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Characteristics of the Onset of the Asian Summer Monsoon and the Importance of Asian-Australian “Land Bridge”

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ABSTRACT

Based on summarizing previous achievements and using data as long and new as possible, the onset characteristics of Asian summer monsoon and the role of Asian-Australian “land bridge” in the onset of summer monsoon are further discussed. In particular, the earliest onset area of Asian summer monsoon is comparatively analyzed, and the sudden and progressive characteristics of the onset of summer monsoon in different regions are discussed. Furthermore, the relationships among such critical events during the onset of Asian summer monsoon as the splitting of subtropical high belt over the Bay of Bengal (BOB), the initiation of convection over Indo-China Peninsula, the westward advance, reestablishment of South Asian High, and the rapid northward progression of convection originated from Sumatra in early summer are studied. The important impact of the proper collocation of the latent heating over Indo-China Peninsula and the sensible heating over Indian Peninsula on the splitting of the subtropical high belt, the deepening of BOB trough, the activating of Sri Lanka vortex (twin vortexes in the Northern and Southern Hemispheres), and the subsequent onset of South China Sea summer monsoon are emphasized.

Key words: Asian summer monsoon onset, Asian-Australian “land bridge”, splitting of subtropical high belt

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1. Introduction

The onset characteristics and their possible mechanisms have always been a major issue addressed in the study of Asian summer monsoon (ASM). In particular, the region where the earliest ASM onset occurs has been the focus of studies (Wang and LinHo, 2002), which is also one of the scientific goals of the South China Sea Monsoon Experiment (SCSMEX) (Ding et al., 2004). However, there is still no solid conclusion as to the initial onset of ASM. Currently, there exist four main viewpoints regarding the regions where the ASM initially established. They are: the South China Sea (SCS) and then northward and westward (Tao and Chen, 1987), the eastern Bay of Bengal (BOB) (Wu and Zhang, 1998), the Indo-China Peninsula (ICP) or its southern surrounding areas (Li and Qu, 1999; Zhang et al., 2004; Lau and Yang, 1997; Matsumoto, 1997; Webster et al., 1998; Wang and Fan, 1999; Lu et al., 2006), and the whole area in BOB, ICP and SCS (simultaneously), respectively. He et al. (1996) suggested that the northward progression of the low TBB center over Sumatra and the occupation of a TBB trough in ICP lead to the onset of monsoonal convection in ICP and BOB, which actually belongs to the third viewpoint. In a word, where, on earth, is the earliest onset place of ASM needs further study.

The Asian monsoon is the most significant monsoon in the world. The Asian summer (winter) monsoon and Australian winter (summer) monsoon are so closely associated with each other that they can even be jointly called the Asian-Australian monsoon system. Therefore, the seasonal transition of the Asian monsoon, the interaction between the Northern and Southern Hemispheric atmospheres, and the seasonal migration of the tropical convection are indivisible. Zeng and Li (2002) suggested that the seasonal migration of planetary thermal convection (the primary driving forcing) in phase with the quasi-stationary planetary waves (such as the land-ocean thermal con-

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trast, topographic height, etc.) (the secondary forcing) is the main reason for the tropical monsoon being most obvious in the Asian-Australian monsoon region. The Maritime Continent (MC), including Sumatra and Kalimantan etc., has the strongest tropical convection in the world, and the seasonal migration of Sumatra convection is well associated with the onset of summer monsoon in ICP (He et al., 1996). If called the ICP and MC as Asian-Australian "land bridge" (He et al., 1996; Chang et al., 2004; Wang et al., 2004), the seasonal migration of the Sumatra convection along "land bridge" is exactly the manifestation of the primary driving forcing of summer monsoon. Therefore, it is of importance to fully comprehend the role of Asian-Australian "land bridge" in the onset of ASM.

In the Asian monsoon region, there are coexistent latitudinal and longitudinal land-sea distributions (the Asian continent with the Indian Ocean, and the Asian continent with the Pacific Ocean, respectively). In addition, the largest plateau in the world, the Tibetan Plateau (TP), is located in the middle of Asian continent, together with several subcontinents such as the Indian Peninsula and ICP in the south, The surface thermal differences among them and their seasonal transition not only bring about complex, strong and sensitive monsoon in Asia (Murakami et al., 1986, Zhu et al., 1986), but also lead to the regional characteristics of the onset of ASM. Besides, due to the moist process known as the tertiary forcing (He et al., 2004), the onset of the summer monsoon is always accompanied with the convective rainfall. Therefore, studies on the onset characteristics of summer monsoon and their associated mechanisms attract much attention in the community of monsoon researchers.

In a word, where and how is the ASM first established? What are the onset characteristics and their associated mechanisms? And as a key factor to summer monsoon onset, what kind of roles does the Asian-Australian "land bridge" play? This paper aims at summarizing previous results and giving an integral image of the ASM onset process.

2. Data

The primary data sets used in this study are as follows:

(1) The daily temperature of black body on the top of cloud (TBB), provided by the Japan Meteorological Agency, derived from 3-hourly Geostationary Meteorological Satellite (GMS) data with the horizontal resolution of 1° × 1° spanning 60°S–60°N, 80°E–160°W,

(2) The daily National Centers for Environmental Prediction-Nation Center of Atmospheric Research (NCEP-NCAR) reanalysis Products, with a global coverage and a 2.5° latitude-longitude resolution;

(3) The pentadly Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), with a global coverage and a 2.5° × 2.5° resolution;

(4) The daily outgoing long-wave radiation (OLR), provided by National Oceanic and Atmospheric Administration (NOAA), also with a global coverage and a 2.5° × 2.5° resolution.

The GMS came into use in 1980 and disused in 2002. In order to coincide with the time span of satellite data, 22 years from 1980 to 2001 are chosen as research period. All climatological fields are the mean of this period if no special announce is declared.

3. The earliest onset of ASM and the regional characteristics

3.1 *The earliest onset area of ASM*

As the onset of summer monsoon is always accompanied with convective rainfall, and the lower TBB can approximately represents convective clouds and heavy rainfall in the tropical and subtropical regions, thus TBB data were here used to discuss the characteristics of seasonal transition in Asian-Australian monsoon region and the initial onset of ASM (He et al., 1996). Considering that there are many disputes on this issue, the latest TBB data are employed to make further analysis. Figure 1 shows the horizontal distribution of the climatological monthly TBB from March to June.

The distribution of TBB in March (Fig. 1a) is still the same as in January (figure omitted). There is a high TBB belt in subtropics in Southern Hemisphere (SH) with its ridgeline at 25°S and core in central Australia, corresponding to the austral subtropical high belt and the Australian high. There is also a high TBB belt in boreal subtropics, with its ridgeline around 15°–20°N and three high centers in West Pacific, SCS and northern BOB, corresponding to the boreal subtropical high belt and three anticyclonic centers, respectively. There is a low TBB between the two high TBB belts, with two low centers in MC and Sumatra. Moreover, a TBB trough extends from the low center over the New Guinea to northern Australia, in correspondence with summer monsoon there.

However, the TBB characteristics change significantly in April (Fig. 1b): (1) the high TBB belt in subtropics in Northern Hemisphere (NH) breaks in ICP (10°–20°N, 100°–110°E) (280 K is the threshold), and an obvious trough extends from the low center in Sumatra to this region, connecting to the low TBB belt in mid-latitude; (2) the high TBB in Australia moves northward notably (the axis moves to 20°S),

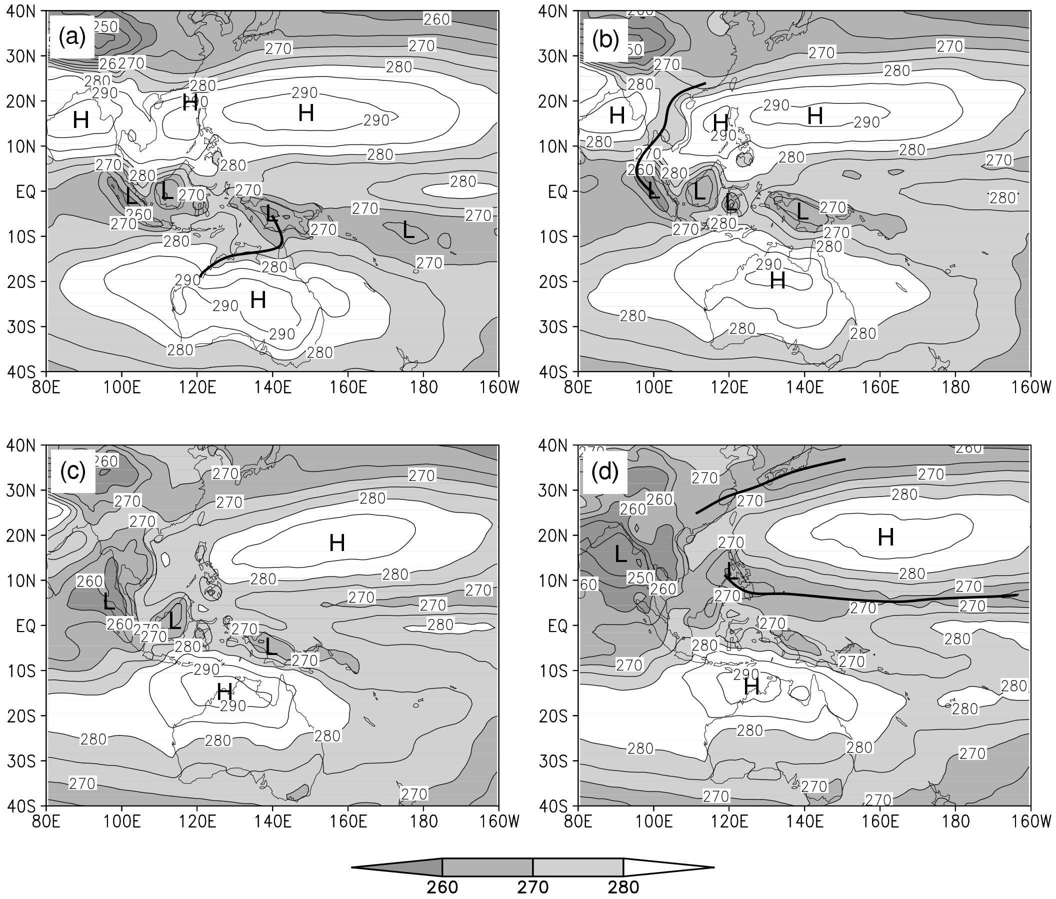

Fig. 1. Distributions of climatological TBB in (a) March, (b) April, (c) May, and (d) June. The thick solid line is the axis of low belt and areas of TBB<280 K are shaded. (Units: K)

so the trough from New Guinea to northern Australia disappears. Those changes imply the northward movement of the entire circulation system, i.e., the first northward crush of the tropical convection into the subtropical high belt along ICP, and the disappearance of summer monsoon in Australia along with the seasonal change and the regional response to solar radiation, signifying the starting of the seasonal transition of large-scale circulation in mid and low latitude in Asian-Australian monsoon region.

In May (Fig. 1c), it is noticeable that: (1) the east part of TBB high belt in boreal subtropics retreat eastward rapidly, and convection from Philippine to SCS begins to flare up; (2) the low TBB center in Sumatra moves northwestward, strengthens and expands to occupy ICP, with the high center in northern BOB shifting northwestward rapidly to (80°E, 25°N). These changes indicate that the monsoonal convection has been fully established over ICP and BOB in May.

In June (Fig. 1d), the high TBB belt in West Pacific continues to retreat eastward along with the obvious jump of the ridge line to around 22°N. There are two low centers in the low belt to the north of the high belt, lying in the lower reaches of Yangtze River and southern Japan respectively. They are in correspondence with mei-yu, whose frontal structures and characteristics have been extensively studied (Gao et al., 2002). The SCS-Philippine is dominated by a strong low center, showing the summer monsoon has fully established in SCS-West Pacific. The low center over Sumatra in winter has disappeared. A large strong low center appears in northeastern BOB in place of a high center in winter, indicating that summer monsoon has fully established from BOB to India.

To sum up, it is the northward progression of the tropical convection in Sumatra that lead to the break of the high TBB belt in ICP and a series of succeeding events resulting in the onset of ASM.

Figure 2a shows the time-longitude section of TBB along (10°–20°N). It can be seen that the convection illustrated by lower TBB flares up initially over ICP, and then extends eastward and westward. If TBB<275 K (shaded areas) is taken as the signal of active con-

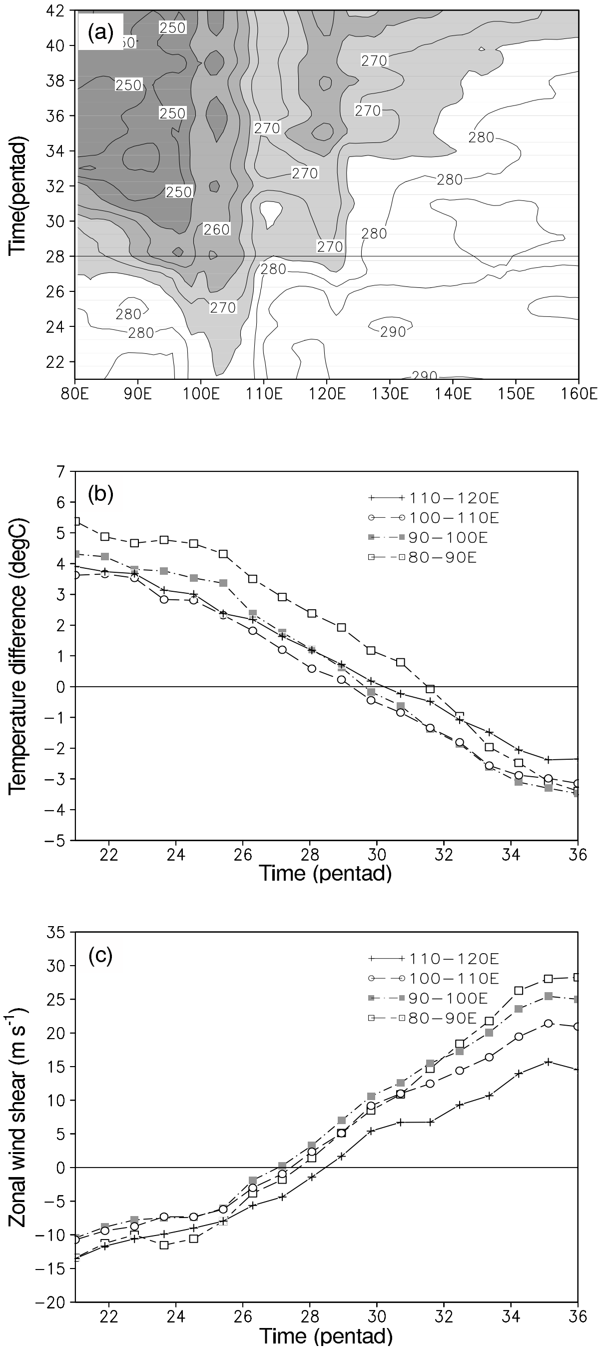

Fig. 2. (a) Time-longitude section of climatological TBB along (10°–20°N). Areas of TBB$\leqslant$275 K are shaded. (Units: K) (b) Climatological evolution of the meridional temperature difference (5°S–5°N minus 20°–30°N) at 500hPa. (Units: °C) (c) Climatological evolution of the zonal wind shear (850 hPa minus 200 hPa) in low-latitude (10°–20°N). (Units: m s^{-1}).

vection, the onset of convection over eastern BOB (east of 90°E) is one pentad earlier than in SCS. In Fig. 2b, the meridional temperature gradient reverses its sign first over ICP (100°–110°E), then over eastern BOB and SCS, and finally over western BOB. Seen from Fig. 2c, the vertical shear of zonal wind reverses its sign almost simultaneously over ICP and BOB, earlier than that over SCS. This course is in agreement with the development of BOB trough and the eastward extension of the southwesterly during the onset of the Southeast Asian summer monsoon. Above results support the viewpoint of the simultaneous onset of summer monsoon over BOB, ICP and SCS in the 27th–28th pentad (Qian et al., 2004).

According to the above results, it is true that convection first flares up over ICP, which is closely associated with the seasonal migration of tropical convection along the Asian-Australian "land bridge". It will be further discussed in the following section.

3.2 *Regional characteristics of the onset of summer monsoon*

In order to discuss the characteristics of the summer monsoon onset and their differences in various regions, the time-latitude sections of climatological pentadly TBB along 80°E, 100°E, 120°E and 140°E are plotted (Fig. 3), respectively.

The characteristics of the summer monsoon onset in East India (west of BOB) are roughly shown in Fig. 3a. It can be seen that the low TBB belt propagates northward gradually from the equator in early May, and a low center is formed in the east of India in early and mid June signaling the onset of Indian summer monsoon. Figure 3b illustrates the onset of summer monsoon in the east of TP and Southeast Asia. It can be seen that this region turns to be a low TBB belt from a high TBB belt in early and mid May, indicating that the onset of summer monsoon in Southeast Asia is one month earlier than in India. In addition, there is also a low belt in June (September in the east of TP (around 32°N), separated from the low belt in Southeast Asia (15°N). This means the summer monsoon over the east of TP is relatively independent of that over Southeast Asia, unlike the summer monsoon over the west of TP which is the northward extension of Indian summer monsoon. Figure 3c shows the evolutions of summer monsoons over Indonesia-Northern Australian, SCS and the subtropical region in eastern China. The rapid transition from a high TBB belt to a low TBB belt in mid May over SCS (12°N) denotes the onset of summer monsoon over SCS. Furthermore, there is a low belt over eastern China in June, corresponding to the subtropical summer monsoon rainfall belt in China (mei-yu). The high belt between them corresponds to the West Pacific subtropical high. A strong low center appears around the equator in December (February, and extends southward to the west

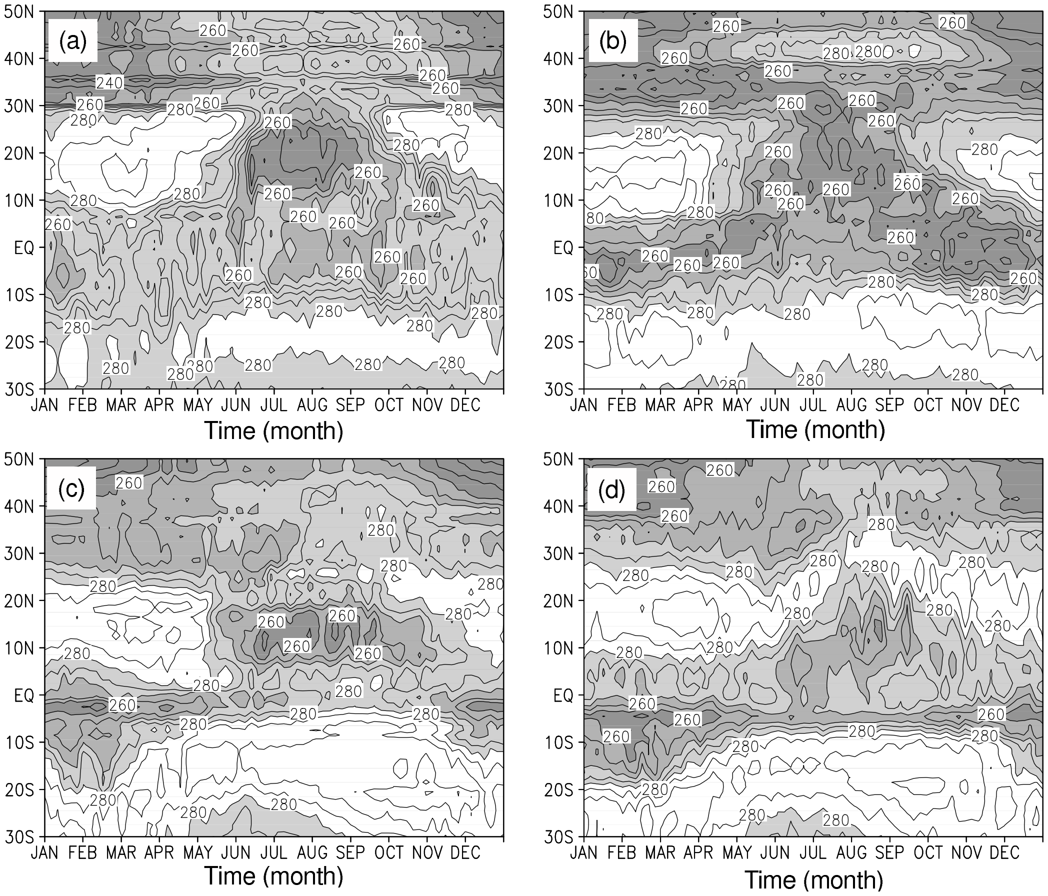

Fig. 3. Time-latitude sections of climatological TBB along (a) 80°E, (b) 100°E, (c) 120°E, and (d) 140°E. (Units: K)

of northern Australia, denoting to the prevalence of Australian summer monsoon in SH. Figure 3d shows the seasonal cycle of monsoon over Japan, West Pacific and the east of northern Australia. Along this longitude, the subtropical high shows an obvious seasonal cycle of meridional fluctuation. There are low belts on both sides of the subtropical high, with the northern one corresponding to Baiu in Japan and the southern one to the West Pacific summer monsoon. A low belt controls northern Australia in December–March, which indicates the prevailing of northern Australian summer monsoon.

In general, three crucial features can be drawn as follows: (1) The summer monsoons over East India and Southeast Asia are established progressively along with the rapid northward migration of the low belt at equator, reflecting the seasonal cycle of tropical convection. However, the onset of summer monsoon over the SCS and Western Pacific are quite different from the above. The establishment of the SCS summer monsoon is simultaneous in a wide range of 20 latitudes, that is, its abrupt behavior is much more obvious than Indian and Southeast Asian summer monsoon. This is directly associated with the rapid eastward retreat of the western Pacific subtropical high belt after its break (He et al., 2002). (2) Besides the low TBB belt over SCS-West Pacific, there is another low belt to the east of 100°E, i.e., the subtropical monsoon rainfall belt in China-Japan (mei-yu). The East Asian monsoon system includes not only tropical summer monsoon, but also subtropical monsoon (Zhu et al., 1986), which is more complicated than Indian monsoon system. (3) The tropical summer monsoon is initially established in ICP, and then advances eastward and westward, respectively. What kind of processes and mechanisms result in such characteristics? Further discussion will be presented in the following sections.

4. Large-scale characteristics of Asian summer monsoon onset

According to Qian et al. (2004), east of 90°E, the tropical Asian summer monsoon bursts simultaneously

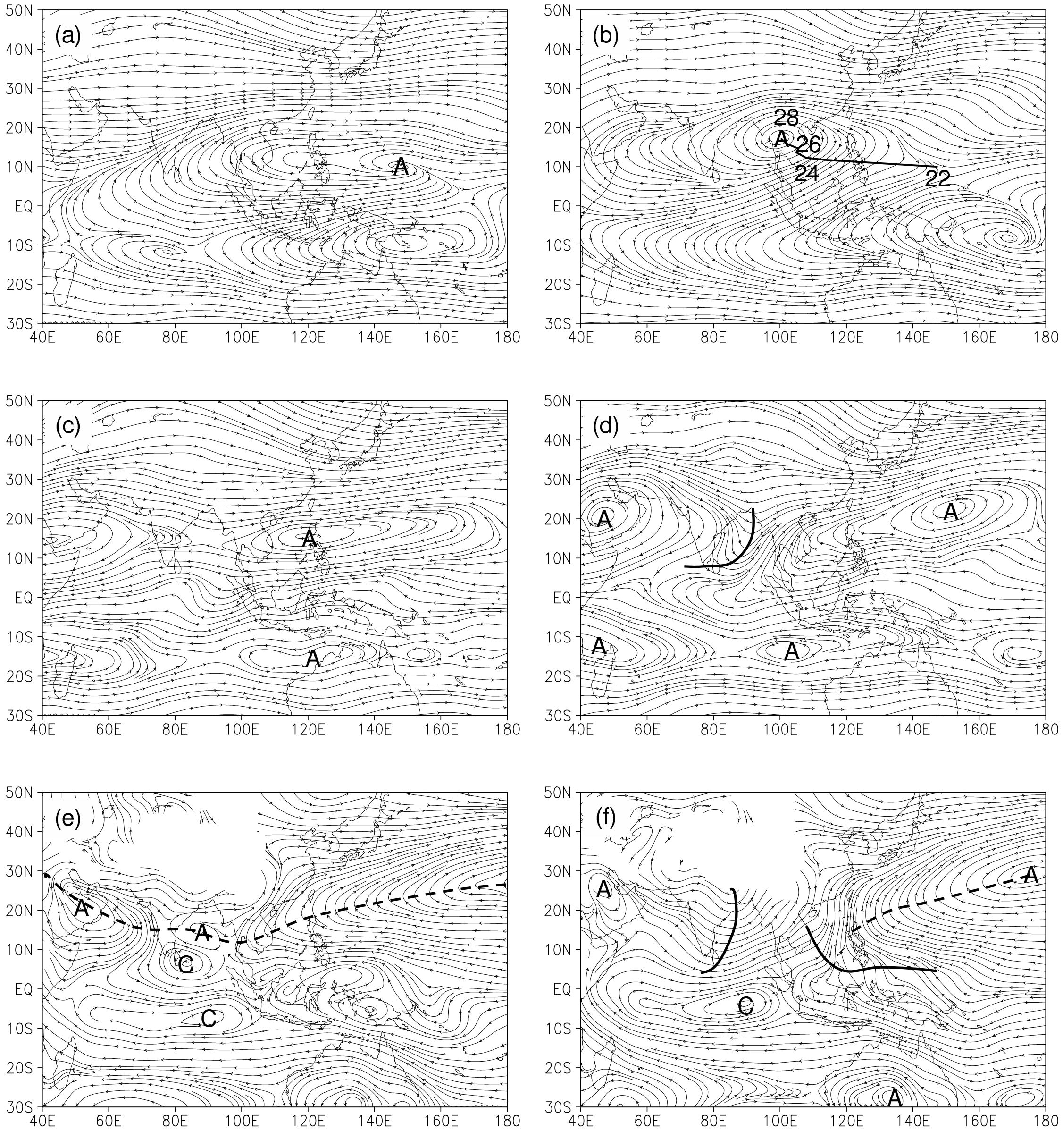

Fig. 4. Climatological circulation fields before and after the onset of South China Sea summer monsoon at (a), (b) 200 hPa, (c), (d) 500 hPa, and (e), (f) 850 hPa. (a), (c) and (e) for the 4th pentad of April; (b), (d) and (f) for the 4th pentad of May. The thick solid line in (b) is the movement of South Asia High center, the numbers on it is the pentad when the center is there. The thick solid lines in other figures are trough lines, and dash line is the ridge line.

and abruptly first over the whole area in BOB, ICP and SCS in the 27th–28th pentad. West of 90°E, the onset of summer monsoon over Indian peninsula and Arabian Sea is relatively late., It first occurs to the south of 10°N and then proceeds northward gradually. Therefore, from a large-scale viewpoint, the onset of the tropical summer monsoon occurs earliest over the SCS and its surrounding areas. After that, the large-scale circulation, water vapor transportation and convection over Asian-Australian monsoon regions have changed significantly (Ding, 2004). We have ever discussed the climatological characteristics of the onset of SCS summer monsoon (He et al., 2003), and further details will be provided below.

4.1 *Large-scale characteristics before and after onset*

Figure 4 displays the upper and lower circulation fields before the onset of SCS summer monsoon (4th pentad of April) and during the onset (4th pentad of

May). The South Asian high (SAH) center at 200 hPa lies over the ocean to the east of Philippine on the 4th pentad of April, then moves rapidly to the southern ICP on the 6th pentad of April. It jumps from south of 15°N to the north, and extends westward on the 2nd–4th pentad of May with its main body over SCS, ICP, BOB, Indian peninsula and Arabian Sea at 10°–25°N and the northeasterly winds to the east of the high overlaying SCS. After the 5th pentad of May, the SAH moves northwestward to the north of 20°N.

The subtropical high at 500 hPa stretches along 15°N with two high centers (Fig. 4c), with one near Philippine and the other in the west of Arabian Sea. The relatively low value region is in BOB. The pattern begins to change on the 2nd pentad of May (Figure omitted): the subtropical high belt tends to break, and the trough in northern BOB strengthens. On the 4th pentad of May, i.e., the onset pentad of SCS summer monsoon (Fig. 4d), The subtropical high belt breaks completely with its east part retreating eastward and its west part controlling areas west of Arabian Sea, so India is controlled by northwesterly.

At 850 hPa (Fig. 4e, f), the splitting of the subtropical high belt, the rapidly eastward (westward) withdrawal of its east (west) part, and the formation and deepening of the BOB trough are similar to those at 500 hPa, but more complicated and a little earlier. In particular, in the mid April, there is a cyclone in the SH, forming twin cyclones straddling the equator with the Sri Lanka vortex. In between, the equatorial westerly accelerates. On the 4th pentad of May, the Sri Lanka vortex moves northward into the BOB trough with its center of cell disappearing. The equatorial westerly between BOB trough and the cyclone in SH is much stronger, originated from mid-latitude northwesterly over Arabian Sea and cross-equator flow from Somali. The westerly reaches the ICP–SCS region and converges at SCS with the cross-equatorial flow from northern Australia and the turning flow from the southern West Pacific subtropical high. Probably it is the frame of three flows that leads to the complexity of the onset course of SCS summer monsoon, furthermore arises controversies.

The meridional temperature and vertical shear of zonal wind in mid- and low- latitudes in Asia have also converted corresponding to changes of large-scale circulation (see Fig. 2). Therefore, it may be considered that the onset of SCS summer monsoon is not a local phenomenon, but the prominent large-scale event that happened earliest during the seasonal transition of the Asian-Australian monsoon region and the onset course of Asian summer monsoon. In this sense, it is reasonable that the Asian summer monsoon is established earliest over SCS, as claimed by Tao and Chen (1987).

The relationship between the movement of SAH and the onset of ASM is widely accepted. Qian et al. (2004) specially emphasized the correlation between the position of SAH center and the onset time of ASM. We can see from Fig. 4 that the SAH advances westward rapidly to southern ICP during the 4th–6th pentad of April, then moves northward, and summer monsoon is established over SCS afterwards. Why does the SAH advance westward rapidly? Why does it move northward along ICP?

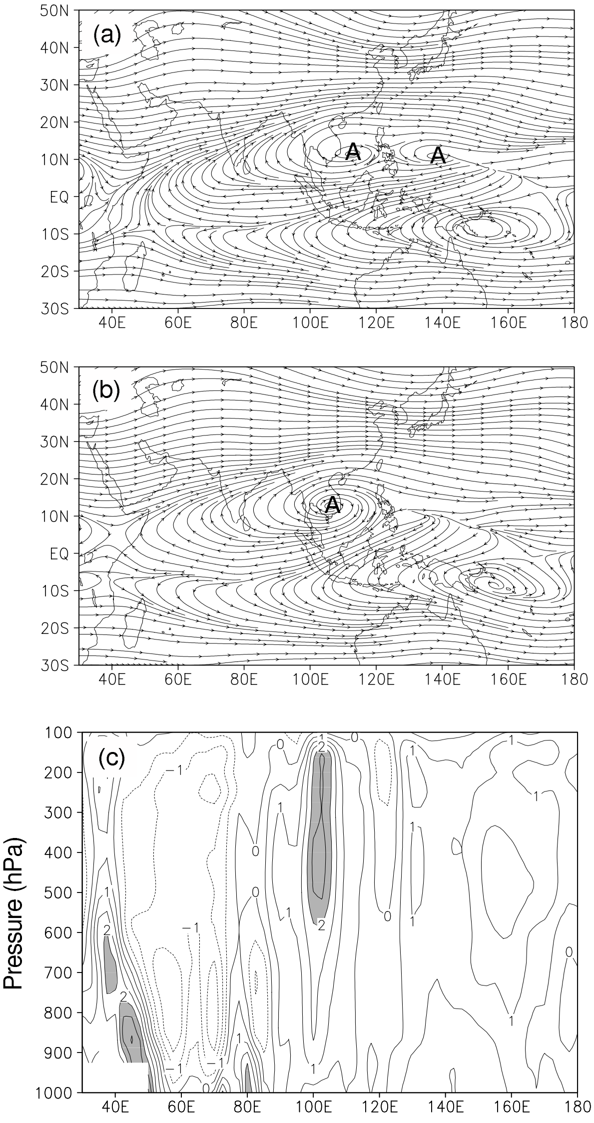

Fig. 5. Climatological circulation fields at 150 hPa on the (a) 5th pentad and (b) 6th pentad of April. (c) Vertical section of heating ratio on the 5th pentad of April averaged in (7.5°–15°N), and areas of heating ratio greater than 2 K d^{-1} are shaded. (Units: K d^{-1})

Figure 5 shows the variation of SAH at 150 hPa on the 5th and 6th pentad of April and the vertical section of apparent heating ratio on the 5th pentad of April. The SAH disintegrates into two centers on the 5th pentad of April, lying on the east and west of Philippine respectively. On the 6th pentad of April, the center on the east weakens and disappears, while the other one on the west strengthens and moves westward to southern ICP. Hence, the rapid westward progression of the SAH on the 4th–6th pentad of April pentad is actually the process of disintegration and reestablishment. It can be seen from Fig. 5c that there is a heating center (the apparent heating ratio is greater than 2 K d^{-1}) at middle and upper troposphere above southern ICP (7.5°–15°N, 105°E) on the 5th pentad of April. The SAH center at 150 hPa is located exactly above the heating center on the next pentad, implying an important role of the upper latent heating in the reestablishment or the rapid westward movement of SAH. It is noticed that the convection over Sumatra strengthens and proceeds northward rapidly in late April and early May. Therefore, we hypothesize that there are some interconnections among the rapid northward progression of convection over Sumatra, the flourish of convection over ICP and the rapid westward movement of SAH.

4.2 *Characteristics of the onset course of SCS summer monsoon*

Figure 6 shows the composite circulation at 850 hPa with the splitting date of the subtropical high belt (Wen et al., 2004) as reference point. Two pentads before the belt breaks, there is still a zonal subtropical high belt over southern Asia, and twin cyclones on both sides of the equator near 80°E. On the pentad of the subtropical high belt break (i.e., pentad 0), Sri Lanka vortex migrates into the trough region, leading to the deepening of the BOB trough. The southwesterly in front of the trough arrives at ICP, but the summer monsoon has not yet established over SCS where is still controlled by the western Pacific subtropical high (WPSH). As the WPSH withdraws eastward rapidly to the east of Philippine two pentads later, the summer

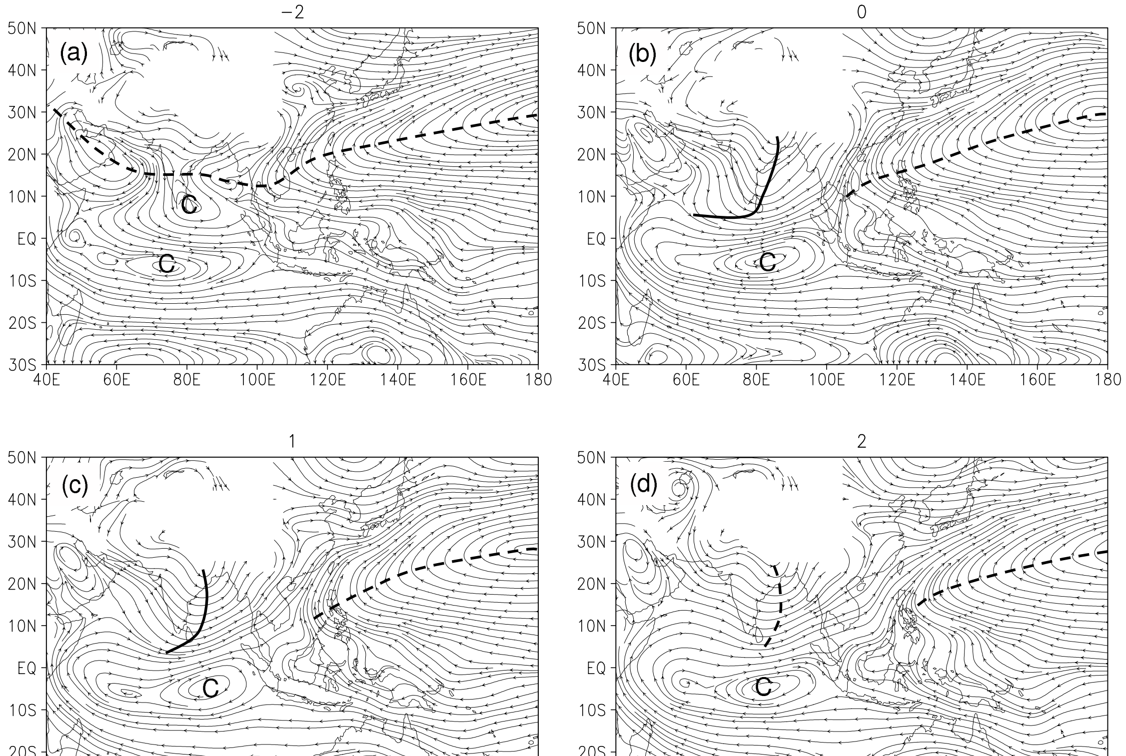

Fig. 6. Composite circulation fields at 850 hPa with the splitting dates of the subtropical high belt as reference point. (a) Pentad −2, (b) Pentad 0, (c) Pentad +1, and (d) Pentad +2. The dashed line is the ridge line of the subtropical high, solid line is the trough line.

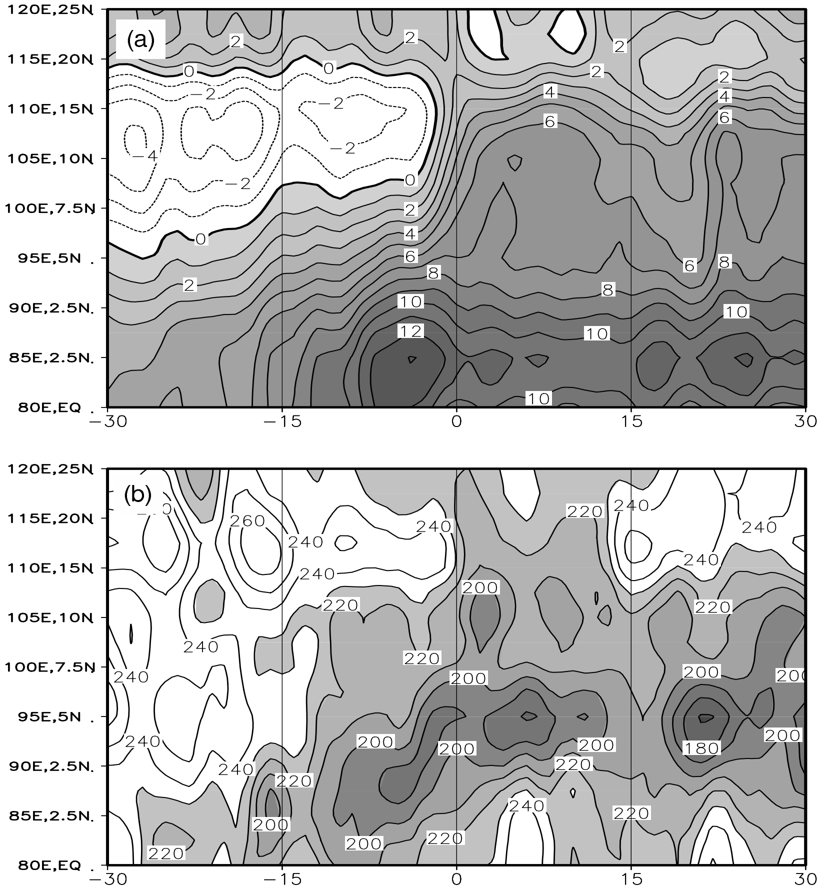

Fig. 7. Time sections of (a) 850 hPa zonal wind (units: m s^{-1}) and (b) OLR (units: W m^{-2}) before and after the onset of South China Sea summer monsoon from (EQ, 80°E) to (25°N, 120°E). Areas of zonal wind at 850 hPa greater than zero are shaded in (a); areas of OLR$\leqslant$230 W m^{-2} are shaded in (b). (adopted from He et al., 2003)

monsoon is fully established over SCS. It is seen that a series of events, such as the appearance of twin cyclones, the northward movement of Sri Lanka vortex, the formation and development of BOB trough, the splitting of zonal subtropical high belt and the rapid eastward withdrawal of WPSH, lead to the onset of summer monsoon over SCS. It is also clear that the onset of SCS summer monsoon proceeds from west to east rather than from south to north (at least this is the case in climatology), which helps to explain why the SCS summer monsoon is established simultaneously over a wide range of 20 latitudes.

The composite time sections of zonal wind at 850 hPa and OLR with the onset date of SCS summer monsoon as reference point are shown in Fig. 7 (He et al., 2003). Before (after) the onset of monsoon, the SCS is controlled by easterly (westerly) and high (low) OLR, exactly the onset characteristics of summer monsoon. In addition, the westerly and low OLR propagate from the equatorial Indian Ocean (80°E) to ICP and SCS, which are associated with the activating of the BOB trough and the strengthening of the westerly in the equatorial Indian Ocean. It is remarkable that the westerly and low OLR from South China propagate southward during the onset of monsoon, which might be the manifestation of the southward movement of South China stationary front triggering the onset of SCS summer monsoon (Chang and Chen, 1995). Liu et al. (2002) stressed that the convective latent heat release may trigger two-dimensional asymmetric Rossby wave train after the onset of BOB summer monsoon. This Rossby wave train is also favorable to the southward movement of South China stationary front. In a word, there are interactions between mid-latitude and low-latitude systems during the onset of SCS summer monsoon, resulting in the abrupt features of SCS summer monsoon onset.

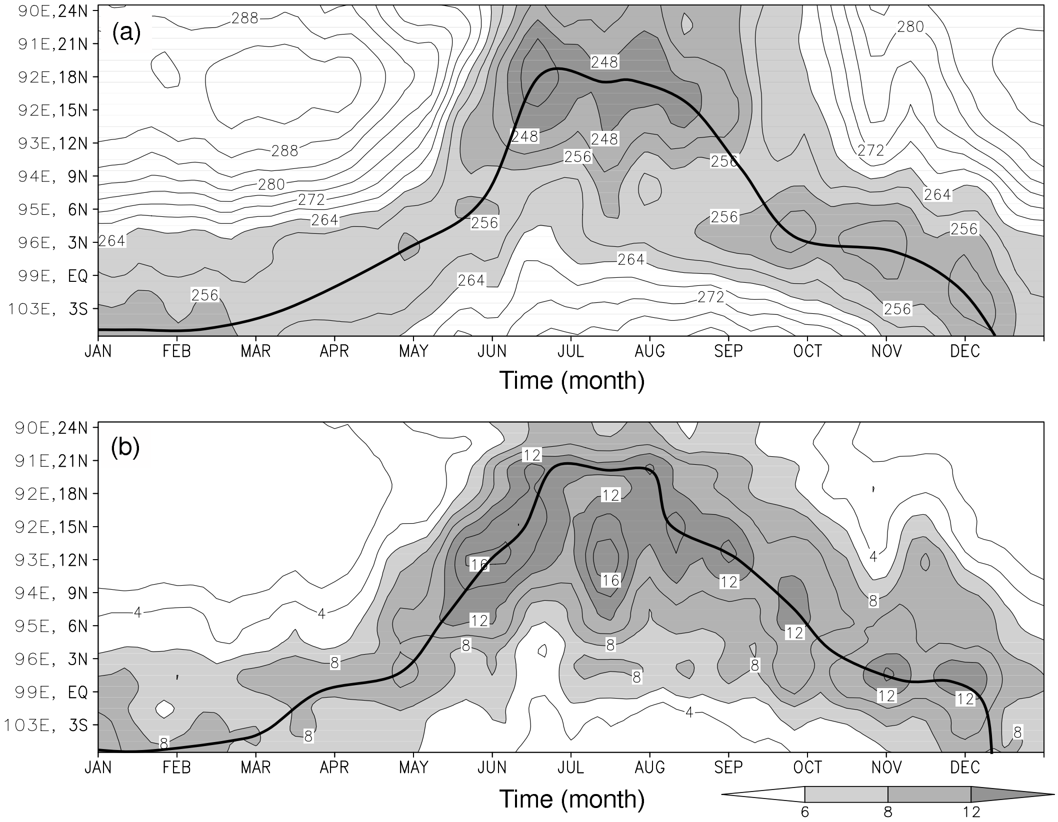

Fig. 8. Climatological (1980–1997) time sections of (a) TBB (units: K) and (b) rainfall (units: mm d^{-1}) along Asian-Australian "land bridge" from (5°S, 105°E) to (25°N, 90°E). In (a), areas of TBB$\leqslant$265 K are shaded, the thick solid line is the axis of low TBB. In (b), areas of rainfall more than 6 mm d^{-1} are shaded, and the thick solid line is the axis of high rainfall. (adopted from Wang et al., 2004)

5. Seasonal cycle of the tropical convection along Asian-Australian "land bridge" and its relationship with other events

We have discussed a series of processes such as the northward progression of the tropical convection over Sumatra, the rapid westward movement of SAH to southern ICP, the activating of convection over ICP and the subsequent splitting of subtropical high belt, the establishment and deepening of BOB trough and the onset of SCS summer monsoon. How are they connected with each other? What is the possible mechanism? We'll discuss these issues in the following.

Figure 8 shows the time section of climatological (1980–1997) low TBB and CMAP rainfall along Asian-Australian "land bridge". It is seen that the low TBB over Sumatra (3°S, 103°E) in winter moves to 3°N in April, proceeds northward rapidly in May–June, reaches its northernmost position in July–August, and retreats to near the equator in September. This seasonal cycle of the movement of the tropical convection is the manifestation of the primary driving forcing of monsoon. It is the movement of the convective center along "land bridge" from winter to summer that denotes the onset of summer monsoon over ICP, east of BOB, SCS and India afterwards.

The tropical convection over Sumatra begins to proceed northward rapidly and strengthens in late April and early May when the SAH advances westward rapidly to southern ICP. Thereby, it is reasonable to consider the rapid northward progression of convection over Sumatra as a critical event of the onset of ASM. Time series of the rapid northward shifting of tropical convection were determined to discuss its relationship with the initiation of convection in ICP, the splitting of subtropical high belt and the onset of SCS summer monsoon (Wang et al., 2004). The results indicate the interannual variation of the tropical convection proceeding northward rapidly is in agreement with that of the flourish of convection over ICP with their corre-

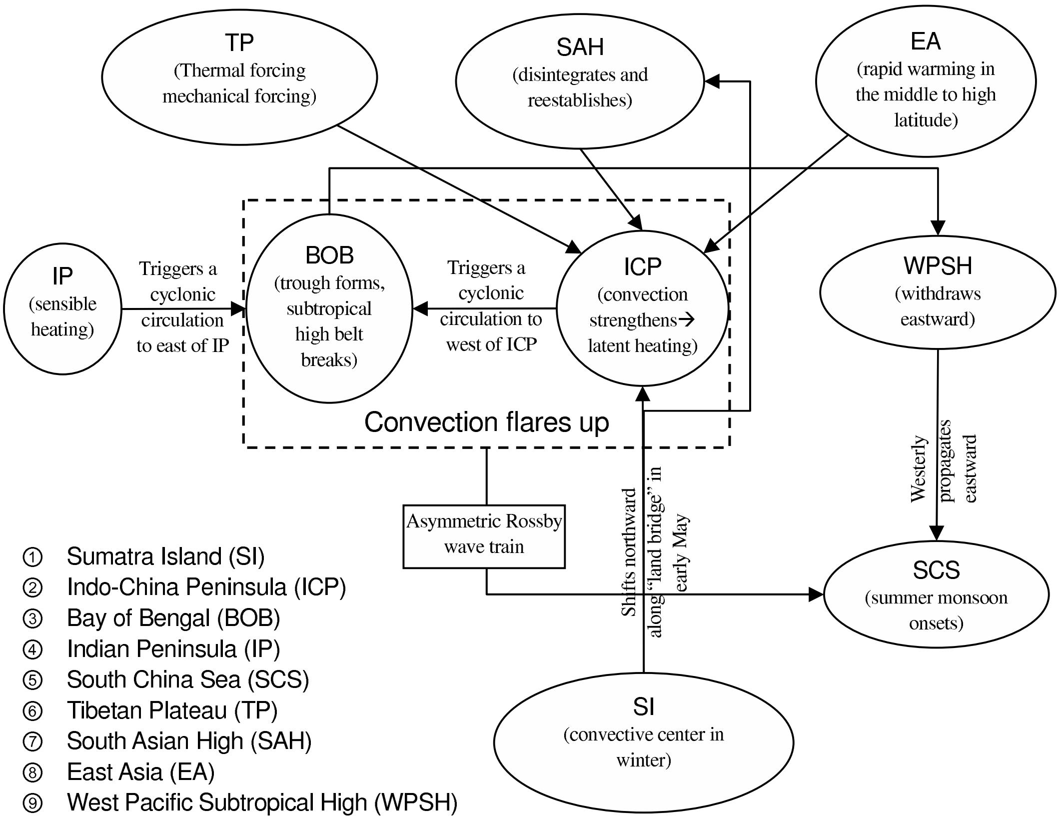

Fig. 9. Schematic illustration of the scenario of the East Asian summer monsoon onset.

lation coefficient is 0.5243. Additionally, in most years, the beginning date of the later tends to lag behind that of the former. Consequently, the rapid northward shifting of convection may have an influence upon the initiation of convection in ICP. Furthermore, the initiation of convection in ICP, the splitting of subtropical high belt and the onset of SCS summer monsoon are so well correlated that the coefficient of the former two is 0.7263 and the coefficient of the latter two is 0.7206. We can conclude that these events have some inner connections and temporal sequences, and the seasonal movement and rapid northward progression of tropical convection may be an important triggering mechanism.

6. Conclusions and discussions

Wu et al. (1998) emphasized the mechanical and thermodynamic effects of TP and pointed out that the summer monsoon is initially established over the east of BOB. Qian et al. (2004) stressed that the surface sensible heat flux in mid- and high- latitudes of East Asia in spring and early summer encourages the tropical low belt to break through the high belt first at 110°–120°E, resulting the earliest onset of southwesterly to the east of 90°E. Based on a summary of their results, it can be found that they all focus on the thermodynamic effect of the earth surface (including TP), which is the most vigorous factor in land-ocean contrast as the secondary forcing. The fact emphasized in this study, however, is the seasonal movement of tropical convection along "land bridge", which leads to the activating of convection in ICP, the splitting of subtropical high belt first in BOB, and the onset of summer monsoon in related regions. Therefore, the disputes on the earliest onset area of ASM are coordinate instead of antagonistic. It can be summarized as the following:

(1) Within the range of southern Asia (10°–20°N), the monsoonal convection flares up initially over ICP, then over BOB and SCS, and last over India. The flare-up of convection over ICP is related to the underlying surface sensible heating, but more importantly, it is the result of the northward progression of tropical convection and the arrival of SAH at this place.

(2) The latent heating over ICP is favorable for the formation of a cyclonic circulation on the west side of the heating (Wen, 2004), while the sensible heating over Indian Peninsula favors the existence of a cy-

clonic circulation or trough on the east side (Xu et al., 2002). The effective combination of both (He et al., 2004), along with the mechanical and thermodynamic effects of TP and the thermodynamic effects in mid- and high-latitudes in East Asia, leads the subtropical high belt to break first over BOB. Accompanied by the formation and deepening of BOB trough, eastern BOB is controlled by tropical southwesterly in front of the trough, so that the convection flares up, and the summer monsoon is established.

(3) In the meantime, the convective latent heat over BOB may trigger an asymmetric Rossby wave train which encourages the overturning of meridional temperature gradient in SCS, thus favors the onset of SCS summer monsoon (Liu et al., 2002). The rapid eastward withdrawal of the eastern subtropical high after the belt breaks results directly in the onset of SCS summer monsoon and its sudden characteristics.

(4) As India is overlaid by northwesterly in front of the ridge of high (i.e., behind BOB trough) after the high belt breaks, it is unfavorable for the onset of summer monsoon over India. Therefore, the summer monsoon is established last over India (He et al., 2000).

As a matter of fact, the splitting of subtropical high belt, the onset of BOB trough, the eastward withdrawal of subtropical high and the onset of SCS summer monsoon are completed rapidly and accompanied by the seasonal abrupt transition of the large-scale circulation and the water vapor transportation in Asia. Therefore, Qian et al. (2004) pointed out that the summer monsoons are established suddenly and simultaneously over BOB, ICP and SCS. However, seen from the source of the onset of summer monsoon, the rapid northward progression of tropical convection over Sumatra in late April and early May is the earliest sign of the onset of ASM. Accordingly, it is reasonable to determine the earliest onset area of ASM in the surrounding areas from southern ICP to northern Sumatra, and Asian-Australian "land bridge" plays an important role during the onset of ASM. Above academic viewpoints can be represented as the following diagrams (Fig. 9).

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REFERENCES

Chang, C. P., and G. T. J. Chen, 1995: Tropical circulations associated with southwest monsoon onset and westerly surges over the South China Sea. *Mon. Wea. Rev.*, **123**, 3254–3267.

Chang, C. P., P. A. Harr, J. McBride, and H. H. Hsu, 2004: Maritime continent monsoon: annual cycle and boreal winter variability. *East Asian Monsoon*, C. P. Chang, Ed, World Scientific Publishing Co. Pte. Ltd., 107–152.

Ding Yihui, 2004: Seasonal march of the East-Asian summer monsoon. East Asian Monsoon, C. P. Chang, Ed, World Scientific Publishing Co. Pte. Ltd., 3–53.

Ding Yihui, and Coauthors, 2004: South China Sea Monsoon Experiment (SCSMEX) and the East-Asian monsoon. *Acta Meteorologica Sinica*, **62**(5), 561–586. (in Chinese)

Gao Shouting, Zhou Yushu, and Lei Ting, 2002: Structural features of the mei-yu front system. *Acta Meteorologica Sinica*, **16**(2), 195–204.

He Jinhai, Zhu Qiangen, 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 Jinhai, Xu Haiming, Zhou Bing, and Wang Lijun, 2000: Large scale features of SCS summer monsoon onset and its possible mechanism. *Climatic and Environmental Research*, **5**(4), 333–344. (in Chinese)

He Jinhai, Wen Min, Shi Xiaohui, and Zhao Qiaohua, 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 Jinhai, Xu Haiming, and Wang Lijuan, 2003: Climatic features of SCS summer monsoon onset and its possible mechanism. *Acta Meteorologica Sinica*, **17**(Suppl.), 19–34.

He Jinhai, Yu Jingjing, Shen Xinyong, and Gao Hui, 2004: Research on mechanism and variability of East Asian monsoon. *Journal of Tropical Meteorology*, **20**(5), 449–459. (in Chinese)

Lau, K. M., and S. Yang, 1997: Climatology and interannual variability of the Southeast Asian summer monsoon. *Adv. Atmos. Sci.*, **14**, 141–162.

Li Chongyin, and Qu Xin, 1999: Characteristics of Atmospheric Circulation Associated with Summer monsoon onset in the South China Sea. *Onset and Evolution of the South China Sea Monsoon and Its Interaction with the Ocean*, Ding Yihui, and Li Chongyin, Eds, Chinese Meteorological Press, Beijing, 200–209.

Liu Yimin, J. Chan, Mao Jiangyu, and Wu Guoxiong, 2002: The role of Bay of Bengal convection in the onset of the 1998 South China Sea summer monsoon. *Mon. Wea. Rev.*, **130**, 2731–2744.

Lu Junmei, Zhang Qingyun, Tao Shiyan, and Ju Jianhua, 2006: The onset and advance of the Asian summer monsoon. *Chinese Science Bulletin*, **51**(1), 80–88.

Matsumoto, J., 1997: Seasonal transition of summer rainy season over Indochina and adjacent monsoon region. *Adv. Atmos. Sci.*, **14**, 231–245.

Murakami, T., L. Chen, and A. Xie, 1986: Relationship among seasonal cycles, low- frequency oscillations and transient disturbances as revealed from outgoing long wave radiation data. *Mon. Wea. Rev.*, **114**, 1456–1465.

Qian Yongfu, Jiang Jing, Zhang Yan, Yao Yonghong, and Xu Zhongfeng, 2004: The earliest onset area of the tropical Asian summer monsoon and its mechanisms. *Acta Meteorologica Sinica*, **62**, 129–139. (in Chinese)

Tao Shiyan, and Chen Longxun, 1987: A review of recent research on East summer monsoon in China. *Monsoon Meteorology*, C. P. Chang and T. N. Krishramurti, Eds, Oxford University Press, Oxford, 60–92.

Wang, B., and Z. Fan, 1999: Choice of South Asian Summer Monsoon Indices. *Bull. Amer. Meteor. Sci.*, **80**, 629–638.

Wang, B., and LinHo, 2002: Rainy season of the Asian-Pacific summer monsoon. *J. Climate*, **15**, 386–398.

Wang Lijuan, He Jinhai, and Guan Zhaoyong, 2004: Characteristic of convective activities over Asian-Australian "land bridge" areas and its possible factors. *Acta Meteorologica Sinica*, **18**, 441–454.

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

Wen Min, He Jinhai, and Xiao Ziniu, 2004: Impact of the convection over the Indochina peninsula on the onset of SCS summer monsoon. *Chinese J. Atmos. Sci.*, **28**(6), 864–875. (in Chinese)

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

Xu Haiming, He Jinhai, Wen Min, and Dong Min, 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)

Zeng Qingcun, and Li Jianping, 2002: Interaction between the northern and southern hemispheric atmospheres and the essence of monsoon. *Chinese J. Atmos. Sci.*, **26**(4), 433–448. (in Chinese)

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

Zhu Qiangen, He Jinhai, and Wang Panxing. 1986: A study of circulation differences between East Asian and Indian summer monsoon with their interaction. *Adv. Atmos. Sci.*, **3**, 466–477.