Discussion of Some Problems as to the East Asian Subtropical Monsoon*

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ABSTRACT

Based on NCEP/NCAR gridded reanalysis, TRMM precipitation data, CMAP, and rainfall observations in East China, a study is conducted with focus on the timing and distinctive establishment of the rainy season of the East Asian subtropical monsoon (EASM) in relation to the South China Sea (SCS) tropical summer monsoon (SCSM). A possible mechanism for the EASM is investigated. The results suggest that 1) the EASM rainy season begins at first over the south of the Jiangnan region to the north of South China in late March to early April (i.e., pentads 16–18), and then the early flooding period in South China starts when southerly winds enhance and convective rainfall increases pronouncedly; 2) the establishment of the EASM rainy season is earlier than that of its counterpart, the SCSM. The EASM and the SCSM each is featured with its own independent rain belt, strong southwesterly wind, intense vertical motion, and robust low-level water vapor convergence. The SCSM interacts with the EASM, causing the EASM rainy belt to move northward. The two systems are responsible for the floods/droughts over the eastern China; and 3) in mid-late March, the eastern Asian landmass (especially the Tibetan Plateau) has its thermal condition changing from a cold to a heat source for the atmosphere. A reversal of the zonal thermal contrast and related temperature and pressure contrasts between the landmass and the western Pacific happens. The argument about whether or not the dynamic and thermal effects of the landmass really act as a mechanism for the earlier establishment of the EASM rain belt is discussed and to be further clarified. Finally, the article presents some common understandings and disagreements regarding the EASM.

Key words: East Asian subtropical monsoon, South China Sea tropical monsoon

1. Introduction

The land-sea distribution of East Asia with the Tibetan Plateau as its prominent terrain causes huge meridional and zonal thermal contrasts, resulting in a complex and unique East Asian monsoon system. One of the features of this monsoon system is that there coexist tropical and subtropical elements.

As indicated in Chen and Jin (1984), as a tropical monsoon system, the South China Sea (SCS) monsoon circulation is independent of the Indian counterpart. Subsequently, Zhu et al. (1986) showed that there is an SCS-western Pacific tropical monsoon system to the south of the western Pacific subtropical high (denoted as sub-high hereinafter) and also a subtropical monsoon circulation north of the sub-high that stretches from the China mainland to Japan. Tao and Chen (1987) presented a complete and explicit picture of the East Asian subtropical monsoon system (see Fig.1), of which the sub-high and Meiyu front are the principal East Asian subtropical monsoon members. This widely cited result contributes greatly to the development of the East Asian monsoon research. In the following decade and more, through the Sino-US and Sino-Japan cooperative monsoon projects such as the SCS Monsoon Experiment (SCSMEX), Chinese scientists achieved encouraging progress in this research field (Chen et al., 1991; Ding et al., 1994; Wu and

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Zhang 1999; Huang et al., 2003; Wu, 2004; Qian et al., 2004; Ding et al., 2004; Li et al., 2006). He, Ju, et al. (2007) made a review on the advances of recent monsoon research by Chinese investigators, finding that not many studies have been carried out on the subtropical monsoon. It is worth noting that the concept of the East Asian subtropical monsoon zone has been proposed on a geographical and biological basis. Gao (1962), for example, delimited clearly the zone over 20°–50°N of eastern China. Later, Zhang et al. (1996) demarcated the zone in latitude and longitude extent, and Li et al. (2003) broadly determined the zone by means of a normalized monsoon index. Qian and Lee (2000) further divided the subtropical monsoon zone from China to Japan into East and Northeast Asian subtropical monsoon regions. Through analyzing monsoon properties at a range of regions, Wang et al. (2000) presented a division of the Asian summer monsoon zone into the SCS-western Pacific zone called the “northwestern Pacific monsoon area”, and China to Japan subtropical zone referred to as the “Eastern Asian summer monsoon area”. This delineation of the monsoon regions has drawn much attention of the meteorological researchers internationally.

To sum up, the East Asian subtropical monsoon (EASM) is a monsoon system that differs from the tropical monsoon. It has its own approximate domain (Fig.1), which has been accepted by the meteorological community (Fig.1) at home and abroad. But there are two misleading ideas about the EASM. one is associated with geography, without understanding the intrinsic features of the system, holding that the monsoon prevailing over the East Asian subtropics is by name none other than the East Asian subtropical monsoon. The other maintains that the northward extension of the SCSM is just the subtropical monsoon. The present work is intended to address such issues as how the EASM rainy season is established, how it marches with season towards the north, how the EASM is related to the SCSM, and what drives the EASM, with an ultimate aim to promote in-depth knowledge of the EASM.

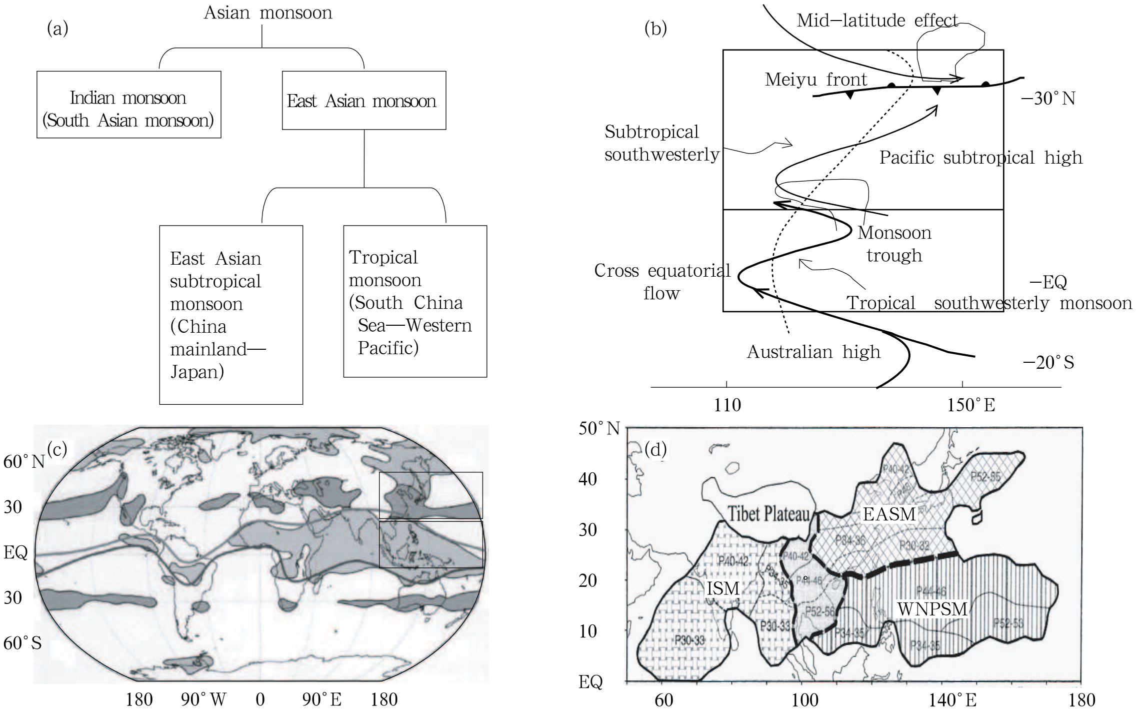

Fig.1. The Asian monsoon regions from different sources. These figures are provided by (a) Zhu et al. (1986), (b) Tao and Chen (1987), (c) Zeng and Li (2000), and (d) Wang et al. (2002).

2. Data sources

The present study used the following datasets:

1) 1961–2000 NCEP/NCAR gridded reanalysis data with 2.5°×2.5° horizontal resolution;

2) 1998–2006 TRMM precipitation data with 2.5°×2.5° resolution;

3) 1981–2000 rainfall data at 693 stations in East China;

4) 1979–2000 precipitation data from Climate Prediction Center Merged Analysis of Precipitation (CMAP) with 2.5°×2.5° resolution.

Climatological means were performed with all the variables. The annual average was removed for some variables and "anomaly or departure" was used herein to reveal the seasonal cycle of the East Asian subtropical monsoon (EASM).

3. Establishment of the EASM rainy season

When and where is the EASM rainy season or rainbelt firstly established and what are its properties? These are the first and foremost problems. Many investigators, Chinese and foreign, have performed considerable studies. For example, the rainfall in late March to early April occurring in South China is denoted an initial stage of the early flooding period (see Bao, 1980) and also called a springtime persistent precipitation stage (Tian and Yasunari, 1988). Subsequently, Wan and Wu (2006) made a pioneer study on the mechanism of the springtime rainfall. The April-June rainfall in South China is referred to as an early summer rainy season (Ding et al., 1994) and also as the South China-Taiwan Meiyu rainfall (Chen, 2004). As indicated in Chen et al. (2000), the EASM rainfall begins early in April in the north of South China and the Jiangnan region, spreading out south- and southwestward into the southern China seaboard and the Indo-China Peninsula by the end of April. Xu et al. (2002) maintained that the EASM breaks out early in April over the central Jiangnan region. The southwest wind prevailing in East Asia to the western Pacific happens first at subtropical latitudes, accompanied by the beginning of the subtropical rainy season (Zhao et al., 2007). Some other researchers pointed out that the seasonal reversal of land-sea thermal contrast between East Asia and the western Pacific takes place at first at subtropics in late March and early April, with the prevailing winter northerlies changed to summer southerlies in the lower troposphere, together with concurrently occurring convective precipitation, which possibly marks the EASM establishment (see Qi et al., 2007). As shown in Wang et al. (2007), there are three rainbelts associated with the East Asian summer monsoon over East China happening, in order, in the Jiangnan zone, mid-lower Yangtze River Valley, and North-Northeast China, with their duration in the pentads 20–34, 35–39, and 40–44, respectively. This suggests that the earliest monsoon rainband starts early in April (pentad 20) over the Jiangnan region. For convenience in later use all the aforementioned viewpoints are collectively referred to as class A. In spite of the fact that the class A viewpoints hold that the EASM rainy season, i.e., its rainbelt, or its sustained rainfall stage, is established first in late March to early April over the southern China-the Jiangnan zone, but the terms and connotations vary greatly, as exemplified by such names as "early flooding season", "Jiangnan spring rainy interval", "early summer rainy season", "South China-Taiwan Meiyu precipitation period", "subtropical monsoon rainy stage", and "subtropical summer monsoon rainfall period".

However, Lau and Yang (1997), Webster et al. (1998), and Wang and Lin (2002) indicated that the EASM rainband is established first around mid May over South China, followed by its northward advance. The dates of its appearance (figure omitted) show that only after the tropical summer monsoon starts over the SCS and its thereabouts is the EASM rainy season established. As seen from the northward moving contours of the establishment dates, the EASM establishment is thought to be the product of the SCSM traveling northward. In addition, Lian et al. (2007) showed the EASM is established at pentad 26. Obviously, these viewpoints differ greatly from class A and are thus grouped as class B. Essentially, the key issue lies in how to define the rainy period lasting from late

March to the time of the SCSM establishment. Could it belong to a part of the EASM rainy season? If this rainy period is cascaded with the South China rainy season, Jiang-Huai Meiyu precipitation, and North-Northeast China rainfall stages, those after the SCSM establishment around mid May, they constitute a complete seasonal cycle of the EASM. It is then natural to regard this late March to mid May rainy period as an early stage of the EASM rainy season. Thereby, the beginning of the EASM rainy season should be shifted ahead from post mid-May to the end of March. This serves as a new line of thinking in predicting summer droughts and floods in the eastern China, so the study of the problem is of much significance in either the theoretical or the application perspective.

To further understand the above problems we have to look at relevant facts. As shown in Fig. 2, rainfall over the southern China (25°–30°N) has been steadily over 6 mm day^{-1} after pentad 16 (late in March), suggestive of the initiation of the rainband, with its maximum reaching 10 mm day^{-1} (Fig.3b), in comparison with a maximum of 2 mm day^{-1} at pentad 6 (late January, Fig.3a). It is of particular note that the rainband, after staying over for a certain time in South China, begins to move southward prior to the SCSM establishment, then advances northward in early June, reaches the Jiang-Huai Basin in mid-late June, and finally arrives in North-Northeast China in July-August. Therefore, the rainbelt produces, all the way to the north, an early flooding rainy reason in South China, the Meiyu rainfall over the Jiang-Huai Basin and a rainy period over North-Northeast China. Then the rainband starts to retreat southward rapidly in September. The aforementioned facts show that the EASM rainy season is established late in March (after pentad 16) in the Jiangnan region-southern China (25°–30°N), advancing northward after the SCSM establishment, and then retrogressing rapidly back to the south in September. The rainband experiences a complete seasonal cycle accompanied by a seasonal cycle of the high meridional gradient zone of θ_{se} (i.e., the frontal zone) and the sub-high, and the associated

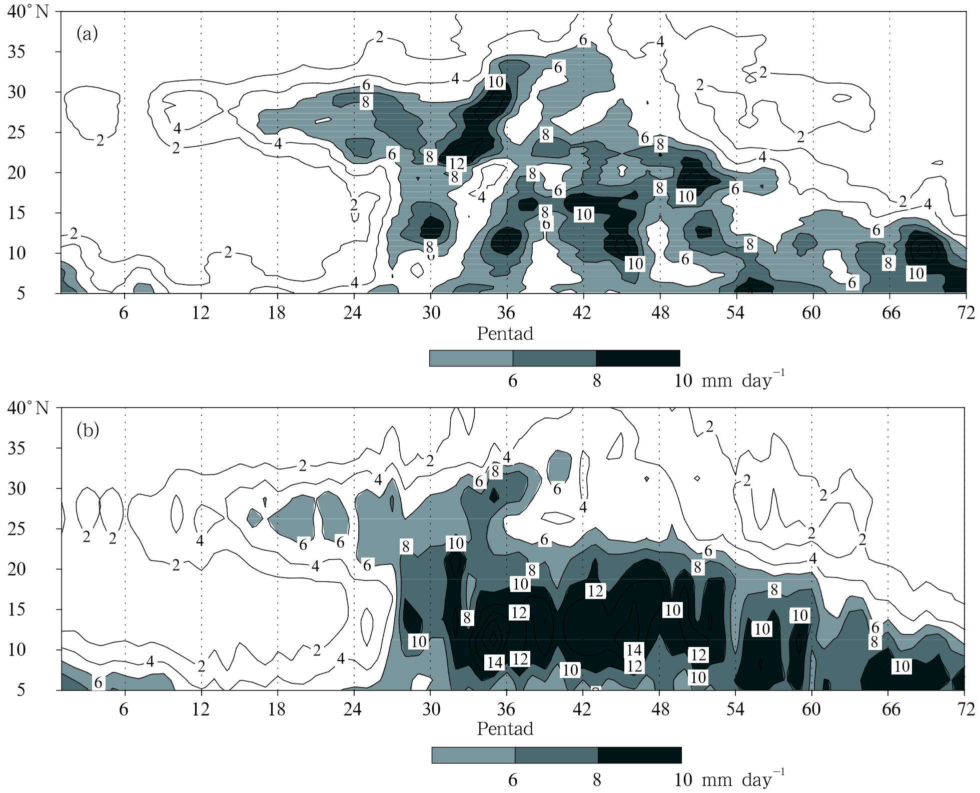

Fig.2. Time-latitude sections of climatological precipitation averaged over 110°–120°E from TRMM (a) and CMAP (b).

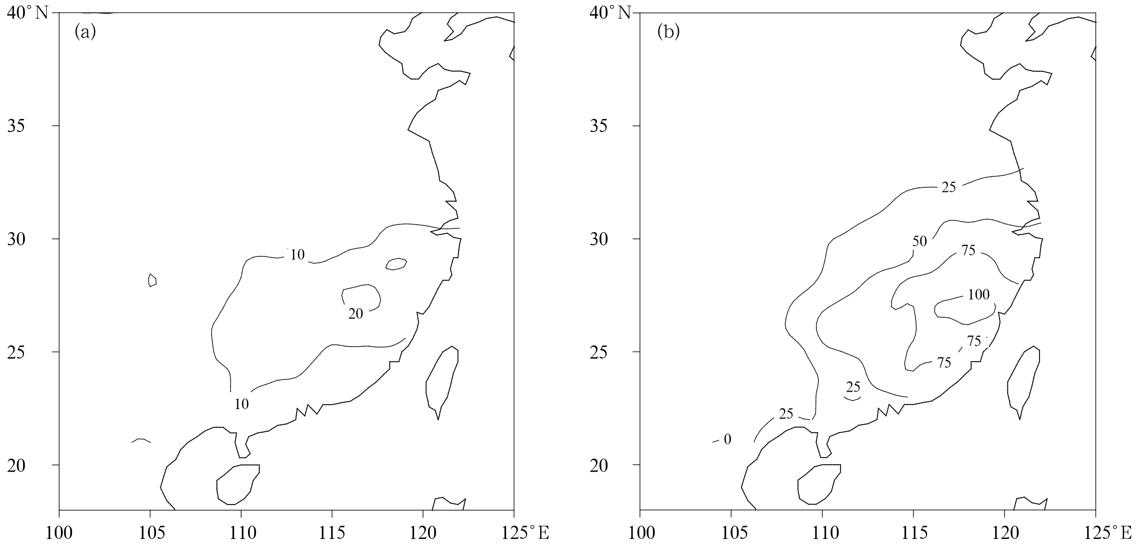

Fig.3. Climatological station rainfall (0.1 mm day^{-1}) for pentads 6 (a) and 16 (b) (from Zhao et al., 2007).

southerly winds undergo a similar seasonal cycle too, a statement that will be detailed later.

In summary, we come to a conclusion that from late March to the time before the SCSM establishment the persistent rainfall period (rainy episode) ought to be considered as a stage of the EASM rainfall. What are the properties of the precipitation? This is a problem to be answered next.

Figure 4 presents the evolution of water vapor transfer around pentad 16 at lower levels, integrated from surface to 700 hPa. It is seen therefrom that the low-latitude water vapor transport by easterly winds is more intense at pentad 13, accompanied by southward cross-equatorial water vapor transfer, a situation that is typical for winter (He, Qi, et al., 2007). When it comes at pentad 16, a distinct water vapor passage is formed that stretches from the western Pacific to South China. And it is the convergence ahead of the strong water vapor passage that leads to the substantial increase of rainfall over the Jiangnan region- South China in late March. At that time, the SCSM and its related water vapor passage have not yet been established. At pentad 28 the water vapor transfer pattern undergoes a dramatic change: the low-latitude easterly water vapor transfer passage and the southward cross-equatorial transport disappear, instead another water vapor corridor is established that originates in the southern low-latitude ocean, crossing the equator in the neighborhood of Somali into the Arabian Sea, following the path through the southern Indian Ocean and Bay of Bengal into South China, a situation typical of summer water vapor transfer. Meanwhile, the SCSM breaks out.

Figure 5 gives latitude-height cross sections of time-dependent vertical velocity averaged between 110° and 120°E, indicating that the meridional distribution of the vertical motion at pentad 1 bears a case for winter, with subsidence everywhere except feeble updrafts observed at mid-lower levels over China in 25°–30°N; at pentad 16 the updrafts have covered the whole troposphere over these latitudes. The related precipitation intensity has arrived at 6 mm day^{-1} (Fig.2c), reaching the level of deep convective rainfall (Lau and Yang, 1997; Qian et al., 2002), during which sinking downdrafts are dominant over the SCS, suggesting that the SCSM has not yet been established there; at pentad 36 the deep convective band moves northward over the Jiang-Huai Basin, producing the so-called "Jiang-Huai Meiyu". At that time, the SCS zone is under the control of deep convection, indicative of the SCSM establishment.

In association with the deep convection establishment and development in the southern part of China, the latent heating height and strength are increased rapidly posterior to pentad 16 (Fig.6). The foregoing analysis shows that the lasting precipitation of China

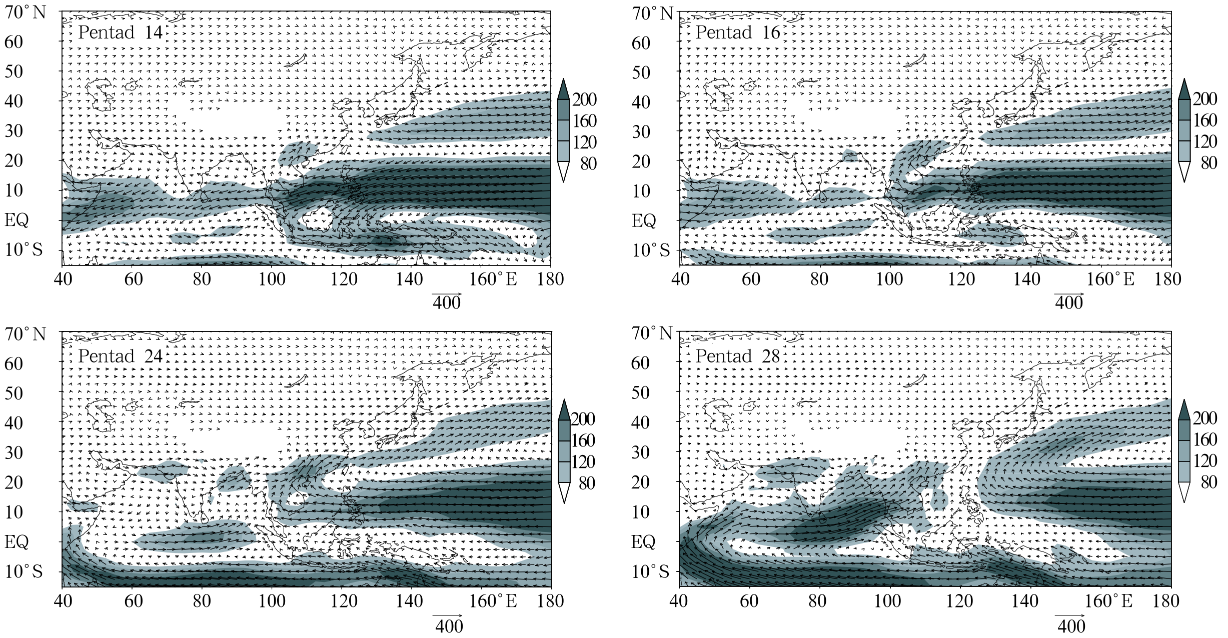

Fig.4. Climatological low-level water vapor transport (kg m^{-1} s^{-1}) integrated from surface to 700 hPa, with shading for the transport>80 kg m^{-1} s^{-1}.

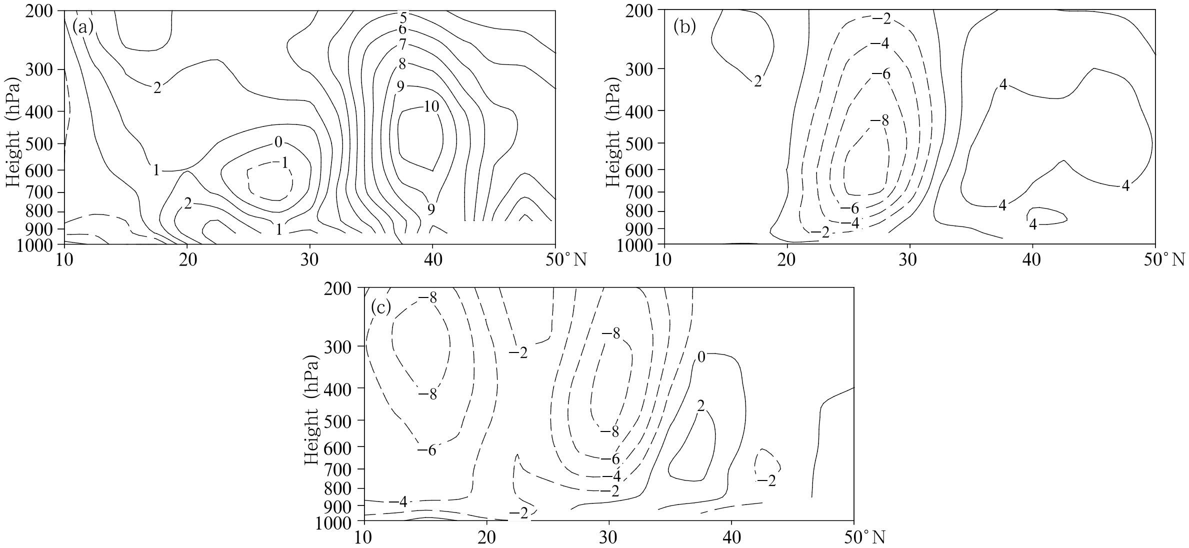

Fig.5. Latitude-height cross sections of climatological vertical velocity averaged over 110°–120°E for pentad 6 (a), pentad 16 (b), and pentad 36 (c) (Zhao et al., 2007).

in 25°–30°N after pentad 16 is of deeply convective character and is linked closely to the subsequent South China rainy season and Jiang-Huai Meiyu rainfall.

To summarize, we have sufficient reasons to give the statement that the sustained convective precipitation over the southern part of China in late March (after pentad 16) represents the beginning of the EASM rainy season, and the rainfall stage covering late March to the time before the SCSM establishment designates the incipient phase of the seasonal cycle of the EASM rainy season.

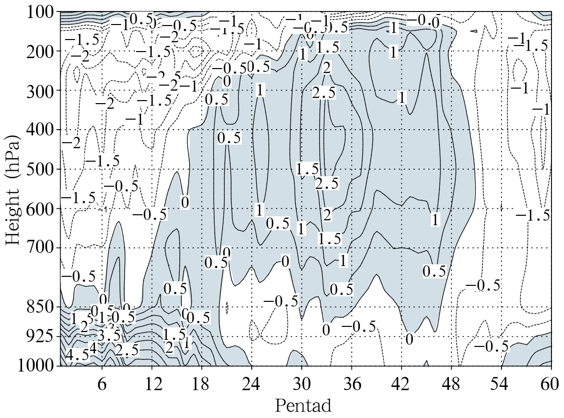

Fig.6. Pentad-varying heating rate (°C day^{-1}) in northern subtropical latitudes over 27.5°–32.5°N, 110°–140°E.

4. Relationship of the EASM and SCSM

As mentioned earlier, the class B viewpoints hold that the EASM rainbelt is established after the tropical summer monsoon has been established over the SCS and its vicinity, and the EASM establishment is the product of the northward movement of the SCSM (Tao and Chen, 1987; Lau and Yang, 1997; Webster et al., 1998; Wang and Lin, 2002). But the foregoing analyses in this study indicate that the persistent rainfall over South China in late March is of deep convective nature and can be classified into the cascade of rainfall events associated with the EASM. We suggest designating the late March persistent rainfall period as the beginning of the EASM rainy period and the initial stage of the EASM seasonal cycle. The establishment of the EASM rainy season is earlier than that of the SCSM rainfall. It is necessary to re-examine the relationship between the EASM and the SCSM.

The time-latitude sections of 850-hPa wind, precipitation anomalies, vorticity and moisture flux divergence are given in Fig.7, showing that positive rainfall anomalies emerge first in 25°–32.5°N around pentad 16 (late March), where the related northwesterly winds change to southwesterly flows, with the low-level water vapor flux convergence and cyclonic vorticity intensified greatly. Through the earlier analysis, the positive rainfall anomalies are associated with the EASM system, and the positive vorticity zone corresponds to the EASM trough. Wang et al. (2007) indicated that the EASM trough differs in character from the SCSM trough; the former is formed earlier than the latter. When the EASM rainy season starts, to its south in the tropical latitudes easterly flows are maintained, water vapor flux divergence and negative vorticity dwell at lower levels, suggesting that the SCSM trough has not yet been established, and no precipitation appears. All these demonstrate that the SCSM has not broken out yet when the EASM already comes into play.

Afterwards, the EASM rainbelt continues to maintain, with southerly winds intensified somewhat, and the tropical wind filed remains nearly unaltered. The EASM rainband begins to spread out southward at pentad 24, reaching the zone south of 20°N at pentad 27; the rainfall anomaly in the SCS region (10°–20°N) changes to be positive at pentad 28, during which easterlies change to westerlies at lower levels, and the lower troposphere moisture fluxes change from divergence to convergence, suggesting the commencement of the SCSM.

Posterior to the SCSM commencement, the EASM rainbelt makes rapid northward movements, arriving at the mid-lower Yangtze River Basin in mid-late June to form the Jiang-Huai Meiyu period and at North-northeast China in July-August to form a North-Northeast China rainy season. When September comes, the rainbelt retreats southward rapidly. And at pentad 54 the rainfall anomalies change fast from positive to negative for the vast expanse north of 25°N and the related southerlies change into northerlies (Fig.7a). This suggests that the EASM as a whole has retreated out of China, implying the advent of pleasant autumnal days. From the above analysis we see that the EASM rainbelt exhibits a progressive establishment and a swift retreat in sharp contrast to the SCSM, which is marked by an explosive establishment and a slow withdrawal.

During the span from the SCSM establishment to the EASM retreat, there are always two rainbands in the north and south with concentrated high rainfall values, corresponding to the rainbelt of the EASM and that of the SCSM. Two positive vorticity zones also exist, namely, the EASM trough and the SCSM trough; they are separated by a band of strong negative vorticity in between. A similar pattern shows up in the moisture flux convergence field as well. Moreover, two zones of upward motion of about the same intensity are separated by downward motion in the middle (Fig.5c), with convective maximums located above 400 hPa. As shown in Yu and Mao (1986) and Zhou et al. (2003), the EASM has its own meridional circulation and heat source.

To sum up, the EASM rainband is established earlier than the SCSM rainbelt. After the SCSM

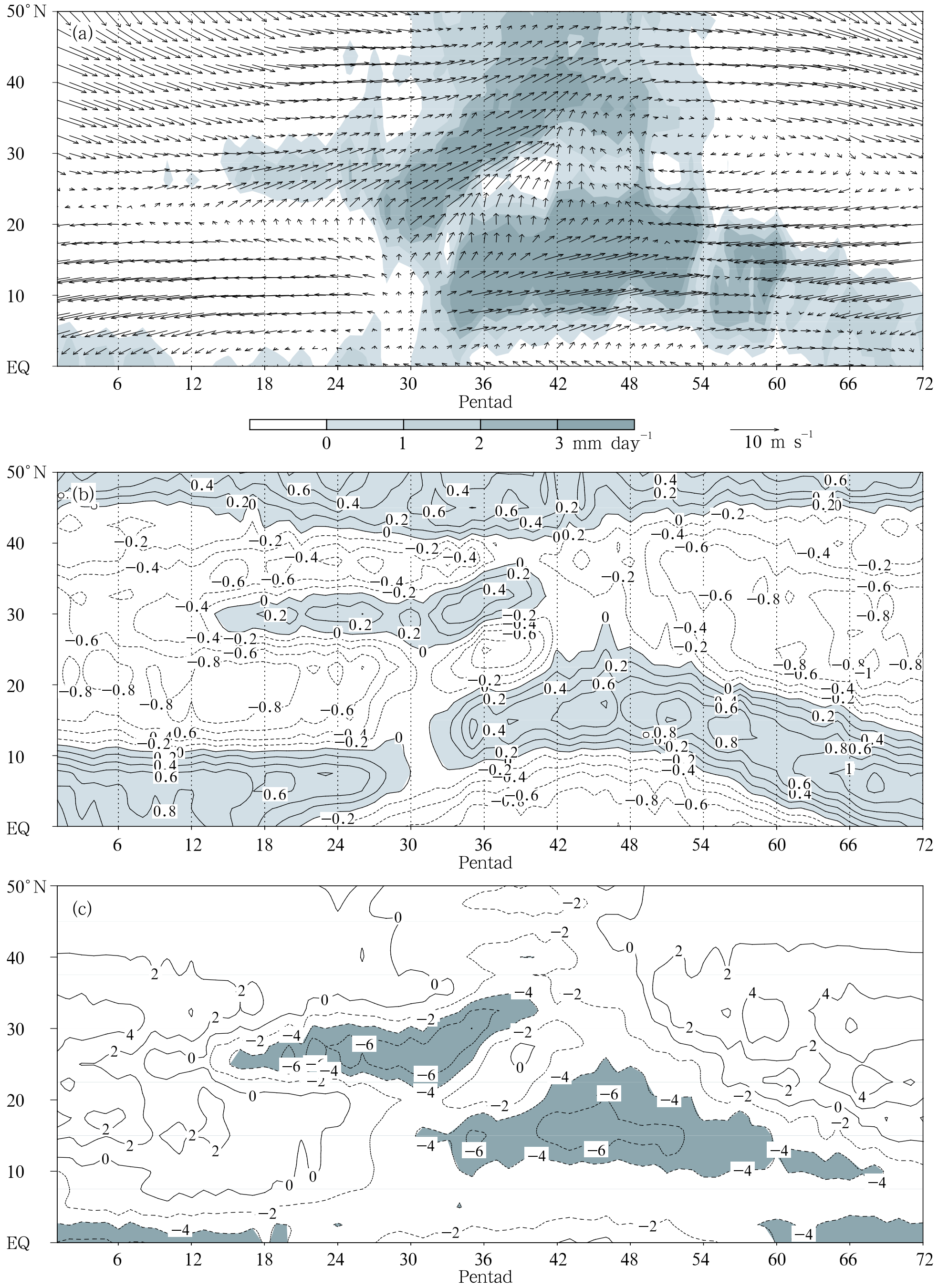

Fig.7. Pentad-dependent climatological variables over East Asia (averaged over 110°–130°E). (a) 850-hPa wind and rainfall anomalies (shaded); (b) 850-hPa vorticity (units of 10^{-5} s^{-1}, cyclonic vorticity shaded); and (c) moisture flux divergence integrated from surface to 700 hPa.

establishment, there are two independent rainbands, each with its own related southwesterlies, strong vertical ascending areas and moisture flux convergence zones. The SCSM, after establishment, interacts with the EASM, causing the latter to make a seasonal northward advance. The two systems are responsible for the floods and droughts over the eastern China.

5. A possible mechanism for the EASM

The land-sea thermal contrast is the principal stimulus. Most researchers emphasize the longitudinal thermal contrast in East Asia (with the Tibetan Plateau) as an essential factor. However, in the subtropics, the plateau acting as an elevated heat (or cold) source increases also the zonal thermal contrast between the Asian landmass and the western Pacific, making the seasonal transition more sensitive and unique. Qian et al. (2004) addressed first an important effect of the zonal thermal difference on summer monsoon, especially the tropical monsoon.

Figure 8 gives the climatological pentad-varying 500-hPa zonal temperature difference (defined as the discrepancy between the temperature at a given longitude and the mean temperature averaged over 80°–150°E (Qi et al., 2008)) at some selected latitudes. We see that the difference increases poleward; south of 35°N the zonal thermal difference is characterized by distinct seasonal reversals: in late March the western Pacific changes from a warm into a cold region and the reverse is true for the East Asian landmass in the west; by the end of September an opposite reversal takes place in both regions. The timing and characteristics of the seasonal reversals at various latitudes differ from one latitude to another. Over 15°–35°N the warming of the East Asian landmass in the north becomes little by little earlier than that in the south, with a warm region appearing at pentad 12 (March) at 30°N, which may be related to the Tibetan Plateau heating at those latitudes. The seasonal evolution of the 20°–35°N mean zonal temperature difference is similar to that at 30°N, showing that the East Asian continent becomes already warm in March. Consequently, the zonal temperature difference at 30°N is selected to represent the East Asian subtropical thermal condition, and utilized to investigate a possible mechanism for the EASM.

Figure 8 shows that the immediate neighborhood along 120°E serves roughly as a partition line between cold and warm areas, so we choose two longitudinal ranges: 120°–150°E (for the western Pacific) and 80°–120°E (for the East Asian continent) to calculate the zonal thermal contrast between land and sea at 30°N (Fig.9a). The subtropical zonal thermal contrast changes from positive to negative in late March, forming a westward temperature gradient, while the tropical meridional thermal contrast is reversed at pentad 24 (He et al., 2007, 2008), lagged behind by one month relative to the above subtropical shift. This explains the discrepancy in the commencing time between the subtropical and tropical summer monsoons over East Asia. Besides, the difference of the vertically integrated heat source between land and ocean reveals that the thermal regime changes from heating (cooling) in the east (west) to the opposite in late March (Fig.10). This demonstrates once again that the seasonal reversal happens first in late March.

As there occurs a seasonal reversal of zonal land-sea thermal contrast in East Asia in late March, the low-level sea level pressure (SLP) changes from a pattern with high (low) values in the west (east) into the opposite (Fig.9b), accompanied by positive anomalies of precipitation in the subtropics (Fig.9a). In the meantime, the lower-level winds veer from northerlies to southerlies. The southerlies originate from two branches of flows: 1) the southwesterly air flows deviated from the easterlies on the southern side of the sub-high over the western Pacific; and 2) the northwesterly air flows detouring along the southern side of the Tibetan Plateau into the subtropics (Qi and He, 2008).

In summary, as the seasonal reversal happens to the zonal land-sea thermal contrast, the EASM rainband is established and the lower-level winds veer from northerlies to southerlies. Such a scenario also holds

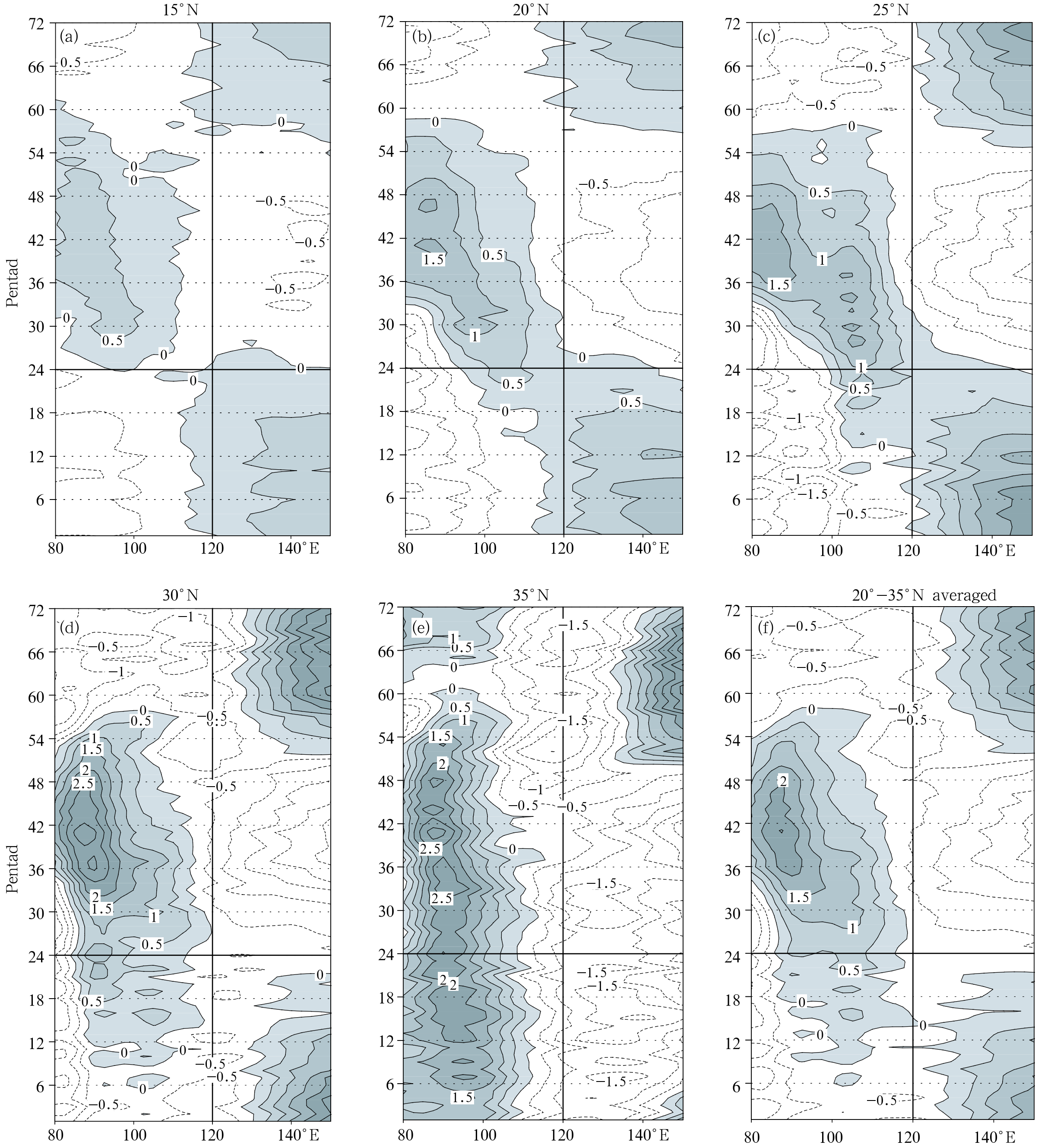

Fig.8. Pentad-dependent zonal difference of 500-hPa temperature for the latitudes of East Asia (from He, Qi, et al., 2007).

true for other key regions of the Asian monsoon on the whole (Fig.9c). Can the temporal consistency in the reversal of the zonal land-sea thermal contrast and low-level wind direction as well as the increase in convective precipitation attest that the East Asian zonal land-sea thermal contrast is the driving force of the EASM? This is a problem that deserves our further efforts.

6. Conclusions and discussion

Based on the above analyses and discussion, the

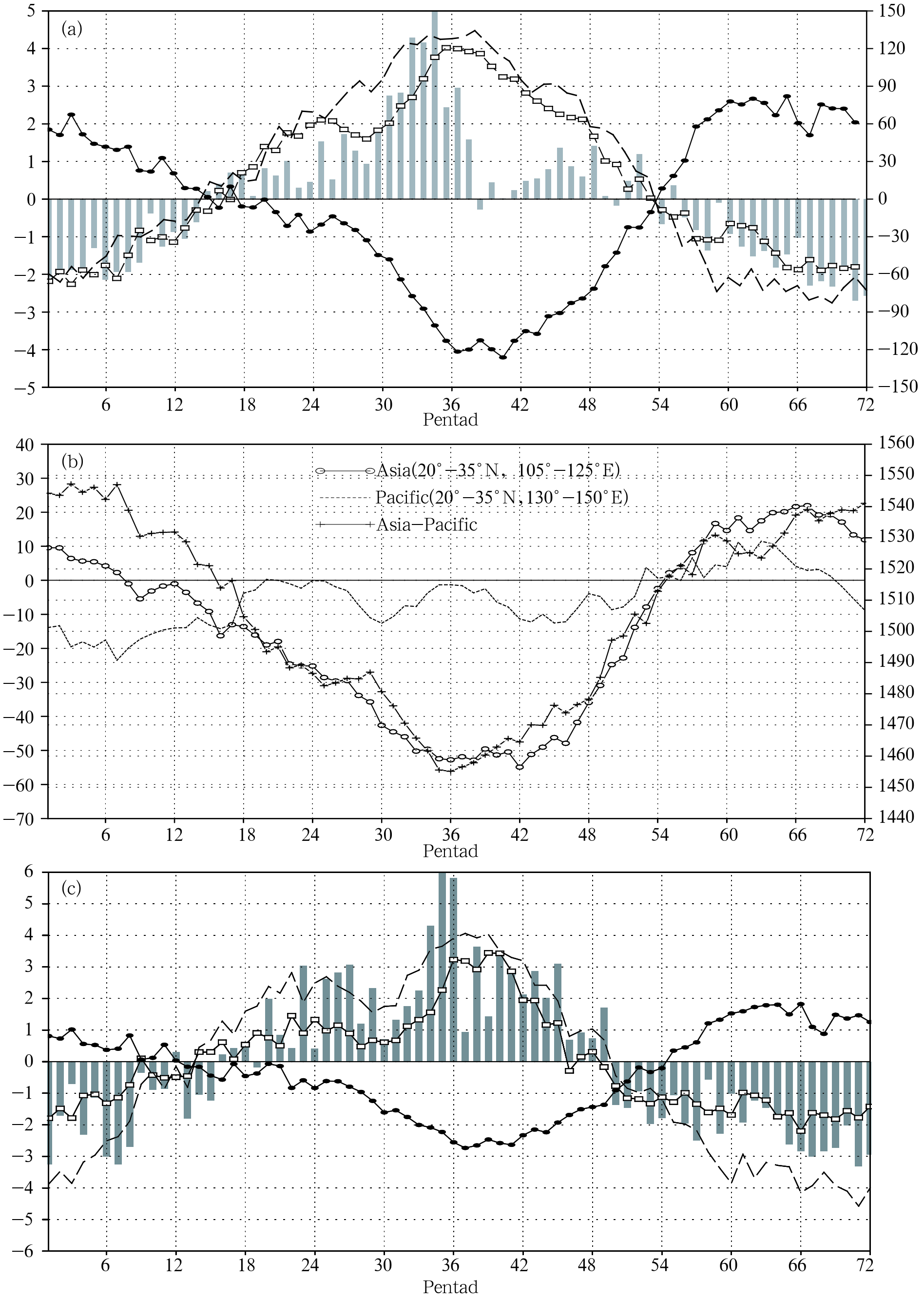

Fig.9. (a) 500-hPa climatological zonal land-sea thermal contrast, averaged across 27.5°–32.5°N (see Sec. 5 for longitude ranges), denoted by solid circle chain; 850-hPa meridional wind in 27.5°–32.5°N, 110°–140°E (open square chain); precipitation anomalies (bars); and the vertically integrated heat source (dashed line) over the Tibetan Plateau in 27.5°–37.5°N, 80°–100°E. (b) Climatological 850-hPa geopotential height and its zonal difference. (c) Climatological 500-hPa zonal land-sea thermal contrast over 25°–35°N (see Sec. 5 for longitude ranges), denoted by solid circle chain; zonal SLP difference (long dash) (see Sec. 5 for longitude ranges); 850-hPa longitudinal wind anomalies averaged over 25°–35°N, 110°–120°E (annual mean removed, open circle chain); TRMM rainfall departures (bars).

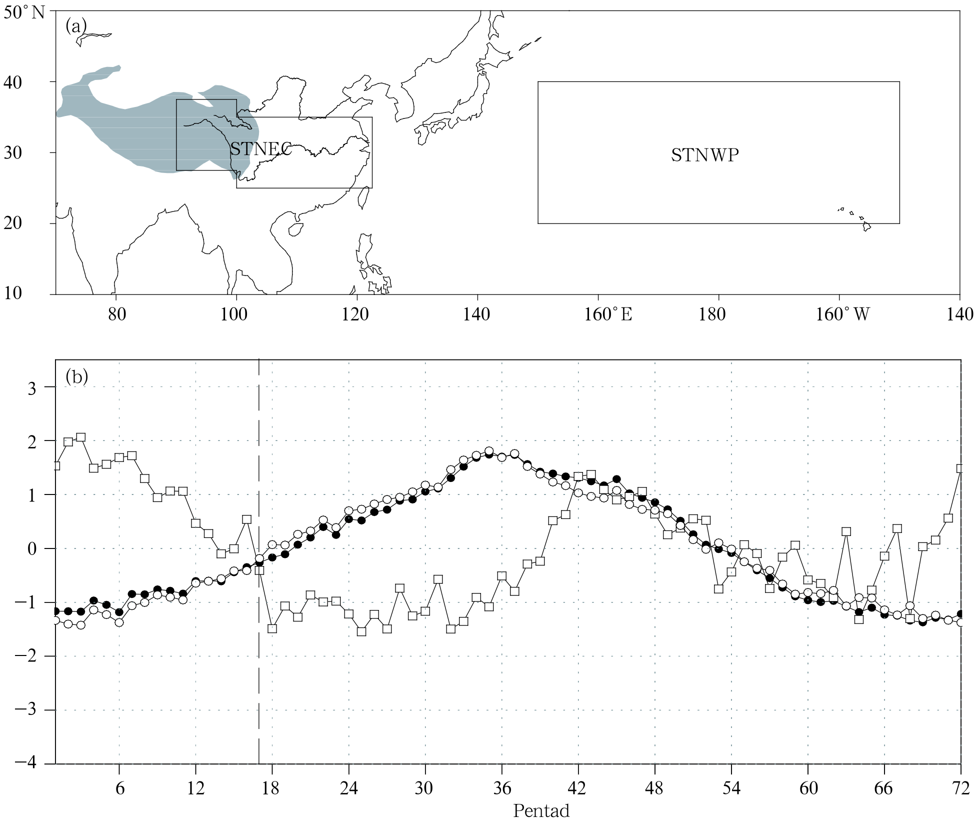

Fig.10. (a) The land and sea domains selected to perform the domain average (STNEC=subtropical NE continent and STNWP=subtropical NW Pacific). (b) Climatological evolution of the vertically integrated atmospheric heat source (normalized) over land (solid circles) and sea (hollow box), and their difference (normalized, hollow circles). This figure is furnished by Chen Longxun.

main conclusions in this paper are summarized as follows:

1) The EASM rainy season begins in late March over the Jiangnan region, with low-level southerlies intensified and convective rainfall enhanced greatly from then on.

2) The EASM rainband is persistent during March to May over the Jiangnan region, meanwhile expanding into South China prior to the SCSM establishment (mid-late May), thereby forming the initial phase of an early flooding season over South China. After the SCSM is established, the EASM marches northward, producing rainfall all the way, in sequence, forming the posterior phase of the South China early rainy season, the Jiang-Huai Meiyu season and the rainy season of North-Northeast China.

3) The rainy season is established earlier for the EASM than for the SCSM. After the SCSM establishment, there are clear differences between the features of the two systems. Each system has its own rainbelt, strong southwestly winds, vigorous low-level moisture convergence and intense vertical motion. They also interact with each other. The SCSM initiation promotes the seasonal northward movement of the EASM rainband.

4) In March, the East Asian continent including the Tibetan Plateau turns from a cold to a warm heat source to the overlying atmosphere. The question about whether the temporal consistency in the reversal of the zonal land-sea thermal contrast and low-level wind direction as well as the increase in convective precipitation can attest that the East Asian zonal land-sea thermal contrast is the driving force of the EASM remains to be further elucidated.

The EASM is a key factor directly influencing the floods and droughts of China. To promote relevant studies and the application of research results, a panel meeting was held in Beijing on May 9, 2008, during which monsoon researchers discussed, debated, and achieved agreements on some issues, meanwhile disagreements and disputes also came forth (Liu, 2008).

The participants diverged regarding the rain-rich phase from late March to the time prior to the SCSM establishment, i.e., about whether the phased rainfall belongs to "spring rainfall" or "summer precipitation". Those who hold the view that it is the spring rains have their principal arguments as follows. 1) It is the frontal precipitation, 2) the summer atmospheric circulation pattern has not been established, and 3) the strengthened southerlies are caused mainly by the Tibetan dynamic effect.

In our view, the above disagreement arises from a different understanding of the EASM. To solve the controversy, let us look at Fig.11, where there is a stretch of high meridional gradient of $\theta_{\rm se}$ over East Asia (the bold dashed line thereof), which we may refer to as an East Asian frontal surface or frontal zone. It is worth noting that the frontal zone is on the northern side of the sub-high, with its annual cycle extremely consistent. This is in fact a manifestation of the meridional yearly cycle of the Meiyu front and sub-high as members of the East-Asian monsoon system, a result given by Tao and Chen (1987). Associated with the $\theta_{\rm se}$ gradient cycle is the yearly cycle of the low-latitude rainband, which is actually a reflection of the meridional annual cycle of the ITCZ rainband. By contrast, the East Asian subtropical rainy zone is established late in March (pentads 16–18), undergoing a similar yearly cycle to that of the frontal zone and the robust southwesterlies. The EASM rainbelt is thus inferred to correlate with the frontal zone, and we can even further claim that the frontal rain is none other than an essential characteristic of the EASM rainband. If we assume that the tropical monsoon is caused by the ITCZ meridional shift driven by the seasonal change of the solar radiation and the meridional land-sea thermal contrast, then we deem it is justifiable as well to believe that the EASM and its meridional jumping rainband are driven by the seasonal variability of the solar radiation and the zonal land-sea thermal contrast. The interactions between the SCSM and the EASM determine the floods/droughts over China.

From the foregoing analysis we already know that the rainy season beginning in late March and the strengthening of the associated southerlies experience a progressive buildup and advance to the north, followed by a swift retreat equatorward, as opposed to an explosive onset and a slow retreat of the SCSM. This result agrees well with the findings of Wang (2007). In other words, the EASM establishment does not necessarily require an abrupt change of the large scale circulation pattern, nor a complete setup of the summer monsoon situation. The establishment means just the incipient phase of the seasonal cycle of the EASM rainy season. Only the Jiang-Huai Meiyu season is the prime stage of the summer monsoon rains, when the EASM is in full swing. For this reason, we maintain

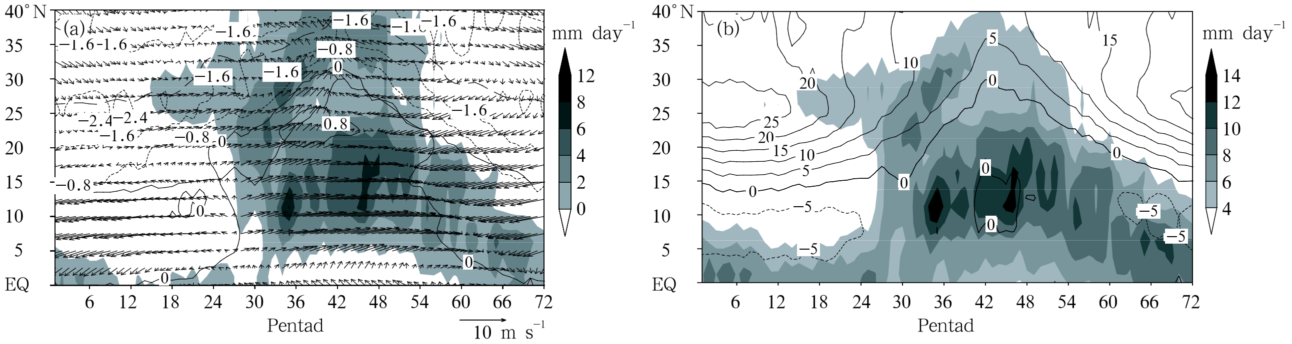

Fig.11. Climatological evolutions of several variables averaged over the subtropics (100°–130°E). (a) Climatological $\partial\theta_{\rm se}/\partial y$ (contour, unit: 10^{-6} K m^{-1}; thick dotted line denotes $\partial^2\theta_{\rm se}/\partial y^2$=0); CMAP precipitation anomalies with annual mean removed (shaded, unit: mm day^{-1}); and wind anomalies at 850 hPa with annual mean removed. (b) Climatological zonal wind (contour, unit: m s^{-1}; thick dotted line: u=0) and CMAP precipitation (shaded, unit: mm day^{-1}). This figure is provided by Zhu et al. (1986).

that the rain-rich phase over the Jiangnan region-South China between late March and the time prior to the SCSM onset is just a preceding stage of the early flooding rainfall period of South China (April-June). It is part of the seasonal cycle of the EASM rainy season and is thus the incipient phase or "pregnant" period of the monsoon rainy season.

Does this initial phase precipitation belong to "spring rains" or "summer precipitation"? If we refer to it as "summer rainfall", it seems unjustifiable because late March to early April (pentads 16–18) is the time shortly after the beginning of spring. The "spring rains" seems a more appropriate title. However, with the concept of "monsoon year", a year can be divided into two parts: winter (wetness) and prevalence of northerly (southerly) winds. During the summer half year, the EASM rainband is established in late March, developing and traveling northward till September, and retreating fast to the south in mid-late September, a period that covers just the summer half year. In the classic works, e.g., Great Britain Encyclopedia and Collier Encyclopedia, and from the meteorological glossary, we can find the definition of the reversal of large-scale meteorological conditions associated with the Asian monsoon on a half-year time frame. Therefore, the rainy period from late March to the time before the establishment of the SCSM is referred to as the start of the EASM rainy season or simply "early summer rainfall stage", which has been termed this way, for example, in Ding (1994) and Wang (2007).

Also, it needs to be noted that throughout the year there is a stretch of southerlies along the eastern flank of the Tibetan Plateau (Zhao, 2007) where air flows detour commonly, and the southerlies have a significant seasonal variation. The rain-rich period in late March-early April in the Jiangnan region and southern China bears a close relation to the enhancement and eastward expansion of the southerly winds in the detouring zone, which may be the evidence of the Tibetan Plateau dynamic effect. In winter, the East Asian northerlies produced by the zonal thermal contrast, i.e., warm air in the east and cold in the west, and the zonal pressure difference, i.e., low air pressure in the east and high in the west, and the Tibetan Plateau cold source effect in combination, inhibit and suppress the detouring southerlies in the eastern Plateau. After late March (pentads 16–18), the reversal in the extensive thermal and pressure contrasts strengthens just the southerlies, thereby causing the so-called "spring rains". Evidently, the constantly detouring zone over the eastern Tibetan Plateau with southerlies prevailing all year long is a region that is less influenced by the large-scale winter circulations. Once the large-scale environmental conditions favor the formation of southerly winds, it can be expected that this region and the vicinity, the Jiangnan-south China is the first place that the summer monsoon and its precipitation should arrive. Hence, it is justifiable to claim that the dynamic effect of the Tibetan Plateau and the reversal of the zonal thermal contrast between the East Asian landmass (including the Tibetan Plateau in particular) and the western Pacific cause the earlier establishment of the EASM but not the SCSM. Nonetheless, which is predominant, the dynamic or the thermal effect remains a problem to be answered.

So far we have made an overview of the issues related to the EASM. The illustration and discussion may seem to involve "more hypotheses than being proven". We count on our colleagues in this research field to make extensive efforts to clarify the problems in a cooperative way. The point is meaningful in that if the rainy season beginning from late March is really recognized as a part of the EASM system, the prediction and monitoring of the system should be advanced to before or as early as March. This is unconventional in the climate prediction practice in China.

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