Accompanied by the formation and strengthening of the BOB trough, the eastern BOB is controlled by tropical southwesterlies in front of the trough, then large quantities of moisture are transported to the SCS whereupon they converge with the flow from the west side of the subtropical high. Therefore, the atmosphere is destabilized, convection perks up, and summer monsoon is established. In the meantime, convective latent heating in the BOB triggers two-dimensional asymmetric Rossby Waves, which generate diversion of the meridional gradient of temperature in the SCS and favor the onset of the SCSM. The rapid eastward retreat of the eastern subtropical high after the belt splits results directly in the onset of the SCSM and its explosive characteristics. As India is controlled by northwesterlies in front of the ridge (i.e., behind the BOB trough) after the high belt breaks, it is unfavorable for the onset of summer monsoon in India. Therefore, summer monsoon is established lastly in India. As a matter of fact, the break of the subtropical high belt, the occurrence of the BOB trough, the eastward retreat of the subtropical high, and the onset of the SCSM are completed rapidly and accompanied by the seasonal abrupt change of large-scale circulation and moisture transport in Asia. However, in terms of the source of the onset of summer monsoon, the rapid northward progression of the tropical convection in Sumatra in late April and early May is the earliest sign of the onset of the ASM (Xu et al., 2001, 2002; He et al., 2002, 2004a, 2006; Zhang and Qian, 2002; Liu et al., 2003a; Luo and Li, 2004; Qian et al., 2004; Wang et al., 2004b; Wen et al., 2004a; Zhang et al., 2004b; Liang et al., 2005; Wen and Zhang, 2005; Zhou et al., 2005b). This process is represented in Fig. 3.

4.2.4 *Impact of the thermal anomalies of the oceans on the onset of the SCSM*

A series of studies have been carried out on the impact of anomalous SSTs in the tropics on the onset of the SCSM. Many researchers have suggested that the preceding SST anomalies (SSTAs) in the tropical Indian Ocean and Pacific Ocean have a good relation with the onset of the SCSM. Wen et al. (2006b) indicated that the sign of the SSTAs in the tropical Indian Ocean and Pacific Ocean are opposite in some years, so their impacts on the early or late onset of the SCSM are different. The negative (positive) SSTA in the tropical Indian Ocean is favorable (unfavorable) to the early establishment of the anti-Walker Circu-

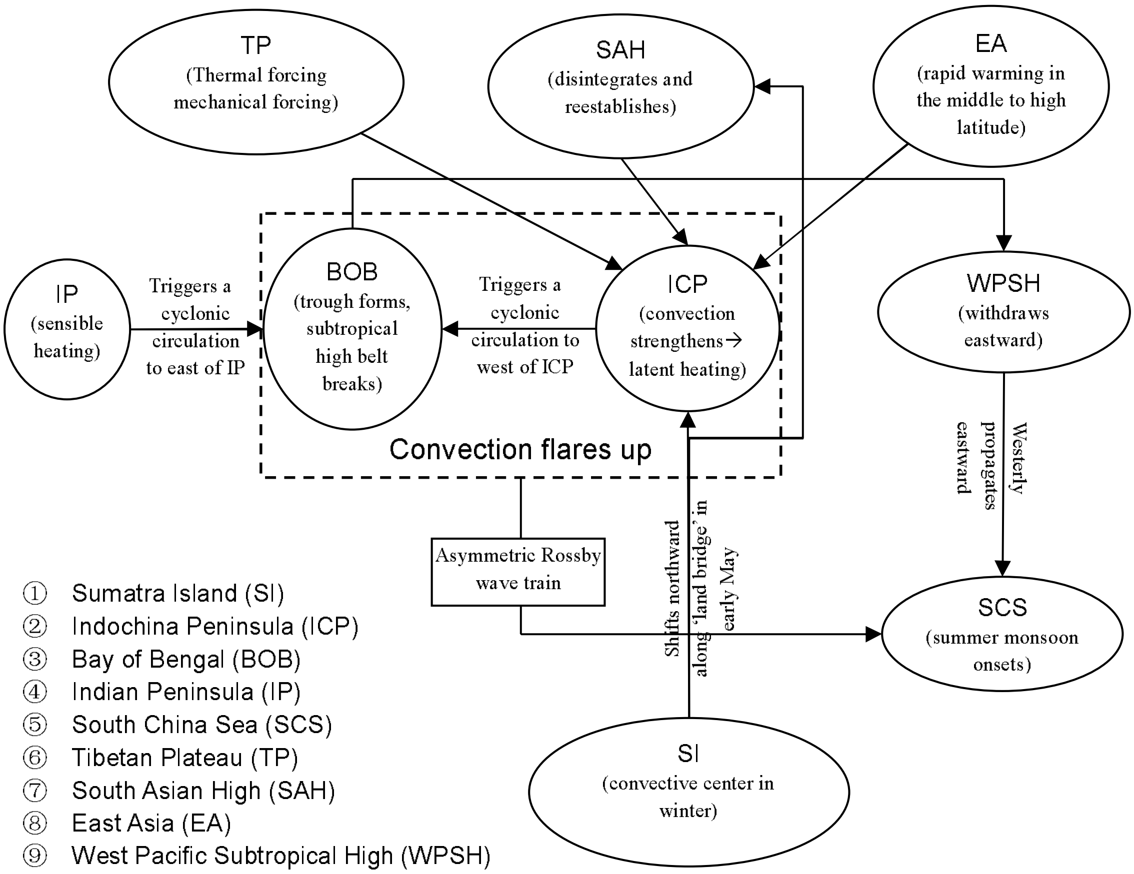

Fig. 3. Relationships among the northwestward movement of convection in the Sumatra along the "land bridge", the onset of convection in the Indochina Peninsula, the break of the subtropical high belt, the formation of the BOB trough, and the onset of the SCS Summer Monsoon (He et al., 2006).

lation over South Asia; while the negative (positive) SSTAs in the tropical Pacific Ocean favor (disfavor) the early strengthening of the Walker Circulation over the Pacific. The SSTAs in the tropical Indian Ocean and Pacific Ocean have an impact on the early or late onset of the SCSM through influencing the Walker Circulation.

Warm SST in the SCS in winter and spring is favorable for the formation of monsoon circulation throughout all levels of the atmosphere over the sea, which hastens the onset of the SCSM. The effect of cold SST is generally the opposite. The local land-sea thermal contrasts in the SCS are one of the possible reasons for the SCSM onset (Ren and Qian, 2003).

4.2.5 *Impacts of anomalous atmospheric circulation in different latitudes on the onset of the SCSM*

The SCSM onset is also influenced by low-latitude circulation and anomalous atmospheric circulation in the mid and high latitudes. Through studying the impacts of mid- and high-latitude atmospheric circulation anomalies, and the activities of 30–60-day low-frequency convection over low latitude areas on the onset of the SCSM, Wen et al. (2006a) discovered that when there exists an anomalous wave train with negative anomalies of geopotential height field (low-frequency cyclone) over the Ural Mountains and its western region and along the seacoast of eastern China, along with positive anomalies (low-frequency anticyclone) over the mid-latitude continent and Sea of Okhotsk during 1–15 May, the ridge of the subtropical high will withdraw earlier from the SCS. At the same time, the low-frequency convection over the eastern part of the BOB is active and moves eastward, develops and moves westward around the Philippines, is active and moves southward over South China, and is also active and moves northward over Kalimantan. In this case, the establishment of the SCSM is earlier.

4.3 *Integrated mechanism of the onset of the EASM*

As shown in Fig. 4, due to the existence of the Indian Peninsula and its corresponding surface sensible heating, the BOB trough strengthens, the convec-

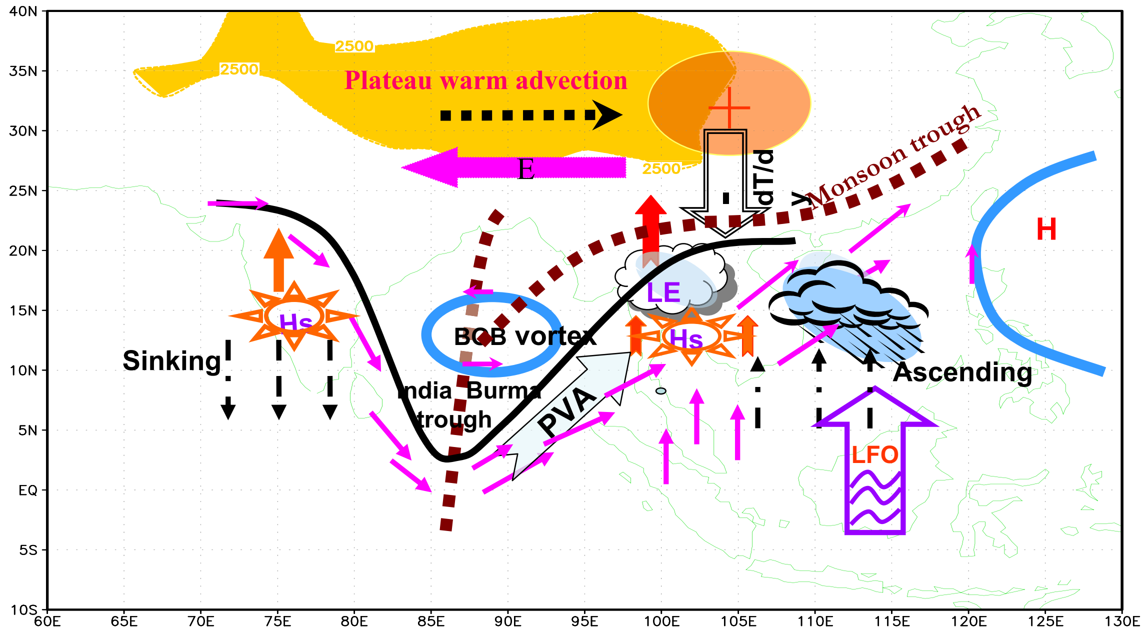

Fig. 4. Sketch map of the onset mechanism of the ASM based on the outcome of the South China Sea Monsoon Experiment (SCSMEX) (Liu and Ding, 2007).

tion and precipitation strengthen initially in this area, and the subtropical high weakens and breaks first here in the seasonal progression of the atmospheric circulation. The ascending motion is evidently set up in the tropical eastern Indian Ocean-Indochina Peninsula and SCS region, subsequently under the effect of the positive vortex advection (PVA) in front of the BOB trough, while the northwesterlies behind the trough are unfavorable for the establishment of southerlies in India and the development of ascending motion (there is descent behind the trough). On the other hand, the cooperation of the warm westerly advection over the eastern Plateau and the sensible and latent heat over the Indochina Peninsula reverses the temperature gradient in the area, builds the upper-level easterlies, and forces the subtropical high to withdraw eastward. The weakening and withdrawal of the subtropical high conduce to the further development and strengthening of convection and precipitation, and then the tropical eastern Indian Ocean-Indochina Peninsula summer monsoon breaks out. Correspondingly, the upper-level westerlies weaken and are entirely substituted by tropical easterlies; the low-level westerlies strengthen and advance eastward to the SCS area. In the meantime, the 30–60-day and 10–20-day low-frequency oscillations from the east and west in the tropics propagating to the north are phase-locked in the SCS and its surrounding areas around mid May, which triggers the rapid onset of the SCSM (Liu and Ding, 2007). Cold air from the north can also trigger the onset of summer monsoon in some years (Ding and Chan, 2005; Zhang et al., 2005).

5. Moisture transport of Asian monsoon

The activities of the ASM are closely associated with moisture transport. Based on vertically integrated moisture transport, Fasullo and Webster (2003) employed the Hydrologic Onset and Withdrawal Index (HOWI) to investigate the interannual variation of the onset date of Indian summer monsoon. The results showed that there is a close relationship between moisture transport and the onset of summer monsoon.

A planetary-scale water vapor transport band of high values is formed through the converging of large-scale water vapor transport bands in the Asian-Australian regions in summer. This starts from the Southern Hemisphere, crosses the Asian monsoon region, and then flows to the North Pacific. The north border of moisture transfer by southerlies is near 50°N in Northeast China, and the west border of moisture transfer by southeasterlies from the south side of the WPSH is near 100°E in the southeast of Gansu Province (Zhou et al., 2005a). The relations between moisture transport from the Indian monsoon region and that over East Asia and their influences on summer rainfall in China have been investigated. It is found that the distribution and transport of moisture in the East Asian monsoon region differed greatly from those in the Indian monsoon region (Huang et al., 1998). That is to say, the former has larger meridional transport, with moisture convergence and divergence resulting primarily from moisture advection, while the latter has more zonal transport and moisture convergence and divergence resulting primarily from convergence and divergence of the wind field. Moreover, the moisture transport from the Indian monsoon region is inverse to that over East Asia, i.e. more Indian monsoon moisture transport corresponds to less moisture transport over East Asia and less rainfall in the middle and lower reaches of the Yangtze River valley (Zhang, 2001).

Further studies have shown that there are four moisture corridors influencing summer rainfall in China: the southwest corridor, SCS corridor, southeast corridor from the low latitudes, and the weak northwest corridor from the high latitudes. These represent the impacts of the South Asian Monsoon, the SCSM, subtropical monsoon and mid-latitude westerlies on summer rainfall in China, respectively. The region affected by the EASM is located to the east of 100°E. The southwest corridor is the moisture source for central South China, Southwest China and Northwest China; the SCS corridor influences rainfall directly in South China; the southeast corridor transfers moisture to the Yangtze River valley; and the northwest corridor transports moisture to the mid and upper reaches of the Yellow River and eastern North China (Tian et al., 2004; Wang et al., 2004a).

There are bifurcations on the primary corridor of moisture transport to the Yangtze River valley. For instance, Xu et al. (2003) considered that the moisture transport of the mei-yu belt has a structure of multi-sources, with the BOB, SCS and the tropical western Pacific the primary sources. There is also a moisture corridor in the mid and high latitudes in the western Pacific, which converges with the former in the Yangtze River valley. The moisture flows from the SCS and the Indian Ocean, converges in the BOB, then transfers northward and turns eastward by the dynamic forcing of the Qinghai-Tibetan Plateau to the Yangtze River valley, which forms the principal moisture corridor of the mei-yu rain belt in the Yangtze River valley.

The water vapor transport in the SCS is closely related to strong rainfall in China. The moisture over the SCS is mainly from the West Pacific before the monsoon onset, while it is from the tropical eastern Indian Ocean and BOB during the onset pentad. After the SCSM onset, moisture from the west side through the Indochina Peninsula to the SCS increases significantly, which becomes the primary water vapor source, and forms an obvious moisture source region in the SCS where large quantities of moisture are accumulated and transferred northward to South China and the Yangtze River valley, providing necessary moisture conditions for strong precipitation (Ding and Hu, 2003; Ding and Chan, 2005; Liu et al., 2005).

6. Variability of monsoon and its relationship with other circulation systems

6.1 *Intraseasonal oscillation of East Asian monsoon*

There is a close relationship between the onset of summer monsoon and intraseasonal oscillation (ISO). Low-frequency zonal westerlies appear two days earlier than the SCSM onset; strong development of atmospheric ISO to the east of the Philippines and its westward extension play an important role in the ISO of the atmosphere in the SCS and the onset of summer monsoon (Li, 2004). The intraseasonal oscillation of the EASM is arranged in a pattern of wave trains along the seacoast of East Asia, and is represented by the northward propagation of monsoon surge with time. The monsoon surge consists of several ISO wet phases, and summer monsoon breaks out when the ISO wet phase is introduced or developed (Ju et al., 2005a; Qian et al., 2000). Quasi-biweekly oscillation of the tropical atmosphere has a critical role in establishing the processes of summer monsoon. Investigations have found that coherent adjustments of the convective disturbance and wind fields associated with atmospheric Rossby-wave response may be an important maintaining mechanism of the tropical quasi-biweekly oscillation (Wen and Zhang, 2005).

Intraseasonal oscillation is one of the factors affecting the early or late onset of summer monsoon. Using 30–60-day filtered data of OLR averaged over the SCS for 1981–1996, Wen et al. (2004b) defined an index to describe the "low-frequency convection outbreak" of the SCS and analyzed ten "low-frequency convection outbreak" years synthetically. They pointed out that the dry phase of ISO in the low latitudes inhibits the development of southwesterlies and cyclonic circulation in the SCS before the outbreak of low-frequency convection; together with the northeastward propagation of ISO in the tropical Indian Ocean areas, there appears anomalous low-frequency cyclonic circulation in the SCS, and the low-frequency southwesterlies and convection strengthen rapidly before the SCSM breaks out.

Two preferential modes (30–60 days and 10–20 days) may play a significant part in the adjustment of the EASM. Analysis of data from 1998 indicates that the activity of the SCS is mainly controlled by 30–60-day oscillation, but adjusted by the 10–20-day mode. The low-frequency oscillation waves propagating northward in the form of a wave train and monsoon surge along the East Asia coast connect activities in the tropics and subtropics, which results in contrary phases in these two regions. Quasi-30–60-day oscillation is obvious in strong monsoon surge years, producing more rainfall in the mid and lower reaches of the Yangtze River; while it weakens in weak monsoon surge years when 10–20-day oscillation is the primary period, producing drought in the mid and lower reaches of the Yangtze River (Ding, 2004; Ju et al., 2005a; Ju and Zhao, 2005). Analysis has shown that no matter whether the EASM is strong or weak, the westward propagation of the atmospheric ISO in the Pacific is stronger in every flood summer for several regions of East Asia, while it is weaker in every drought summer, indicating that strong or weak westward propagation of the ISO in the Pacific is the necessary condition for the precipitation amount in the EASM region (Han et al., 2006).

ISO also has two significant modes in the western North Pacific (WNP) monsoon region, in which the 30–60-day mode is predominant (Wang et al., 2005). Synthetic analysis of different phases has pointed out that the low-frequency convection and westerlies in the WNP propagate to the west and to the north. The monsoon rainfall, convection and active-break cycle in the WNP are adjusted by 30–60- and 10–20-day low-frequency oscillation to a great extent. However, 30–60-day oscillation in the SCS and tropical WNP in summer is also influenced by ENSO in the preceding winter (Lu and Ren, 2005).

The strongest center of kinetic energy in the tropical ASM region is located over 75°–95°E, with a secondary center over the Somali jet channel, around 50°E. The disturbances of both kinetic energy and meridional wind are observed east of 90°E, mainly coming from the western Pacific and propagating westward to the BOB through the SCS. However, the propagation directions of both kinetic energy and meridional wind are rather disorderly between the BOB and the Somali jet channel. Therefore, the EASM and Indian Summer Monsoon are different in the propagation features of the disturbances of kinetic energy and meridional wind. The above facts indicate that the East Asian monsoon system undoubtedly exists even in the equatorial region, and quite distinct from the Indian monsoon system, it is mainly affected by the disturbances coming from the tropical western Pacific rather than from the Indian monsoon region. The boundary of the two monsoon systems is around 95°–100°E, which is more westward (5°–10°E) than its counterpart, as proposed in earlier studies (Chen et al., 2004; Gao et al., 2005).

In addition, Wu et al. (2006a,b) proposed a new concept of the droughts-floods coexistence during the normal summer monsoons which has close association with the EASM ISO anomalies.

6.2 *Factors affecting the interannual variation of East Asian monsoon and its possible mechanisms*

Huang et al. (2003a,b) summarized that the reasons for the interannual variation of East Asian monsoon are complicated and affected by many factors. The interannual variation of East Asian monsoon is jointly influenced by the Indian Monsoon, the WPSH, mid-latitude disturbances, the ENSO cycle, the warm pool in the tropical western Pacific, the thermal conditions of the tropical Indian Ocean, land surface processes, snow cover in Eurasia, the dynamic and thermal effects of the Tibetan Plateau, sea ice in the Arctic Ocean, and so on.

6.2.1 *Warm pool in the western Pacific, its convective activity and interannual variation of the EASM*

Huang et al. (2005) perfected and developed viewpoints on the characteristics of the interannual variation of the onset and advance of the EASM and their associations with thermal states of the tropical western Pacific. Figure 5 shows that when the tropical western Pacific is in a warming (cooling) state in spring and summer, convective activities are intensified (weakened) around the Philippines. In this case, there is an anomalous cyclonic (anticyclonic) circulation in the lower troposphere over the SCS, and the WPSH shifts eastward (westward); thus, an earlier (later) onset of the SCSM can be caused. Moreover, since the WPSH shifts abruptly northward in mid June and early July, respectively, when the tropical western Pacific is warm, the abrupt northward shift of the EASM rain band from South China to the Yangtze River and the Huaihe River valleys is obvious in mid June and this monsoon rain band again jumps northward to the Yellow River valley, North China and Northeast China in early July. As a result, summer monsoon rainfall is below normal and drought may occur in the Yangtze River and the Huaihe River valleys, but summer rainfall is normal or above normal in the Yellow River valley, North China and Northeast China. On the other hand, when the tropical western Pacific is in a cooling state in spring and summer, the EASM rain band can be maintained in the Yangtze River and Huaihe River valleys. That is to say, the summer monsoon rainfall is above normal and flooding may occur in these two valleys, but summer rainfall is below normal and drought may occur in North China.

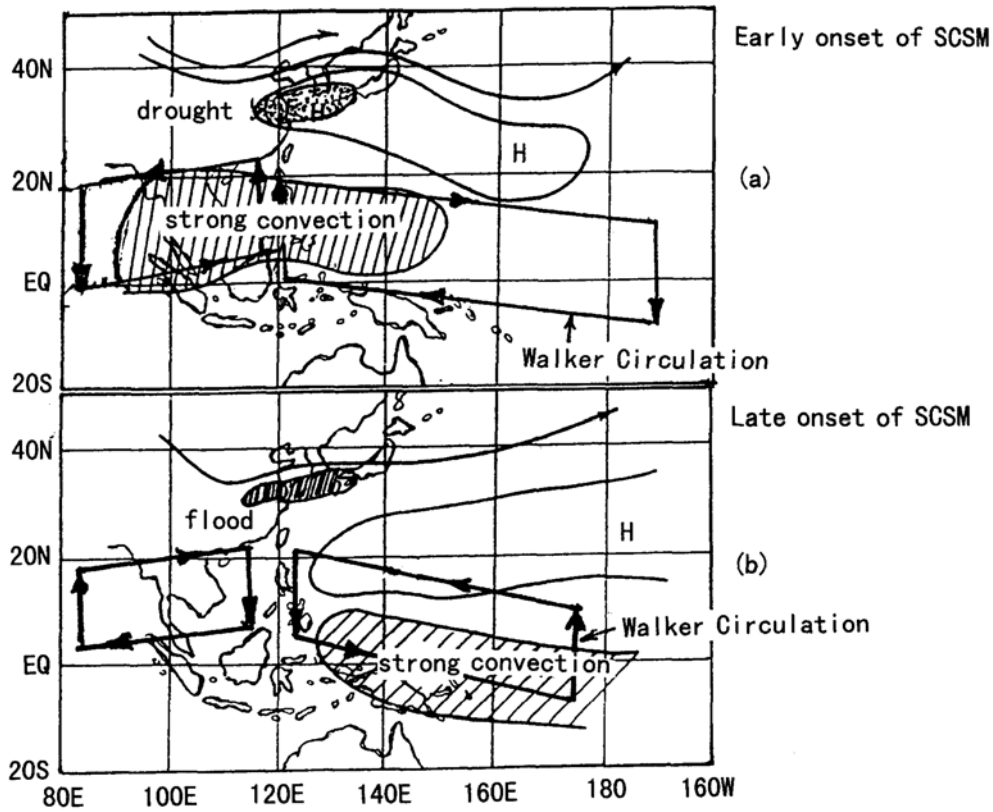

Fig. 5. Sketch map of the relationships among the thermal states of the tropical western Pacific (warm pool), the convective activities around the Philippines, the early or late onset of the SCSM, the Western Pacific Subtropical High, and the distribution of drought and flood in the Yangtze River and Huaihe River valleys: (a) warm pool in a warm state; and (b) warm pool in a cold state (Huang et al., 2005).

6.2.2 *El Niño*

Observational analyses and numerical experiments found that El Niño has a certain impact on the early or late onset of southwesterly monsoon in the SCS, which is less significant than the anomalous SST in the western Pacific has. In the preceding periods of strong (weak) SCSM years, the tropical SST is distributed as a La Niña (El Niño) pattern, in which the distribution of SST in December relates mostly to the intensity of the coming SCSM (Liang and Wu, 2002, 2003; Zhang et al., 2004a).

Zhang and Sumi (2002) investigated features of the moisture circulation over East Asia during different El Niño episodes. It was found that in the El Niño mature phase, the anomalies of precipitation in China, water vapor transport and moisture divergence over East Asia differ from those in the rest of the phases, and the impact of El Niño on the East Asian climate is significant. The physical process through which El Niño affects the climate in East Asia was also discussed.

6.2.3 *SST in the Indian Ocean*

The Indian Ocean Dipole (IOD) has significant impacts on weather and climate in the East Asian monsoon region, especially in summer and in El Niño periods. In the positive phase of the IOD, southwesterly monsoon in East Asia breaks out later, with its intensity strengthening and rainfall increasing in China; while in the negative phase of the IOD, southwesterly monsoon in East Asia breaks out earlier, with its intensity weakening and plentiful rainfall in Southeast China (Yan and Zhang, 2004a). Furthermore, the SSTA in the equatorial east Pacific and the IOD exert cooperative influences on climate variation over the East Asian monsoon region. The possible processes, through which the Indian Ocean SSTA impacts on the onset of the SCSM, are also different when the ENSO signal is included or removed (Yan and Zhang, 2004b; Wen et al., 2006b). Lu et al. (2006) pointed out that SST in the Atlantic also has important impacts on the EASM and rainfall.

6.2.4 *Snow state over the Tibetan Plateau*

Numerical simulation shows that the increase of both snow cover and snow depth over the Tibetan Plateau can delay the onset and weaken the intensity of summer monsoon obviously, resulting in a decrease of precipitation in South China and North China and an increase in the Yangtze River and Huaihe River basins. The influence of winter snow depth is more substantial than that of both winter snow cover and spring snow depth. The snow anomalies over the Tibetan Plateau firstly change the soil moisture and surface temperature through snow melting processes; in the meantime, heat, moisture and radiation fluxes from the surface to the atmosphere are altered. Abnormal circulation conditions induced by changes of surface fluxes may in turn affect the underlying surface properties. Such a long period of interaction between the wetland and atmosphere is the key process resulting in later climate changes (Qian et al., 2003).

6.2.5 *Somali jet*

The Somali jet, the predominant cross-equatorial flow, plays a key role in water vapor transport between the two hemispheres. It transports water vapor through the equator from the Southern Hemisphere to the Northern Hemisphere during boreal summer time, and from the Northern Hemisphere to the Southern Hemisphere during boreal winter time. The interannual variation of the Somali jet is found to be linked with many changes around the globe, including the wave pattern along the East Asia coast, the South Asian High, the dipole pattern to the southeast of Australia, and the SSTA in the northern Indian Ocean in spring. Results have also revealed that interannual variation of the Somali jet in boreal spring has significant influences on East Asian summer rainfall and atmospheric circulation (Wang and Xue, 2003).

6.2.6 *Circulations in the Southern Hemisphere*

Studies on the interannual variation of the Mascarene High and Australian High indicated that the former is controlled by Antarctic Oscillation (AAO), while the latter is related to both ENSO and AAO. In spring and summer, especially in spring, the intensity of the Mascarene High and Australian High is closely associated with summer rainfall in East Asia. When the Mascarene High strengthens in spring and summer, there is more rainfall from the Yangtze River valley to Japan and less rainfall from South China to the western Pacific east of Taiwan and the mid latitudes in East Asia. The influence of the Australian High on summer rainfall in East Asia is restricted in specific area. When the Australian High strengthens, rainfall is less in South China. The influence of the Australian High on East Asia monsoon is weaker than that of the Mascarene High, which plays a crucial role in the interactions between the atmospheric circulations of the two hemispheres. Studies have proven that the AAO is another strong interannual signal influencing summer rainfall in East Asia (Xue et al., 2003a,b).

Nan and Li (2005) found that there is a significantly positive correlation between the boreal spring southern hemisphere annular mode (SAM) and the following summer precipitation in the mid and lower reaches of the Yangtze River valley. While there is a strong SAM in spring, a pair of anomalous anticyclones exist in the Mongolian Plateau and Tianshan Mountains, respectively. Meanwhile the anomalous northerlies prevail from Northeast China to the mid latitudes of South China. These anomalous circulations may persist until the following summer and weaken the EASM; the west ridge of the WPSH strengthens and extends westward in summer following the spring of a strong SAM. These circulation anomalies are related to more precipitation in the mid and lower reaches of Yangtze River valley.

6.2.7 *The activities of stationary planetary waves and East Asian winter monsoon*

Chen et al. (2005) investigated the relationship between the activities of stationary planetary waves and East Asian winter monsoon and suggested that in winter when the stationary planetary waves act frequently, the upward propagations of the waves from troposphere to stratosphere weaken, along with small polar vortex disturbance, which results in chilling and strengthening of the polar vortex. In the meantime, the westerly jet in East Asia, the East Asian trough, the Siberian High and the Aleutian Low become significantly weakened, which also weakens the northeasterlies over East Asia and warms this area. Further studies have pointed out that the planetary waves of zonal two-wave patterns play a leading role in the variability of East Asia winter monsoon.

6.3 ***Interdecadal variation of the Asian monsoon***

There exists interdecadal variation in Asian monsoon circulation (Fong et al., 2005; Jiang and Wang, 2005; Li and Zeng, 2005; Wu et al., 2005; Zhao and Zhou, 2005; Zhao and Zhang, 2006). The EASM has been weakening since the 1960s on a decadal scale, with two abrupt interdecadal changes having appeared in the mid 1960s and late 1970s, but there is still dispute over whether or not such decadal weakening is related to global warming induced by human activity. Obvious interdecadal variation in the position and intensity of the WPSH also occurred in the mid 1970s. As a result, summer southwesterlies influence directly the areas from the lower reaches of the Yangtze River to Korea after the mid 1970s when rainfall was lower in North China and higher in the Yangtze River to Korea; while before the mid 1970s, summer southwesterlies could reach North China, and then rainfall was higher in North China and lower in the Yangtze River (Dai et al., 2003; LÜ et al., 2004; Qian, 2005). The East Asian Winter Monsoon also has obvious interdecadal. The temperature in the north of East Asia has been rising significantly since the mid 1970s, which is directly influenced by the interdecadal variation of the East Asian Winter Monsoon (Ju et al., 2004).

The interdecadal variation of Asian monsoon may be associated with temperature decrease in the troposphere and the interdecadal variation of the sea thermal states. Wu et al. (2005) found that in the two weakening processes of Indian summer monsoon in the mid 1960s and late 1970s, the thermal contrast in the troposphere decreases between East Asia and the tropical regions from the east Indian Ocean to the tropical western Pacific, which weakens the Indian Summer Monsoon circulation. In the last 20 years, the impact of El Niño on East Asian summer circulation has been increasing, and the warm phase of the Pacific Decadal Oscillation (PDO) has basically synchronized with the interdecadal variation of the atmospheric circulation in East Asia (Wang and Kiyotoshi, 2005). Yang et al. (2005) pointed out that the interdecadal anomaly of rainfall in North China is significantly correlated with the anomalous sea thermal states in the upper layer in the Pacific, and further revealed the related mechanism.

Another possible affecting factor is the Arctic Oscillation (AO) (Ju et al., 2005b). In the last 20 years, the Asian continent in winter and spring warms in mid and high latitudes and cools in lower latitudes, along with the trend in the AO toward its high-index polarity after the late 1970s. In the meantime, rainfall increases in the Tibetan Plateau and South China, which increases the soil moisture. Due to the memory of soil moisture, the cooling of the southern continent is maintained in summer and the warming of the Asian continent in summer slows down. Moreover, the Pacific to the east and the Indian Ocean to the south of Asia are warming from winter to summer; therefore, the land-sea thermal contrast decreases in summer, which results in a weakening of the EASM circulation.

6.4 *Relationship between the ASM and other circulation systems*

6.4.1 *Relationship between summer rainfall in East Asia and the WPSH*

The northward progression of summer monsoon in East Asia is closely associated with the variation of the subtropical high. The seasonal northward advancement of the subtropical high in March-July is represented mainly by three abrupt changes, corresponding temporally to the onset of the SCSM, the occurrence of the mei-yu and the end of the mei-yu, respectively (Shu and Luo, 2003).

When the ridge line of the WPSH shifts more southward than normal, or the ridge point shifts more west than normal, the EASM circulation is weaker. Correspondingly, there is an anti-cyclonic circulation in the anomalous wind field at 850 hPa over the tropical area in East Asia, and there is a cyclonic circulation over the subtropical area. The anomalous ascending motion at 500 hPa weakens over the tropical area in East Asia, while the ascending motion over the mei-yu frontal area strengthens. Meanwhile, at 500 hPa there is a blocking situation over the Sea of Okhotsk, which is located in the high latitudes of East Asia. The cold air from the high latitudes reaches the mid latitudes and strengthens the disturbance of the mei-yu Front. As a result, the rainfall in the Yangtze River valley is above normal. On the contrary, when the ridge line of the subtropical anticyclone over the western Pacific shifts more northward than normal, or the ridge point shifts more east than normal, the EASM circulation is stronger. The activities of the circulation systems appear opposite in anomaly patterns, and the rainfall in the Yangtze River valley is below normal (Zhang et al., 2003). Studies have also shown that the WPSH sometimes has two ridge lines, influencing the distribution of rainfall in eastern China and the genesis and lysis of mei-yu (Zhan et al., 2005; Qi et al., 2006).

At the seasonal scale, the intensity of the WPSH, the position of its western boundary, and the intensity of the South Asia High are closely associated with the strength of the EASM, while the meridional position of the northern boundary of the WPSH and the blocking situation over the Urals area are related to the rainfall amount in East Asia (Liu et al., 2004).

Lu and Dong (2001) pointed out that the monsoon rainfall in East Asia is influenced by not only the meridional, but also the east-west movement of the subtropical high. Lu also showed that the anomalous atmospheric convection over the Philippines impacts the east-west movement of the subtropical high through Rossby Waves, which modifies Gill's theory (Gill, 1980) and makes new progress.

6.4.2 *Multi-scale conditions of strong summer monsoon rainfall*

The east-west movement and meridional shift of the subtropical high determines the position of the EASM rain belt; the SCSM surge transports large amounts of warm and wet air from sea to land, ensuring abundant provision of moisture for continuous rainfall; cold air in the mid and high latitudes increases the moisture contrast of the air in the north and south, maintains and strengthens the mei-yu Front; and the meso-σ scale convective systems in the Plateau propagate eastward to the Yangtze River valley, promoting the formation and development of the meso-σ scale systems in the mei-yu Front. Such interactions among different scale systems provide the circulation conditions for the occurrence of continuous strong rainfall in the mid and lower reaches of the Yangtze River valley. When the above systems are best combined (locked), i.e., they are all in an active phase, it is common to see large-scale and long-lasting rainstorms, which may cause severe floods (Zhang et al., 2002). Gao et al. (2002) and Zhou et al. (2004) found "double fronts" (dew-point front and mei-yu front) structure of the summer monsoon rainfall in East Asia, and further suggested the conception of the mei-yu front system, which sheds light on the structure of summer monsoon rainfall.

6.4.3 *Relationship between monsoon circulation and meso-scale systems*

There is a kind of positive feedback mechanism between large-scale circulations and meso-scale convective systems. At the early stage of monsoon onset, the wide range background provides favorable synoptic and dynamic conditions for the summer monsoon onset and the formation of meso-scale convective activities; whereas after the summer monsoon onset, occurrence of persistent and large-scale meso-scale convective activities produces an obvious feedback effect on large-scale circulation. Because of the release of latent heat driven by enhanced convective activity, intense atmospheric heating appears over the northern SCS, which results in the meridional temperature gradient over the SCS reversing from the upper level to the lower level, and then the large-scale circulations become changed seasonally. Correspondingly, the surface pressure over the northern SCS deepens continually and forms broad monsoon troughs and obvious pressure-reducing areas, thus causing the subtropical high to eventually move out of the SCS. With the development of low-pressure circulations in the mid and lower troposphere, the meso-scale convective systems further enhance and extend southward, which is favorable for the onset of the SCSM and its maintenance over the central and southern SCS. The deepening of the monsoon trough promotes strengthening of monsoon flow and moisture transport on the southern side of it, and consequently the onset of monsoon prevails (Liu and Ding, 2007; Liu et al., 2005).

6.4.4 *Relationship between monsoon and the westerly jet*

Liao et al. (2004) analyzed the activities of the subtropical westerly jet in boreal summer and the association with the distribution of anomalous SST in the equatorial-central-Pacific-subtropical-North-Pacific-extratropical-central-North-Pacific, which exert influences on the intensity of the South Asia High at 200 hPa, the anomaly of the EASM and the anomaly of rainfall in East China.

The upper westerly jet jumps northward twice during the transition process from winter to summer, which are periods closely related to EASM activities. Li et al. (2004) emphasized that the northward jump of the upper westerly jet in East Asia occurs for the first time on average around 8 May, and it is about seven days earlier than the onset date of the SCSM (mean date is 15 May). The northward jump of the upper westerly jet over East Asia for the second time occurs on average around 7 June, and is about 10 days earlier than the beginning date of the mei-yu rainfall in the Yangtze River and Huaihe River basins (mean date is 18 June) and can be the forewarning of the commencement of mei-yu rainfall. These two-time northward jumps of the upper westerly jet are related to two-time reverses of meridional temperature gradient in the upper middle troposphere (500–200 hPa), respectively. During the seasonal transition, the continent is heated quickly, so that the meridional temperature gradient in the upper-middle troposphere will be reversed at 5°–25°N in South Asia. Then, through the geostrophic adjustment, the flow field adjusts to the pressure field (temperature field) and it will lead to the northward jumps of the upper westerly jet location. Analyses have also shown that sometimes the enhancement and northward movement of the upper westerly jet in the southern hemispheric subtropics can also influence the first northward jump of the upper westerly jet in East Asia.

6.4.5 *Correlation with the anomalous circulation in the western Pacific*

There is key relation between the tropical western Pacific circulation anomaly in winter and the following ASM. The winter anti-cyclonic (cyclonic) circulation anomaly in the tropical western Pacific moves gradually northeastward and expands westward, and the anomalous easterlies (westerlies) to the south of the anti-cyclonic (cyclonic) circulation extend westward to the Indian Peninsula, leading to the weakening (strengthening) of South Asian summer monsoon (Huang et al., 2003a,b; Wu et al., 2003a).

Li and his research group (Li et al., 2005; Pu et al., 2006) paid special attention to the impact of the East Asian Winter Monsoon on the anomalous circulation in the western Pacific, and pointed out that an anomalous pattern of pressure exists for a long period in the western Pacific and Southeast Asia (Fig. 6). The different pressure gradients in the equatorial western Pacific region induced by strong (weak) East Asian winter monsoon play an important role in the formation of anomalous westerlies (easterlies) in the equatorial western Pacific; meanwhile, the anomalous westerlies (easterlies) formed in the equatorial western Pacific and the anomalous easterlies (westerlies) triggered in and around 20°N cooperate with the anomalous northerlies (southerlies) along the East Asian coast, favoring the anomalous cyclonic (anti-cyclonic) circulation to the east of the Philippines, which is a key factor influencing monsoon weather and climate and provides a critical signal for the prediction of weather and climate in China.

7. Problems and outlook

(1) How to describe quantitatively the intensity of the East Asian Monsoon and its interannual variability is still a basic scientific problem in the study of monsoon. Obviously, we expect using a simple and effective index to represent the intensity and variability of monsoon. The Southern Oscillation Index is the best example of employing one parameter to describe a complex phenomenon. An appropriate monsoon index is favorable to the quest of correlation among monsoon variability, other circulation systems and climate variability, to the establishment of association among monsoon variability and the inner and outer forcing factors, and to the objective evaluation of numerical models' potential to reproduce monsoon variability. Various monsoon indices so far have certain effects, but they are not conformable to all wishes. The key problem lies in that the East Asian Monsoon contains both the SCS western Pacific tropical monsoon and the China mainland/Japan subtropical monsoon. It covers a distance of 40–50 latitudes and is significantly influenced by mid and high latitudes. Therefore, the choice of East Asian monsoon index is much more difficult than the choice of Indian monsoon index. The circulation intensity and rainfall amount in the East Asian monsoon region have the characteristic of "distribution" rather than "unanimity", and so indices defined by different sub-areas and different parameters have no "comparability", and even attain contrary conclusions. We believe a "common area" and a "common parameter" should be chosen to define an East Asian monsoon index that can reflect both the wind and rain, thus allowing scholars to discuss it in a "common language". Hence, further exploration is needed to obtain an accepted monsoon index.

(2) The essence of East Asian subtropical monsoon and its interaction with the tropical monsoon is a scientific problem that is not paid much attention. As mentioned above, East Asian monsoon contains both the tropical monsoon and subtropical monsoon, which interact and influence directly large-scale flooding and drought in China. But what actually is subtropical monsoon? Or what is the essence of subtropical monsoon? There are generally two misunderstandings: one is based on regions, i.e. monsoon prevalent in the subtropical areas in East Asia is called "East Asian subtropical monsoon"; the other considers the northward extension of tropical monsoon in East Asia as subtropical monsoon. Both neglect the reason why subtropical monsoon exists. We believe that the meridional land-sea thermal contrast in East Asia is the key driving force of tropical monsoon, while the seasonal cycle formed by the thermal contrast between Asian continent (including the Plateau) and the western Pacific may be an independent driving force of subtropical monsoon. Obviously, if there was no land-sea contrast between the Asian continent and western Pacific, the subtropical high belt would not break, and the East Asian tropical monsoon could not extend to Northeast China at around 50°N. We may imagine that the northward progression of East Asian monsoon is the result of coordination and interaction between the East Asian tropical monsoon and the East Asian subtropical monsoon. Therefore, we have to study thoroughly the essence of East Asian subtropical monsoon and its interaction with tropical monsoon, which will improve the prediction of flooding and drought in China.

(3) If the East Asian Subtropical Monsoon is an independent system from tropical monsoon, what members are involved in the East Asian subtropical monsoon system? What about the seasonal cycle? When is the East Asian subtropical monsoon established and when does it end? It is related directly to the seasonal cycle in East China, so it is a scientific problem worthy of study.

(4) The thermal effect of the Tibetan Plateau strengthens the meridional land-sea (Asian continent and Indian Ocean) thermal contrast and the zonal land-sea thermal contrast (Asian continent and the Pacific). Especially, as an uplifted heat source (or cold source), the Plateau makes the seasonal transition of thermal contrast more sensitive and more advanced.

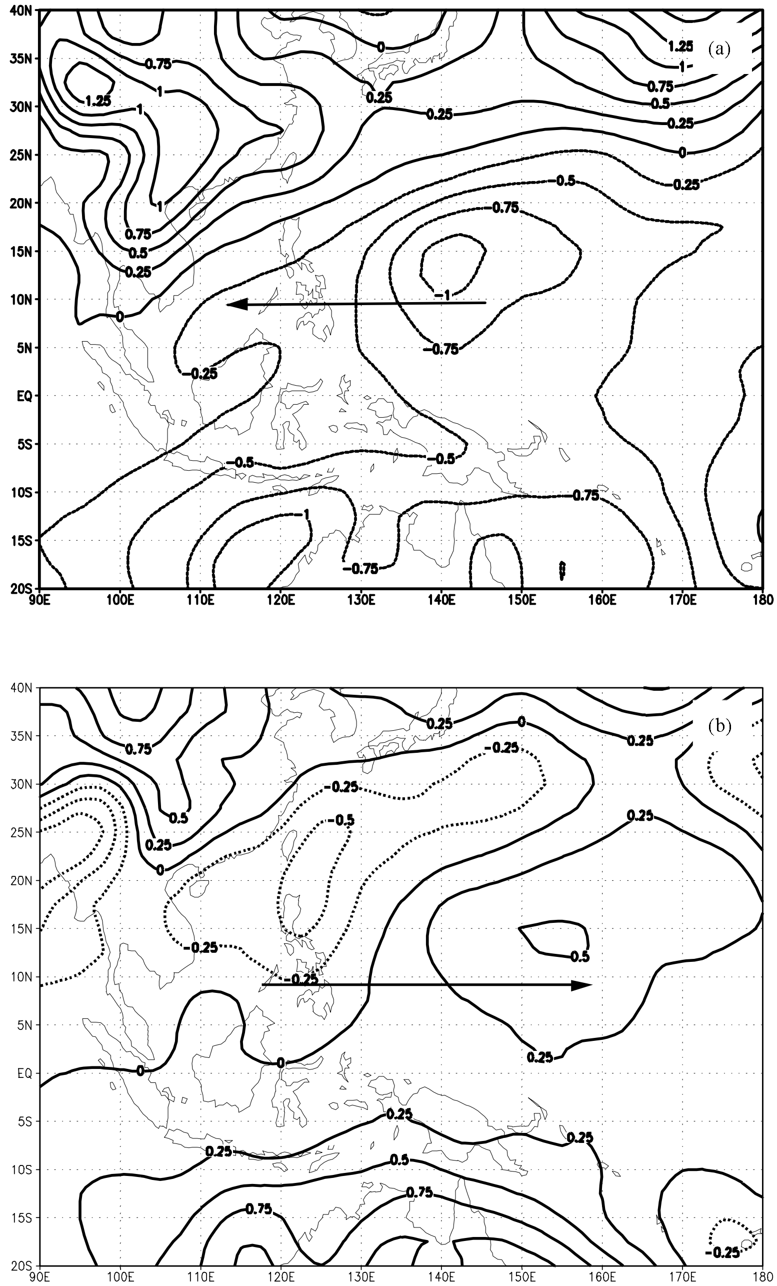

Fig. 6. Distribution of the sea surface pressure anomaly in December in the tropical western Pacific region in (a) strong and (b) weak East Asian Winter Monsoon (Li et al., 2005).

That is to say, the Plateau is a key and sensitive area for monitoring and predicting monsoon. Therefore, studies on the Plateau are very important.

(5) The East Asian subtropical summer monsoon rain belt locates on the forward side of summer monsoon, so the rain belt moves northward as the summer monsoon marches northward. Rainfall is relatively less in the controlling region of summer monsoon, i.e. the activity on the forward side of summer monsoon is directly related to the progression of the rain belt. Hereby, the research on monsoon edge is also a meaningful problem.

(6) Asian monsoon is the outcome of interactions among the Earth, ocean, atmosphere, hydrosphere, biosphere, and cryosphere, and the evolving rule and variability of monsoon influences greatly the plantation, bio-Earth, chemistry, economy and society in the entire Asian monsoon region. Therefore, it is necessary

to place monsoon in the coupled system of land-sea-atmosphere and to know its characteristics and mechanisms through studying the interactions among different spheres, layers, systems and scales.

(7) The seasonal prediction of monsoon activity is critical to national economy and social development, but the predicting ability of the present coupled model of land-sea-atmosphere has many difficulties. A proper description of the Tibetan Plateau in the model, a correct introduction of land-atmosphere processes, and a reasonable parameterization of physical processes are critical to upgrade the ability to predict the East Asian Monsoon. Thus, progress in the study of models is highly necessary.

(8) The change of the coverage on land and the atmospheric components at both regional and global scales induced by human activity may influence the future of Asian monsoon to a great extent. Research on this aspect helps to regulate human activity, realize the harmony between human and nature, and protect the living environment of human beings.

To sum up, the mechanisms of variation of East Asian monsoon, the mechanisms of East Asian monsoon influencing weather and climate in China, especially flooding and drought, and the theories and methods of predicting East Asian monsoon are still the primary aims in the study of monsoon in future.

Acknowledgements. The authors would like to thank all the authors of the references for their research achievements. We also wish to thank Chen Hua, Wei Jin and Zhu Xiaying for their kind assistance. This work was jointly supported by the National Natural Science Foundation of China (Grant Nos. 40633018; 40675056) and the key project A of the State Ministry of Science and Technology of China "South China Sea Monsoon Experiment (SCSMEX)".

REFERENCES

Chao, W. C., 2000: Multiple quasi equilibria of the ITCZ and the origin of monsoon onset. *J. Atmos. Sci.*, **57**, 641–651.

Chao, W. C., and B. Chen, 2001: Multiple quasi equilibria of the ITCZ and the origin of monsoon onset. Part II: Rotational ITCZ attractors. *J. Atmos. Sci.*, **58**, 2820–2831.

Chen, L., Q. Zhu, H. Luo, J. He, M. Dong, and Z. Feng, 1991: *East Asian Monsoon*. China Meteorological Press, Beijing, 362pp. (in Chinese)

Chen, L., H. Gao, J. He, S. Tao, and Z. Jin, 2004: Zonal propagation of kinetic energy and convection in the South China Sea and Indian monsoon regions in boreal summer. *Science in China* (*Series D*), **34**(2), 171–179. (in Chinese)

Chen, W., H.-F. Graf, and R. 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., S. Yang, and R. Huang, 2005: Relationship between stationary planetary wave activity and the East Asian winter monsoon. *J. Geophys. Res.*, **110**, D14110, doi:10.1029/2004JD005669.

Dai, X., P. Wang, and J. Chou, 2003: Multiscale characteristics of the rainy season rainfall and interdecadal decaying of summer monsoon in North China. *Chinese Science Bulletin*, **38**(23), 2483–2487. (in Chinese)

Ding, Y., 1994: *Monsoons over China*. Kluwer Academic Publishers, Dordrecht, Boston, London, 420pp.

Ding, Y., 2004: Seasonal march of the East-Asia summer monsoon. *East Asian Monsoon*, C. P. Chang, Ed., World Scientific Publishing, Singapore, 562–563.

Ding, Y., and G. Hu, 2003: A study on water vapor budget over China during the 1998 severe flood periods. *Acta Meteorologica Sinica*, **61**(2), 129–145. (in Chinese)

Ding, Y., and J. C. L. Chan, 2005: The East Asian summer monsoon: An overview. *Meteor. Atmos. Phys.*, **89**, 117–142.

Ding, Y., C. Li, J. He, and L. Chen, 2004: South China Sea monsoon experiment (SCSMEX) and the East-Asian monsoon. *Acta Meteorologica Sinica*, **62**(5), 561–586. (in Chinese)

Fasullo, J., and P. J. Webster, 2003: A hydrological definition of Indian monsoon onset and withdrawal. *J. Climate*, **16**, 3200–3211.

Fong, S., A. Wang, T. Tong, G. Li, K. Lam, J. Liang, C. Wu, and Q. Fan, 2005: Climatological characteristics of the maintaining period of South China Sea summer monsoon, II: Interdecadal Variation. *Journal of Tropical Meteorology*, **21**(2), 123–130. (in Chinese)

Gao, H., L. Chen, J. He, S. Tao, and Z. Jin, 2005: Characteristics of zonal propagation of atmospheric kinetic energy at equatorial region in Asia. *Acta Meteorologica Sinica*, **63**(1), 21–29. (in Chinese)

Gao, S., Y. Zhou, and T. Lei, 2002: Structural features of the mei-yu front system. *Acta Meteorologica Sinica*, **16**(2), 195–204. (in Chinese)

Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteor. Soc.*, **106**, 447–462.

Han, R., W. Li, and M. Dong, 2006: The impact of 30–60 day oscillations over the subtropical Pacific on the East Asian summer rainfall. *Acta Meteorologica Sinica*, **64**(2), 149–163. (in Chinese)

He, H., C.-H. Sui, M. Jian, Z. Wen, and G. Lan, 2003: The evolution of tropospheric temperature field and its relationship with the onset of Asian summer monsoon. *J. Meteor. Soc. Japan*, **81**(5), 1201–1223.

He, J., Q. Zhu, and M. Murakami, 1996: TBB data-revealed features of Asian-Australian monsoon seasonal transition and Asian summer monsoon establishment. *Journal of Tropical Meteorology*, **12**(1), 34–42. (in Chinese)

He, J., Y. Ding, H. Gao, and H. Xu, 2001: *The Definition of Onset Date of South China Sea Summer Monsoon and the Monsoon Indices*. China Meteorological Press, Beijing, 123pp. (in Chinese)

He, J., M. Wen, X. Shi, and Q. Zhao, 2002: Splitting and eastward withdrawal of the subtropical high belt during the onset of the South China Sea summer monsoon and their possible mechanism. *Journal of Nanjing University* (*Natural Sciences*), **38**(3), 318–330. (in Chinese)

He, J., L. Wang, H. Xu, and B. Zhou, 2004a: Climatic features of SCS summer monsoon onset and its possible mechanism. *Bimonthly of Xinjiang Meteorology*, **27**(1), 1–7. (in Chinese)

He, J., J. Yu, X. Shen, and H. Gao, 2004b: Research on mechanism and variability of East Asian monsoon. *Journal of Tropical Meteorology*, **20**(5), 449–459. (in Chinese)

He, J., M. Wen, L. Wang, and H. Xu, 2006: Characteristics of the onset of the Asian Summer Monsoon and the importance of Asian-Australian "land bridge". *Adv. Atmos. Sci.*, **23**(6), 951–963.

Huang, R., Z. Zhang, G. Huang, and B. Ren, 1998: Characteristics of the water vapor transport in East Asian monsoon region and its difference from that in South Asian monsoon region in summer. *Scientia Atmospherica Sinica*, **22**(4), 460–469. (in Chinese)

Huang, R., W. Chen, Y. Ding, and C. Li, 2003a: Studies on the monsoon dynamics and the interaction between monsoon and ENSO cycle. *Chinese J. Atmos. Sci.*,.**27**(4), 484–502. (in Chinese)

Huang, R., L. Zhou, and W. Chen, 2003b: The progress of recent studies on the variability of the East Asian monsoon and their causes. *Adv. Atmos. Sci.*, **20**(1), 55–69.

Huang, R., L. Gu, Y. Xu, Q. Zhang, 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**(1), 20–36. (in Chinese)

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.

Jiang, D., and H. Wang, 2005: Natural interdecadal weakening of East Asian summer monsoon in the late 20th century. *Chinese Science Bulletin*, **50**(20), 2256–2262. (in Chinese)

Jiang, Z., J. He, J. Li, J. Yang, and J. Wang, 2006: Northerly advancement characteristics of the East Asian summer monsoon with its interdecadal variations. *Acta Geographica Sinica*, **61**(7), 675–686. (in Chinese)

Jin, Q., J. He, L. Chen, and C. Zhu, 2006: Impact of ocean-continent distribution over southern Asian on the formation of summer monsoon. *Acta Meteorologica Sinica*, **20**(1), 95–108.

Ju, J., and E. Zhao, 2005: Impacts of the low frequency oscillation in East Asian summer monsoon on the drought and flooding in the middle and lower valley of the Yangtze River. *Journal of Tropical Meteorology*, **21**(2), 163–173. (in Chinese)

Ju, J., J. Ren, and J. LÜ, 2004: Effect of interdecadal variation of Arctic Oscillation on temperature increasing in North of East Asian Winter. *Plateau Meteorology*, **23**(4), 429–434. (in Chinese)

Ju, J., C. Qian, and J. Cao, 2005a: The intraseasonal oscillation of East Asian summer monsoon. *Chinese J. Atmos. Sci.*, **29**(2), 187–194. (in Chinese)

Ju, J., J. LÜ, J. Cao, and J. Ren, 2005b: Possible impacts of the Arctic Oscillation on the interdecadal variation of summer monsoon rainfall in East Asia. *Adv. Atmos. Sci.*, **22**(1), 39–48.

Li, C., 2004: Recent progress in atmospheric intraseasonal oscillation research. *Progress in Natural Science*, **14**(7), 734–741. (in Chinese)

Li, C., Z. Wang, S. Lin, and H. Gao, 2004: The relationship between East Asian summer monsoon activity and northward jump of the upper westerly jet location. *Chinese J. Atmos. Sci.*, **28**(5), 641–658. (in Chinese)

Li, C., S. Pei, and Y. Pu, 2005: Dynamical influence of anomalous East Asian winter monsoon on zonal wind over the equatorial western Pacific. *Chinese Science Bulletin*, **50**(11), 1136–1141. (in Chinese)

Li, J., and Q. Zeng, 2003a: A new monsoon index and the geographical distribution of the global monsoons. *Adv. Atmos. Sci.*, **20**(2), 299–302.

Li, J., and Q. Zeng, 2003b: A unified monsoon index. *Geophys. Res. Lett.*, **29**(8), 1151–1154.

Li, J., and Q. Zeng, 2005: A new monsoon index, its interannual variability and relation with monsoon precipitation. *Climatic and Environmental Research*, **10**(3), 351–365. (in Chinese)

Liang, J., and S. Wu, 2002: A study of southwest monsoon onset date over the South China Sea and its impact factors. *Chinese J. Atmos. Sci.*, **26**(6), 829–841. (in Chinese)

Liang, J., and S. Wu, 2003: The study on the mechanism of SSTA in the Pacific Ocean affecting the onset of summer monsoon in the South China Sea—Numerical experiments. *Acta Oceanologica Sinica*, **25**(1), 28–41. (in Chinese)

Liang, X., Y. Liu, and G. Wu, 2005: Effect of Tibetan Plateau on the site of onset and intensity of the Asian summer monsoon. *Acta Meteorologica Sinica*, **63**(5), 799–805. (in Chinese)

Liao, Q., S. Gao, H. Wang, and S. Tao, 2004: Anomalies of the extratropical westerly jet in the North Hemisphere and their impacts on East Asian summer monsoon climate anomalies. *Chinese Journal of Geophysics*, **47**(1), 10–18. (in Chinese)

Liu, C., H. Wang, and D. Jiang, 2004: The configurable relationships between summer monsoon and precipitation over East Asia. *Chinese J. Atmos. Sci.*, **28**(5), 700–712. (in Chinese)

Liu, Y., and Y. Ding, 2005: A study on the meso-scale convective systems during summer monsoon onset over the South China Sea in 1998, II: Effect of the meso-scale convective systems on large-scale fields. *Acta Meteorologica Sinica*, **63**(4), 443–454. (in Chinese)

Liu, Y., and Y. Ding, 2007: Analysis of the Basic Features of the onset of the Asian Summer Monsoon. *Acta Mteteorological Sinica*, **21**(3), 257–276

Liu, Y., Z. Chen, J. Mao, and G. Wu, 2003a: Impacts of the onset of the Bay of Bengal monsoon on the onset of the South China Sea monsoon. Part I: A case study. *Acta Meteorologica Sinica*, **61**(1), 1–10. (in Chinese)

Liu, Y., Z. Chen, and G. Wu, 2003b: Impacts of the onset of the Bay of Bengal monsoon on the onset of the South China Sea monsoon. Part II: Numerical experiments. *Acta Meteorologica Sinica*, **61**(1), 11–19. (in Chinese)

Liu, Y., Y. Ding, and N. Zhao, 2005: A study on the meso-scale convective systems during summer monsoon onset over the South China Sea in 1998, I: analysis of large-scale fields for occurrence and development of meso-scale convective systems. *Acta Meteorologica Sinica*, **63**(4), 431–442. (in Chinese)

LÜ, J., J. Ren, and J. Ju, 2004: The interdecadal variability of East Asian Monsoon and its effect on the rainfall over China. *Journal of Tropical Meteorology*, **20**(1), 74–80. (in Chinese)

LÜ, J., Q. Zhang, S. Tao, and J. Ju, 2006: The onset and advance of the Asian summer monsoon. *Chinese Science Bulletin*, **51**(1), 80–88.

Lu, R. and B. Dong, 2001: Westward extension of North Pacific subtropical high in summer. *J. Meteor. Soc. Japan*, **79**, 1229–1241.

Lu, R., and B. Ren, 2005: The influence of ENSO on the seasonal convection evolution and the phase of 30-60-day oscillations during boreal summer. *J. Meteor. Soc. Japan*, **83**, 1025–1040.

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

Luo, M., and C. Li, 2004: A study of the onset of the summer monsoon over the South China Sea. *Climatic and Environmental Research*, **9**(3), 495–509. (in Chinese)

Mooley, D. A., and J. Shukla, 1987: Variability and forecasting of the summer monsoon rainfall over India. *Monsoon Meterorlogy*, C.-P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, Oxford, 26–59.

Nan, S., and J. Li, 2005: The relationship between the summer precipitation in the Yangtze River Valley and the boreal spring Southern Hemisphere annular mode. I: Basic facts. *Acta Meteorologica Sinica*, **63**(6), 837–846. (in Chinese)

Pu, Y., S. Pei, C. Li, and Y. Chen, 2006: Influence of anomalous East Asian winter monsoon on zonal wind anomalies over the equatorial western Pacific. *Chinese J. Atmos. Sci.*, **30**(1), 69–79. (in Chinese)

Qi, L., J. He, R. Zhan, and Z. Zhang, 2006: Characteristics of the western Pacific subtropical high double ridges process in 1962. *Chinese J. Atmos. Sci.*, **30**(4), 682–692. (in Chinese)

Qian, W., 2005: Review of variations of the summer monsoon from seasonal to interannual and interdecadal scales. *Journal of Tropical Meteorology*, **21**(2), 199–206. (in Chinese)

Qian, W. H., H. S. Kang, and D. K. Lee, 2000: Seasonal march of Asian summer monsoon. *International Journal of Climatology*, **20**(11), 1371–1378.

Qian, Y., Y. Zhang, and Y. Zheng, 2003: Impacts of the Tibetan Plateau snow anomaly in winter and spring on precipitation in China in spring and summer. *Arid Meteorology*, **21**(3), 1–7. (in Chinese)

Qian, Y., J. Jiang, Y. Zhang, Y. Yao, and Z. Xu, 2004: The earliest onset area of the tropical Asian Summer monsoon and its mechanism. *Acta Meteorologica Sinica*, **42**(2), 129–139. (in Chinese)

Ren, X., and Y. Qian, 2003: Numerical simulation experiments of the impacts of local land-sea thermodynamic contrasts on the SCS summer monsoon onset. *Journal of Tropical Meteorology*, **9**(1), 1–8.

Shu, T., and H. Luo, 2003: Abrupt change of the west Pacific subtropical high and its interannual variation during the later spring and early summer. *Journal of Tropical Meteorology*, **19**(1), 17–26. (in Chinese)

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

Tian, H., P. Guo, and W. Lu, 2004: Characteristics of vapor inflow corridors related to summer rainfall in China and impact factors. *Journal of Tropical Meteorology*, **20**(4), 401–408. (in Chinese)

Tu, C., S. Huang, and Y. Gao, 1944: The advance and retreat of the summer monsoon. *Meteor. Mag.*, **18**, 1–20.

Wang, B., Y. Huang, J. He, and L. Wang, 2004a: Relation between vapor transportation in the period of East Asian summer monsoon and drought in Northwest China. *Plateau Meteorology*, **23**(6), 912–918. (in Chinese)

Wang, H., and F. Xue, 2003: Interannual variability of Somali jet and its influences on the inter-hemispheric water vapor transport and on the East Asian summer rainfall. *Chinese Journal of Geophysics*, **46**(1), 18–25. (in Chinese)

Wang, H., Y. Ding, and J. He, 2005: The climate research of summer monsoon over the western North Pacific. *Acta Meteorologica Sinica*, **63**(4), 418–430. (in Chinese)

Wang, L., J. He, and Z. Guan, 2004b: Characteristics of convection activities over Sumatra area and its relationship with SCS summer monsoon onset. *Journal of Nanjing Institute of Meteorology*, **27**(4), 451–460. (in Chinese)

Wang, Y., and T. Kiyotoshi, 2005: Decadal climate variability of rainfall around the middle and lower reaches of Yangtzs River and atmospheric circulation. *Journal of Tropical Meteorology*, **21**(4), 351–358. (in Chinese)

Wen, M., and R. Zhang, 2005: Possible maintaining mechanism of climatological atmospheric quasi-biweekly oscillation around Sumatra. *Chinese Science Bulletin*, **50**(10), 1054–1056.

Wen, M., J. He, and Z. Xiao, 2004a: Impact of the convection over the Indo-China Peninsula on the onset of SCS summer monsoon. *Chinese J. Atmos. Sci.*, **28**(6), 864–875. (in Chinese)

Wen, Z., H. He, and R. Huang, 2004b: The influences of 30–60 d oscillation on the development of the South China Sea summer monsoon. *Acta Oceanologica Sinica*, **23**(4), 568–579.

Wen, Z., R. Huang, H. He, and G. Lan, 2006a: The influences of anomalous atmospheric circulation over mid-high latitudes and the activities of 30–60 d low frequency convection over low latitudes on the onset of the South China Sea summer monsoon. *Chinese J. Atmos. Sci.*, **30**(5), 952–964. (in Chinese)

Wen, Z., Z. Liang, and L. Wu, 2006b: The relationship between the Indian Ocean sea surface temperature anomaly and the onset of South China Sea summer monsoon, II: mechanism analysis. *Chinese J. Atmos. Sci.*, **30**(6), 1138–1146. (in Chinese)

Wu, B., 2005: Weakening of Indian summer monsoon in recent decades. *Adv. Atmos. Sci.*, **22**(1), 21–29.

Wu, B., and J. Wang, 2002: Winter Arctic Oscillation, Siberian high and East Asian winter monsoon. *Geophys. Res. Lett.*, **29**, 1897, doi:10.1029/2002GL015373.

Wu, B., D. Wang, and R. Huang, 2003a: Relationship between sea level pressures of the winter tropical western Pacific and the subsequent Asian summer monsoon. *Adv. Atmos. Sci.*, **20**(4), 496–510.

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

Wu, G., J. Mao, A. Duan, and Q. Zhang, 2004: Recent progress in the study on the impacts of Tibetan Plateau on Asian summer climate. *Acta Meteorologica Sinica*, **62**(5), 528–540. (in Chinese)

Wu, G., Y. Liu, X. Liu, A. Duan, and X. Liang, 2005: How the heating over the Tibetan Plateau affects the Asian climate in summer. *Chinese J. Atmos. Sci.*, **29**(1), 47–56. (in Chinese)

Wu, S., J. Liang, and C. Li, 2003b: Relationship between the intensity of South China Sea summer monsoon and the precipitation in raining seasons in China. *Journal of Tropical Meteorology*, **19**(Suppl.), 25–36. (in Chinese)

Wu, Z. W., J. P. Li, J. H. He, 2006a: The occurrence of droughts and floods during the normal summer monsoons in the mid- and lower reaches of the Yangtze River. *Geophys. Res. Lett.*, **33**, L05813, doi:10.1029/2005GL024487.

Wu, Z. W., J. P. Li, J. H. He, 2006b: The large-scale atmospheric singularities and the summer long-cycle droughts-floods abrupt alternation in the middle and lower reaches of the Yangtze River. *Chinese Science Bulletin*, **51**(16), 2027–2034.

Xu, H., J. He, and M. Dong, 2001: Numerical study of the effect of Indian peninsula on South Asian summer monsoon process. *Journal of Tropical Meteorology*, **17**(2), 117–124. (in Chinese)

Xu, H., J. He, M. Wen, and M. Dong, 2002: A numerical study of effects of the Indo-China Peninsula on the establishment and maintenance of the South China Sea summer monsoon. *Chinese J. Atmos. Sci.*, **26**(3), 330–342. (in Chinese)

Xu, X., L. Chen, X. Wang, Q. Miao, and S. Tao, 2003: Moisture sink and source for the mei-yu rain band in the Yangtze River valley. *Chinese Science Bulletin*, **48**(21), 2288–2294. (in Chinese)

Xue, F., D. Jiang, X. Lan, and H. Wang, 2003a: Influence of the Mascarene high and Australian high on the summer monsoon in east Asia: Ensemble simulation. *Adv. Atmos. Sci.*, **20**(5), 799–809.

Xue, F., H. Wang, and J. He, 2003b: Interannual variability of Mascarene high and Australian high and their influences on summer rainfall over East Asia. *Chinese Science Bulletin*, **48**(3), 287–291. (in Chinese)

Yan, X., and M. Zhang, 2004a: A study of the Indian Ocean dipole influence on climate variations over East Asian monsoon region. *Climatic and Environmental Research*, **9**(3), 427–436. (in Chinese)

Yan, X., and M. Zhang, 2004b: Numerical simulation of the Indian Ocean dipole influence on climate variations over East Asian monsoon region during equator east Pacific SSTA. *Journal of Tropical Meteorology*, **20**(4), 376–382. (in Chinese)

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. Xie, Y. Zhu, X. Sun, and Y. Guo, 2005: Decadal-to-interdecadal variability of precipitation in North China and associated atmospheric and oceanic anomaly patterns. *Chinese Journal of Geophysics*, **48**(4), 789–797. (in Chinese)

Yano, J.-I., and J. L. McBride, 1998: An Aquaplanet Monsoon. *J. Atmos. Sci.*, **55**, 1373–1399.

Ye, D., S. Tao, and M. Li, 1959: The abrupt change of circulation over the Northern Hemisphere during June and October. *The Atmosphere and the Sea in Motion*, Rockefeller Institute, New York, 249–267.

Zeng, Q., and J. Li, 2002: Interactions between the Northern and Southern Hemispheric atmospheres and the essence of monsoon. *Chinese J. Atmos. Sci.*, **26**(4), 433–448. (in Chinese)

Zeng, Q., and Coauthors, 2005: The abrupt seasonal transitions in the atmospheric general circulation and the onset of monsoons. Part I: Basic theoretical method and its application to the analysis of climatological mean observations. *Climatic and Environmental Research*, **10**(3), 285–302. (in Chinese)

Zhan, R., J. Li, and J. He, 2005: Statistical characteristics of the double ridges of subtropical high in the Northern Hemisphere. *Chinese Science Bulletin*, **50**(20), 2336–2341.

Zhang, M., D. Zhang, R. Zuo, J. He, and Q. Zeng, 2005: The abrupt seasonal transitions in the atmospheric general circulation and the onset of monsoons. Part II: The onset of summer monsoon in South China Sea region. *Climatic and Environmental Research*, **10**(3), 303–314. (in Chinese)

Zhang, Q., S. Tao, and L. Chen, 2003: The interannual variability of East Asian summer monsoon indices and its association with the pattern of general circulation over East Asia. *Acta Meteorologica Sinica*, **61**(4), 559–568. (in Chinese)

Zhang, R., 2001: Relations of water vapor transports from Indian monsoon with those over East Asia and the summer rainfall in China. *Adv. Atmos. Sci.*, **18**, 1005–1017.

Zhang, R., and A. Sumi, 2002: Moisture circulation over East Asia during El Niño episode in northern winter, spring and autumn. *J. Meteor. Soc. Japan*, **80**, 213–227.

Zhang, S., S. Tao, Q. Zhang, and J. Wei, 2002: Multiscale conditions of torrential rain causing floods in the mid- and lower-reaches of the Yangtze River. *Chinese Science Bulletin*, **47**(6), 467–473. (in Chinese)

Zhang, Y., and Y. Qian, 2002: Mechanism of thermal features over the Indo-China Peninsula and possible effects on the onset of the South China Sea monsoon. *Adv. Atmos. Sci.*, **19**(5), 885–900.

Zhang, Y., A. Xie, and N. Dai, 2004a: Preceding features associated with the anomalous summer monsoon over the South China Sea. *Journal of Tropical Meteorology*, **20**(5), 460–471. (in Chinese)

Zhang, Z., J. C. L. Chan, and Y. Ding, 2004b: Characteristics, evolution and mechanisms of the summer monsoon onset over Southeast Asia. *International Journal of Climatology*, **24**, 1461–1482.

Zhao, P., and Z. Zhou, 2005: East Asian subtropical summer monsoon index and its relationships to rainfall. *Acta Meteorologica Sinica*, **63**(6), 933–941. (in Chinese)

Zhao, P., and R. Zhang, 2006: Relationship of interannual variation between an Eastern Asia-Pacific dipole pressure pattern and East Asian monsoon. *Chinese J. Atmos. Sci.*, **30**(2), 307–316. (in Chinese)

Zhao, P., R. Zhang, J. Liu, X. Zhou, and J. He, 2006: Onset of southwesterly wind over eastern China and associated atmospheric circulation and rainfall. *Climate Dyn.*, doi:10.1007/s00382-006-0212-y.

Zhou, C., J. He, W. Li, and L. Chen, 2005a: Climatological characteristics of water vapor transfer over East Asia in summer. *Journal of Nanjing Institute of Meteorology*, **28**(1), 18–27. (in Chinese)

Zhou, W., Z. Chen, and C. Li, 2005b: South China Sea summer monsoon onset in relation to the off-equatorial ITCZ. *Adv. Atmos. Sci.*, **22**(5), 665–676.

Zhou, Y. S., S. T. Gao, and S. Shen, 2004: A diagnostic study of formation and structures of the mei-yu front system over East Asia. *J. Meteor. Soc. Japan*, **82**(6), 1565–1576.

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