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Congbin Fu · Zhihong Jiang · Zhaoyong Guan ·
Jinhai He · Zhongfeng Xu (Eds.)

Regional Climate Studies of China

With 164 Figures and 42 Tables

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Editors
Prof. Congbin Fu
RCE-TEA
Institute of Atmospheric Physics
Chinese Academy of Sciences
100029 Beijing
P. R. China
fcb@tea.ac.cn

Prof. Jinhai He
Key Laboratory of Meteorological Disaster
Nanjing University of Information Science & Technology
114 Pangcheng New Street, Pukou District
210044 Nanjing
P. R. China
hejhnew@jsmail.com.cn

Prof. Zhihong Jiang
Key Laboratory of Meteorological Disaster
Nanjing University of Information Science & Technology
114 Pangcheng New Street, Pukou District
210044 Nanjing
P. R. China
zhjiang@nuist.edu.cn

Dr. Zhongfeng Xu
RCE-TEA
Institute of Atmospheric Physics
Chinese Academy of Sciences
100029 Beijing
P. R. China
xuzhf@tea.ac.cn

Prof. Zhaoyong Guan
Key Laboratory of Meteorological Disaster
Nanjing University of Information Science & Technology
114 Pangcheng New Street, Pukou District
210044 Nanjing
P. R. China
guanzy@nuist.edu.cn

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Preface

China, located in East Asia, is characterized by monsoon climate, an unique climate type among various climate classification of the world.

There has been long history of regional climate study in China, beginning from late 1890s, represented by a number of scientists, such as Zhu, K. Z., Tu, C. W., Zhu, B. H., Yao, Z. S. and Zhang, B. K., etc. The introduction of modern atmospheric dynamics, synoptic meteorology and numerical modeling into the climate research has made further development of regional climatology in China (e. g. Ye, D. Z., Tao, S. Y., Chao, J. P., and Zeng, Q. C., etc).

In last several decades, the development of regional climate model, application of satellite information and information technique, implementation of continental scale experiments of energy/water balance of land surface and other advanced approaches have significantly promoted the progress of regional climate study in various parts of world.

As one volume of the book series of *Regional Climate Studies*, this book aims to summarize the progress of regional climate study of China mainly in last decade. It focuses on the physical and dynamic characteristics of climate of China based on current researches by applying these advanced approaches, rather than giving detail description of regional climate variables.

The volume consists of 11 chapters, beginning with the general introduction of monsoonal features of climate, followed by the paleo-climate (chapter 2), inter-decadal (chapter 3), interannual (chapter 4) climate variabilities and aridity trend of northern China as a specific regional climate issue (chapter 5). The effects of Tibetan Plateau, and soil moisture of land surface process on the regional climate of China are analyzed to understand the physical basis of climate variation in Chapter 6 and 7. To link with the impact of climate, the climate extremes and climate related disasters are presented in Chapter 8. Chapter 9 is a special one deal with the regional climate modeling. Finally, Chapter 10 and 11 present the projection of future climate and the assessment on impacts of climate variation on water resource and agriculture in China.

We would like to thank Drs Ichtiaque Rasool and Hans-Jurgen Bolle to invite us to make our contributions to the book series of Regional Climate

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The Editors

Contents

Contributing Authors

Chen X.
Department of Atmospheric Sciences, Nanjing University
22 Hankou Road, Nanjing, 210093
China
xchen@nju.edu.cn

Fan L. J.
Institute of Atmospheric Physics, Chinese Academy of Sciences
P. O. Box 9804, Beijing, 100029
China
fanlj@tea.ac.cn

Feng J. M.
RCE-TEA
Institute of Atmospheric Physics, Chinese Academy of Sciences
P. O. Box 9804, Beijing, 100029
China
fengjm@tea.ac.cn

Fu C. B.
RCE-TEA
Institute of Atmospheric Physics
Chinese Academy of Sciences
100029 Beijing
P. R. China
fcb@tea.ac.cn

Guan Z. Y.
Key Laboratory of Meteorological Disaster
Nanjing University of Information Science & Technology
114 Pangcheng New Street
Pukou District, 210044 Nanjing
P. R. China
guanzy@nuist.edu.cn

Guo W. D.
RCE-TEA
Institute of Atmospheric Physics, Chinese Academy of Sciences
P. O. Box 9804, Beijing, 100029
China
guowd@tea.ac.cn

He J. H.
Key Laboratory of Meteorological Disaster
Nanjing University of Information Science & Technology
114 Pangcheng New Street
Pukou District, 210044 Nanjing
P. R. China
hejhnew@jsmail.com.cn

Jia W. J.
RCE-TEA
Institute of Atmospheric Physics, Chinese Academy of Sciences
P. O. Box 9804, Beijing, 100029
China
jiawj@tea.ac.cn

Jiang Z. H.
Key Laboratory of Meteorological Disaster
Nanjing University of Information Science & Technology
114 Pangcheng New Street
Pukou District, 210044 Nanjing
P. R. China
zhjiang@nuist.edu.cn

Li L. P.
KLME, NIM, Nanjing University of Information Science & Technology
114 Pangcheng New Street, Pukou District, Nanjing, 210044
China
liliping@nuist.edu.cn

Ma Z. G.
RCE-TEA
Institute of Atmospheric Physics, Chinese Academy of Sciences
P. O. Box 9804, Beijing, 100029
China
mazg@tea.ac.cn

Ning J. H.
College of Applied Meteorology, Nanjing University of Information Science & Technology
114 Pangcheng New Street, Pukou District, Nanjing, 210044
China

Shen S. H.
College of Applied Meteorology, Nanjing University of Information Science & Technology
114 Pangcheng New Street, Pukou District, Nanjing, 210044
China
yqzhr@nuist.edu.cn

Wang S. Y.
RCE-TEA
Institute of Atmospheric Physics, Chinese Academy of Sciences
P. O. Box 9804, Beijing, 100029
China
wsy@mail.tea.ac.cn

Wang Z. Y.
National Climate Center, China Meteorological Administration
46 Zhong Guan Cun Nan Dajie, Beijing, 100081
China
wangzunya_cma@163.com

Wu Z. W.
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, P. O. Box 9804, Beijing, 100029
China
wzw@lasg.iap.ac.cn

Xu Z. F.
RCE-TEA
Institute of Atmospheric Physics
Chinese Academy of Sciences
100029 Beijing
P. R. China
xuzhf@tea.ac.cn

Yan Z. W.
RCE-TEA
Institute of Atmospheric Physics, Chinese Academy of Sciences
P. O. Box 9804, Beijing, 100029
China
yzw@mail.tea.ac.cn

Yang X. Q.
Department of Atmospheric Sciences, Nanjing University
22 Hankou Road, Nanjing, 210093
China
xqyang@nju.edu.cn

Zhai P. M.
Department of Forecasting Services and Disaster Mitigation, China Meteorological Administration
46 Zhong Guan Cun Nan Dajie, Beijing, 100081
China
pmzhai@cma.gov.cn

Zhang Y. C.
Department of Atmospheric Sciences, Nanjing University
22 Hankou Road, Nanjing, 210093
China
yczhang@nju.edu.cn

Zhao D. M.
RCE-TEA
Institute of Atmospheric Physics, Chinese Academy of Sciences
P. O. Box 9804, Beijing, 100029
China
zhaodm@tea.ac.cn

Zhao Z. C.
National Climate Center, China Meteorological Administration
46 Zhong Guan Cun Nan Dajie
Beijing, 100081
China
zhaozc@cma.gov.cn

Zhu Y. M.
Institute of Meteorology, PLA University of Science and Technology
60 Shuanglong Street, Nanjing 211101
China
yiminz@21cn.com

Zou X. K.
National Climate Center, China Meteorological Administration
46 Zhong Guan Cun Nan Dajie, Beijing, 100081
China

Chapter 1 Climate of China and East Asian Monsoon

1.1 Introduction

The East Asian monsoon is the principle component of the Asian monsoon system and plays an important part in the weather and climate in China. The regional flood and drought disasters in summer in China are closely related to the seasonal anomalies of the main rain belt whose progression is significantly influenced by the East Asian summer monsoon (Ding, 1992). The huge floods during Meiyu period in 1991 and 1998 are caused by the anomalies of East Asian summer monsoon, resulting in the property loss of around 100 billion and large casualty, and direct economic loss of 180 billion RMB, respectively (Ding, 1993; NCC, 1998). The East Asian winter monsoon works on the weather and climate in China in the form of cold air, of which the cold wave is the strongest and affects the widest areas, usually accompanying sudden temperature drop and blast and sometimes rain, snow, glitter ice or frost, even disasters when severe (Li, 1955). Therefore, the importance of East Asian monsoon is of self-evidence.

Tao and Chen (1987) provided the circulation model of the East Asian summer monsoon system, showing clearly the members and their allocation (Fig1.1). Circulations of East Asian monsoon and Indian monsoon are associated in some way, but the two systems are independent from each other. In the Indian monsoon system, the monsoonal current, namely southwesterly, comes from the Mascarene High in the Southern Hemisphere (SH), with Somalia jet traversing the equator and advancing from south to north, and the low-frequency waves in the equatorial Indian Ocean propagating from south to north as well. The Indian monsoon regions are influenced by both the tropical circulation and monsoon trough because of the barrier effect of the Qinghai-Tibet Plateau, indicating that the Indian summer monsoon system is a pure tropical circulation system. However, the origin of the monsoonal currents of the East Asian monsoon system is quite different. Seen from Fig1.1, the cross-equatorial southerly in 105°E–120°E from the SH converges with the westerly from the Indian

Ocean and the easterly from the south of the West Pacific subtropical high (WPSH) to form southwesterly which is tropical monsoonal current and southeasterly which is subtropical monsoonal current respectively, providing warm and moist southerly currents for the East Asian monsoon regions including the areas east of 100°E in the East Asian continent, Korea and Japan. These currents are primary water vapor sources of summer rainfalls in East China. The warm and moist currents advancing northward meet the cold air from the middle and high latitudes to form the Meiyu front (subtropical monsoon). The duration of Meiyu period and the total rainfall amounts are not only related to the position, intensity and water vapor transport of the circulation system in the south, but also limited by the circulation in the middle and high latitudes, which is the main difference between the circulations of the East Asian summer monsoon and Indian summer monsoon. That is, the circulation system in the middle and high latitudes has more impacts on the circulation and rainfalls in summer East-Asia (Zhang and Tao, 1998).

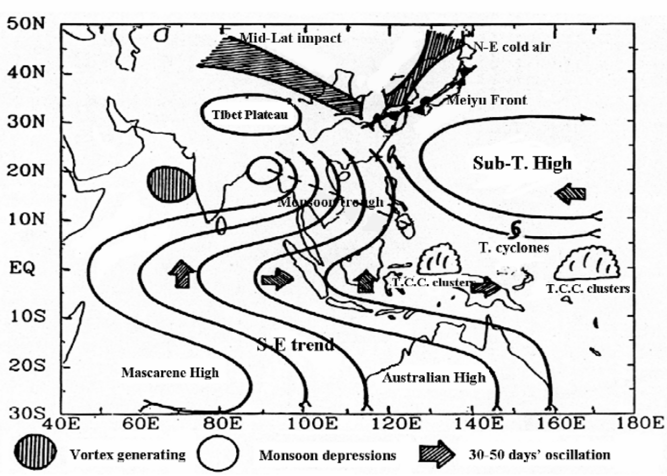


Fig. 1.1 A schematic map of members and circulation characters of Asian summer monsoon system (Zhang and Tao, 1998).

The northward advancement of summer monsoon in East Asia is closely associated with the variation of the WPSH whose intraseasonal oscillation (ISO) from April to July is represented by three mutation processes, corresponding in time to the onset of South China Sea (SCS) monsoon, the onset of Meiyu and the end of Meiyu, respectively.

When the ridge line of WPSH in summer is abnormally more southward or the ridge point is more westward, the circulation of East Asian summer monsoon is weaker; with an anti-cyclonic circulation at 850 hPa over the tropical areas in East-Asia, a cyclonic circulation in the subtropical areas, the ascending motion at 500 hPa being weak over the tropical areas in East-Asia but strong in the Meiyu front areas, blocking high occurring at 500 hPa over the Okhotsk Sea in the high latitude of East-Asia and leading the cold air from the high latitude to the mid-latitude, and the disturbance in Meiyu front being strong and resulting in more rainfalls in Jiang-Huai Valley in the flood season. On the contrary, when the ridge line of WPSH in summer is abnormally more northward or the ridge point is more eastward, the circulation of East Asian summer monsoon is stronger and the atmospheric circulation systems in East-Asia show the opposite abnormal patterns, with less rainfalls in Jiang-Huai Valley in flooding seasons (Zhang and Tao, 2003).

On the seasonal scale, the intensity of WPSH, its west boundary position and the intensity of South Asian High (SAH) are all closely related to the intensity of the East Asian summer monsoon. Moreover, positions of the north boundary of WPSH and the blocking pattern in Ural are closely associated with rainfall amounts in summer East-Asia (Liu et al., 2004; Wu et al., 2006a,b,c).

In addition to the obvious seasonal variation, the East Asian summer monsoon also has prominent ISO which is related to the onset of summer monsoon (Wu et al., 2006d,e). The low-frequency westerly occurs 2d earlier than the onset of SCS summer monsoon. And its development and westward extension to the east of Philippine play a crucial role in the ISO in SCS, and trigger the outbreak of the summer monsoon (Li, 2004). ISO in the East Asian summer monsoon shows the pattern of wave-train along the coast and is represented by the monsoon surge propagating to the north, which consists of several ISO wet phases. The summer monsoon is established when the ISO wet phase is introduced or develops (Qian et al., 2000; Ju et al., 2005b).

The activities of the atmospheric ISO over SCS and its surrounding areas play an important part in the establishment of the strong East Asian summer monsoon (Li, 2004). When the SCS summer monsoon is strong, a strong ISO field is observed, with a strong cyclonic circulation being over SCS and West Pacific; on the contrary, the weak SCS summer monsoon corresponds to a weak ISO field, with a weak anti-cyclonic circulation being over SCS and West Pacific.

Two preferential modes (30–60d and 10–20d) may play a critical role in the modulation of summer monsoon activities in the East Asian monsoon region. Based on the case study of 1998, it is observed that the SCS summer monsoon is mainly controlled by the 30–60d mode, but it is modulated by 10–20d mode (Ding, 2004; Ju et al., 2005b; Ju and Zhao, 2005). In years with strong East Asian monsoon surge, the impact of the quasi–30–60d oscillation is significant, resulting in more rainfalls in the mid- and lower reaches of Yangtze River; while in years with weak East Asian monsoon surge, the quasi–30–60d oscillation weakens and 10–20d oscillation becomes primary, resulting in droughts in the mid-lower reaches of Yangtze River.

ISO is significant in the Western North Pacific (WNP) monsoon region as well (Wang et al., 2005). Such climatological ISO consists mainly of 30–60d and 10–20d oscillations and the former is predominant. According to the phase-distribution of the convection and low-level westerly in the WNP, it is observed that the low-frequency convection and westerly in the WNP propagates westward and northward, and the convection and active-break cycle of westerly in the WNP are modulated by the low-frequency oscillations of 30–60d and 10–20d to a great extent.

The inter-annual variation of the intensity of East Asian summer monsoon has important impacts on rainfalls in China. There are more or normal Meiyu rainfalls in the mid-lower reaches of Yangtze River in weak SCS summer monsoon years; while there are normal or less Meiyu rainfalls in strong SCS summer monsoon years. And, the route and process of the water vapor transporting to the mid-lower reaches of Yangtze River are different in the early and late onset years of SCS summer monsoon. In the early onset years, the water vapor transports clockwise through Indo-China peninsula to the mid-lower reaches of Yangtze River, and returns to SCS, corresponding to more rainfalls (floods) in Yangtze River valley. While in the late onset years, the water vapor transports anticlockwise from SCS to South China, corresponding to less rainfalls (droughts) in the Yangtze River valley (Wu et al., 2003; Wu et al., 2006a).

The atmospheric circulation of East Asian monsoon and SST field exhibit interdecadal variation as well. East Asian summer monsoon has weakened since 1960s in the interdecadal scale, which has no obvious association with the global warming induced by human activities in the late 20th century, and there are two abrupt changes in mid 1960s and in mid and late 1970s. The interdecadal variation of East Asian winter monsoon is significant as well. The prominent increase of temperature in the north of East-Asia since mid 1970s is directly influenced by the East Asian winter monsoon (Li and Zeng, 2002; Jiang and Wang, 2005; Wu, 2005; Zhao and Zhou, 2005; Zhao and Zhang, 2006).

The interdecadal variation of SCS summer monsoon in its maintenance period shows, divided by the year 1978, the SCS summer monsoon started later and ended earlier in the first twenty years, accompanied by less rainfalls, weaker convection and weaker monsoon, while summer monsoon started later and ended later in the last twenty years, along with more rainfalls, stronger convection and stronger monsoon. Such variation is significantly influenced by the abrupt change of the atmospheric circulation in late 1970s. The intensity and position of WPSH also show obvious interdecadal variation in mid-1970s, after which the southwesterly influences the lower reaches of Yangtze River and South Korea in summer, producing less rainfalls and droughts in North China and more rainfalls in the Yangtze River and South Korea, and before which the southwesterly may reach North and Northeast China, causing more rainfalls in the north and less rainfalls in the Yangtze River (Dai et al., 2003; Qian, 2005).

1.2 Characteristics of the onset of Asian summer monsoon

The onset characteristics and the possible mechanisms have always been the highlight in the study of Asian summer monsoon (ASM). In particular, over where the earliest onset occurs has been the focus of investigations (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 agreement as to this problem. Four major viewpoints are as follows: First, the ASM initially establishes in the SCS, and then advances northward and westward (Tao and Chen, 1987); second, in eastern Bay of Bengal (BOB) (Wu and Zhang, 1998); third, in Indo-China Peninsula (ICP) or its southern surrounding areas (He et al., 1996; Zhang et al., 2004; Lau and Yang, 1997; Matsumoto, 1997; Webster et al., 1998; Wang and Fan, 1999), and fourth, simultaneously over the whole areas of BOB, ICP and SCS. In a word, where on earth the ASM breaks out earliest needs further study.

The Asian summer (winter) monsoon and Australian winter (summer) monsoon are so closely associated with each other that they can 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. 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 related to the onset of summer monsoon in ICP (He et al., 1996). If ICP and MC are considered 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 the “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.

1.2.1 The earliest onset of Asian summer monsoon and the regional characteristics

As the onset of summer monsoon is always accompanied with convective rainfalls, and, low TBB can figure convective clouds and rainfalls, TBB data are used to discuss the characteristics of seasonal transition in Asian-Australian monsoon region and the initial onset of ASM. Fig1.2 shows the horizontal distribution of the climatological TBB from March to June.

The distribution of TBB in March (Fig1.2a) is still the same as in January (figure omitted). There is a high TBB belt in the subtropics in Southern Hemisphere (SH) with the ridgeline at 25ºS and core in central Australia, corresponding to the austral subtropical high belt and the Australian high. There is also a high TBB belt in the boreal subtropics, with the ridgeline at 15º–20ºN and centers in West Pacific, SCS and northern BOB, corresponding to the boreal subtropical high belt and centers of discrete anti-cyclones. In between, a low TBB belt locates in the tropics, with low centers being in MC and the minimum in Sumatra. Moreover, a TBB trough extends from the New Guinea low center to North Australia, in correspondence with the summer monsoon there.

However, the characteristics change significantly in April (Fig1.2b): (1) the high TBB belt in the subtropics in Northern Hemisphere (NH) breaks in ICP (100ºE–110ºE, 10ºN–20ºN) (280K is the threshold), and an obvious trough extends from the low center in Sumatra to this region, connecting with the low TBB belt in the mid-latitude; (2) the high TBB in Australia moves northward notably (the axis moves to 20ºS), so the trough from New Guinea to northern Australia disappears. Those changes imply the northward movement of the entire circulation system, 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 radiations, signifying the start of the seasonal transition of large-scale circulation in middle and low latitudes in the Asian-Australian monsoon region.

In May (Fig1.2c), it is noticeable that: (1) the eastern part of TBB high belt in the boreal subtropics retreats eastward rapidly, and the 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 North BOB shifting northwestward rapidly to the region around (80ºE, 25ºN). These changes indicate that the monsoonal convection has been fully established over ICP and BOB.

In June (Fig1.2d), the high TBB belt in West Pacific continues to retreat eastward along with the obvious jump of the ridge line to around 22ºN. 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 the southern Japan, respectively. They are in correspondence with Meiyu in China and Baiu in Japan, whose frontal structures and characteristics have been thoroughly studied (Gao et al., 2002a,b). The SCS-Philippine has been controlled by a strong low center, showing the summer monsoon has been fully established in SCS-West Pacific. The low center over Sumatra in winter has disappeared. A large strong low center appears in North BOB in place of the high center in winter, indicating that the summer monsoon has been fully established from BOB to India.

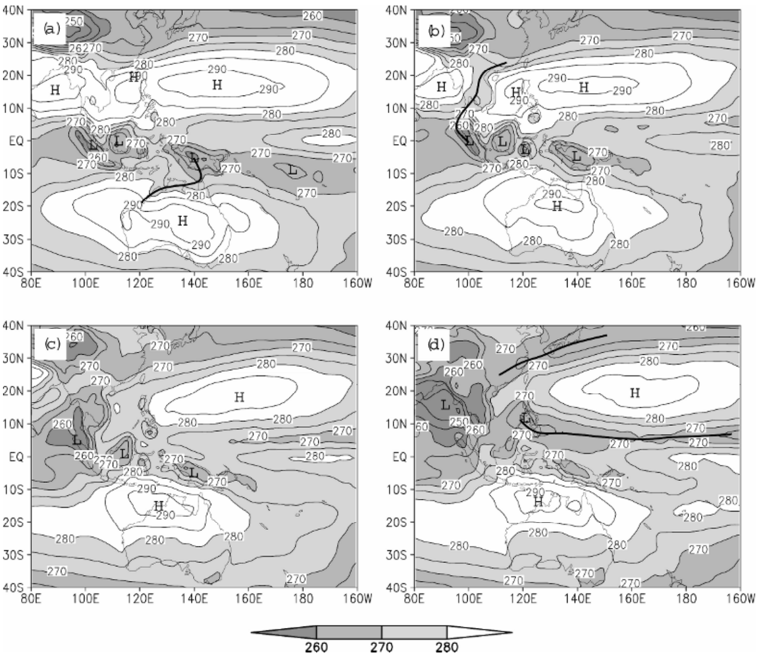


Fig. 1.2 Distributions of climatological TBB in (a) March, (b) April, (c) May, and (d) June. The thick solid line is the axis of low belt and areas of TBB<280K are shaded. (Units: K)

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

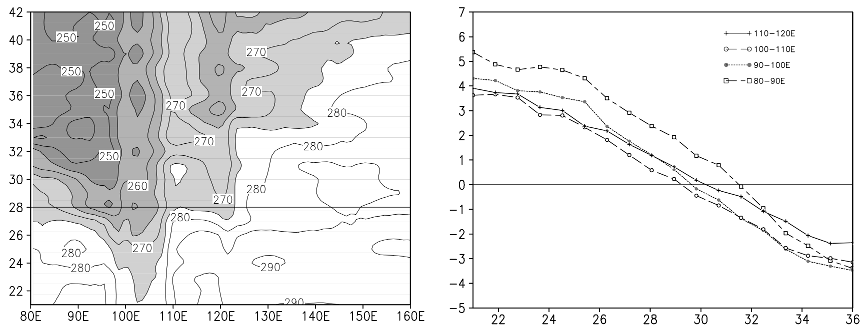
Fig. 1.3a shows the time-longitude section of TBB along (10ºN–20ºN). It can be seen that the convection illustrated by low TBB flares up initially over ICP, and then extends to the east and west. If TBB<275K (shaded areas) is taken as the sign of active convection, the onset of convection over eastern BOB (east of 90ºE) is one pentad earlier than in SCS. In Fig. 1.3b, the meridional temperature gradient overturns earliest over ICP (100º–110ºE), then over the eastern BOB and SCS, and last over the western BOB. Seen from Fig. 1.3c, the vertical shear of zonal wind reverses 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 indicating the simultaneous onset of summer monsoon over BOB, ICP and SCS in the 27th-28th pentad, claimed by Qian et al. (2004), coordinate the disputes on the earliest onset area.

According to above results, it is true that the convection first bursts out over ICP, which is closely associated with the seasonal migration of tropical convection over Sumatra along Asian-Australian “land bridge”. It will be further discussed in the following part.

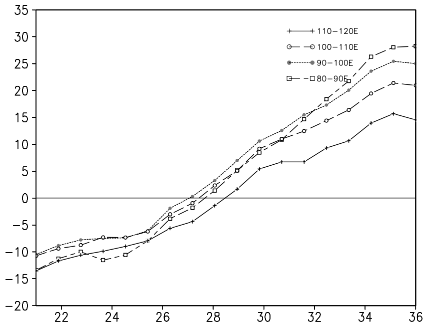
In order to discuss the characteristics of the summer monsoon onset and their differences in various regions, the time-latitude sections of climatological TBB along 80ºE, 100ºE, 120ºE and 140ºE are computed (not shown), respectively.

The characteristic of the summer monsoon onset in East India (west of BOB) is that the low TBB belt propagates northward gradually from the equator in early May, and a low center is formed in East India in early and mid-June presenting the onset of Indian summer monsoon. East TP and Southeast Asia turns to be overlaid by low TBB belt from 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 from June to September in East TP (around 32ºN), separated from the low belt in Southeast Asia (15ºN) by a relatively high belt. This means the summer monsoon over East TP is relatively independent of that over Southeast Asia, unlike the summer monsoon over West TP which is the northward extension of Indian summer monsoon. The rapid transition from high TBB belt to low TBB belt in mid-May over SCS (12ºN) denotes the onset of summer monsoon over SCS. Furthermore, there is a low belt over East China in June, corresponding to the subtropical summer monsoon rain belt in China (Meiyu). The high belt between them corresponds to the West Pacific subtropical high. A strong low center appears around the equator from December to February, and extends southward to the west of North Australia, denoting the prevalence of Australian summer monsoon in SH. Along the longitude of Japan, West Pacific and the eastern part of North Australia, 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 North Australia from December to March, which embodies the prevalence of North 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 TBB belt at equator, reflecting the seasonal cycle of tropical convection. However, the onset of summer monsoon over SCS and West Pacific are quite different. The establishment of SCS summer monsoon is simultaneous in a wide range of 20 latitudes, that is, its abrupt behavior is much more obvious than India and Southeast Asia summer monsoons. This is directly associated with the rapid eastward retreat of the subtropical high belt after break (He et al., 2002). (2) Besides the low TBB belt over SCS-West Pacific, there is another low belt to the east of 100ºE, i.e. the subtropical monsoon rain belt in China-Japan (Meiyu in China and Baiu in Japan). The East Asian monsoon system includes not only tropical summer monsoon, but also subtropical monsoon (Zhu et al., 1986) and is more complex than Indian monsoon system. (3) The tropical summer monsoon is initially established in the longitude of ICP, and then advances eastward and westward, respectively. What processes and mechanisms result in such characteristics? Further discussion will be presented in the following section.



(a) (b)



(c)

Fig. 1.3 (a) Time-longitude section of climatological TBB (10ºN–20ºN). Areas of TBB⩽275K are shaded. (Units: K) (b) Climatological evolution of the meridional temperature difference (5ºS–5ºN minus 20ºN–30ºN) at 500 hPa. (Units: degC) (c) Climatological evolution of the zonal wind shear (850 hPa minus 200 hPa) in low-latitude (10ºN–20ºN). (Units: m s^{-1})

1.2.2 Large-scale characteristics of Asian summer monsoon onset

According to the study of Qian et al. (2004), the tropical Asian summer monsoon to the east of 90ºE bursts simultaneously and abruptly firstly over the whole area in BOB, ICP and SCS in the 27^{th}–28^{th} pentad. While to the west of 90ºE, the onset of summer monsoon over Indian peninsula and Arabian Sea is later, firstly to the south of 10ºN and proceeding northward gradually. Thereby, from a large-scale viewpoint, the onset of the tropical summer monsoon occurs earliest over SCS and its surrounding areas. After then, 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., 2002), and further details will be provided below.

Fig. 1.4 shows the upper and lower circulation fields before the onset of SCS summer monsoon (4^{th} pentad of April) and during the onset (4^{th} pentad of May). The SAH center at 200 hPa lies in the ocean to the east of Philippine in the 4^{th} pentad of April, and moves rapidly to southern ICP in the 6^{th} pentad of April. It jumps from south of 15ºN to the north, and extends westward in the 2^{nd}–4^{th} pentad of May with the main body over SCS, ICP, BOB, Indian peninsula and Arabian Sea at 10ºN−25ºN. After the 5^{th} pentad of May, the SAH continues to move northwestward to the north of 20ºN.

The subtropical high at 500 hPa distributes zonally along 15ºN with two centers in Philippine and West Arabian Sea, respectively (Fig. 1.4c), while the relatively low region is over BOB. The pattern changes on the 2nd pentad of May (Figure omitted), with the subtropical high belt tending to break, a closed cyclonic circulation (Sri Lanka vortex) appearing around (80ºE, 5ºN) and tending to extend northward, and the trough in northern BOB strengthening. In the 4th pentad of May, when SCS summer monsoon bursts out, Sri Lanka vortex combines with the trough over North BOB to form the well-known BOB trough (Fig. 1.4d). The subtropical high belt breaks completely with its eastern part retreating eastward and its western part controlling areas to the west of Arabian Sea, so India is controlled by northwesterly.

At 850 hPa (Fig. 1.4e, 1.4f), the splitting of the subtropical high belt, the rapidly eastward (westward) withdrawal of its eastern (western) part, and the formation and deepening of the BOB trough are similar to those at 500 hPa, but are more complex and a bit earlier. In particular, in mid-April, there is a cyclone in SH forming twin cyclone straddling the equator with the Sri Lanka vortex. In between, the equatorial westerly accelerates. In the 4th pentad of May, the Sri Lanka vortex moves northward into the BOB trough with the circulation center 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. And the westerly flows to ICP-SCS region and converges at SCS with the cross-equatorial current from North Australia and the returning current from the southern part of West Pacific subtropical high. Probably, it is the frame of three currents that leads to the complexity of the onset course of SCS summer monsoon, furthermore arises controversies.

The meridional temperature gradient and vertical shear of zonal wind in middle and low latitudes in Asia have also converted corresponding to changes of large-scale circulations (see Fig. 1.3). Therefore, it may be believed that the onset of SCS summer monsoon is not a local phenomenon, but a prominent large-scale event that occurs 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).

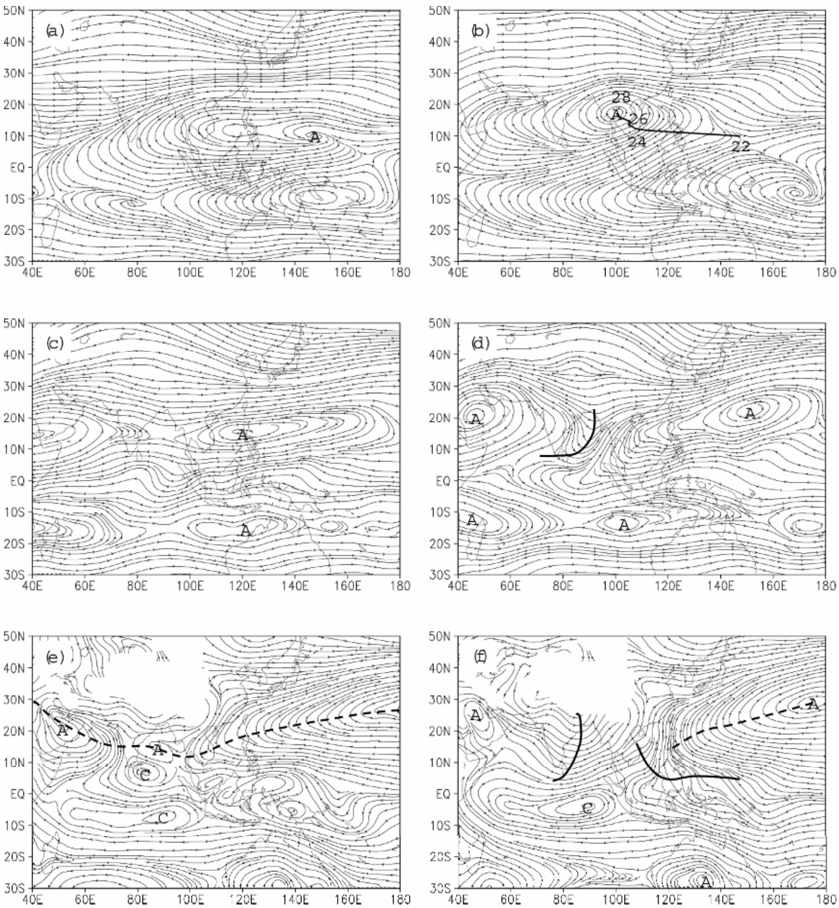


Fig. 1.4 Climatological circulation fields before and after the onset of South China Sea summer monsoon at (a),(b) 200 hPa, (c),(d) 500 hPa, and (e),(f) 850 hPa. (a), (c) and (e) for the 4th pentad of April; (b), (d) and (f) for the 4th pentad of May. The thick solid line in (b) denotes the movement 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 lines are the ridge line.

The relationship between the movement of SAH and the onset of ASM is widely accepted. Qian et al. (2004) especially emphasized the correlation between the position of SAH center and the onset date of ASM. It can be seen from Fig. 1.4 that the SAH advances westward rapidly to South ICP during the 4^{th}–6^{th} pentad of April, then moves northward, and summer monsoon is established over SCS afterwards. Then, why does the SAH advance westward rapidly? Why does it move northward along ICP?

Fig. 1.5 shows the variation of SAH at 150 hPa in the 5^{th} and 6^{th} pentad of April and the vertical section of apparent heating ratio in the 5^{th} pentad of April. The SAH disintegrates into two centers in the 5^{th} pentad of April, lying over East and West Philippine, respectively. In the 6^{th} pentad of April, the center in the east weakens and disappears, while the west one strengthens and moves westward to South ICP. Hence, the rapid westward progression of SAH during the 4^{th}–6^{th} pentad of April is actually a process of disintegration and reestablishment. It can be seen from Fig. 1.5c that there is a heating center (the apparent heating ratio is greater than 2 degK day^{-1}) at mid-upper troposphere above South ICP (7.5ºN–15ºN, 105ºE) in the 5^{th} pentad of April. The SAH center at 150 hPa is located exactly above the heating center in the next pentad, implying the great attribution of the upper latent heating to 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 suppose with venture that there are some inner connections among the rapid northward progression of convection over Sumatra, the outbreak of convection over ICP and the rapid westward movement of SAH.

Fig. 1.6 presents the composite circulation at 850 hPa with the date when the subtropical high belt splits (Wen et al. 2004) as the reference point. Two pentads before the belt breaks, there is still a zonal subtropical high belt over South Asia, and twin cyclones on both sides of the equator near 80ºE. In the pentad when the subtropical high belt breaks (i.e. pentad 0), Sri Lanka vortex enters into the trough region and deepens the trough. The southwesterly in front of the trough arrives at ICP, but the summer monsoon has not yet been established over SCS where is still controlled by the WPSH. As the WPSH withdraws eastward rapidly to the east of Philippine two pentads later, the summer monsoon is fully established over SCS. It can be observed 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 and so on, lead to the onset of summer monsoon over SCS. It is also clear that the onset of SCS summer monsoon is the process that the southwesterly advances from west to east rather than from south to north (at least it is the case in climatology), which helps to explain why SCS summer monsoon is established simultaneously in a wide range of 20 latitudes.

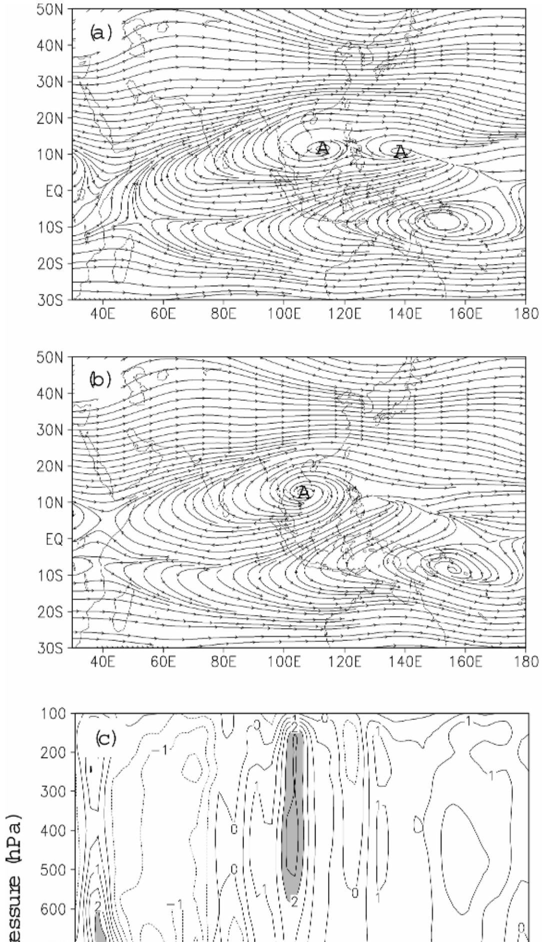


Fig. 1.5 Climatological circulation fields at 150 hPa in the (a) 5th pentad and (b) 6th pentad of April. (c) Vertical section of heating ratio in the 5th pentad of April averaged in (7.5ºN−15ºN), and areas of heating ratio greater than 3degK day^{-1} are shaded. (Units: degK day^{-1})

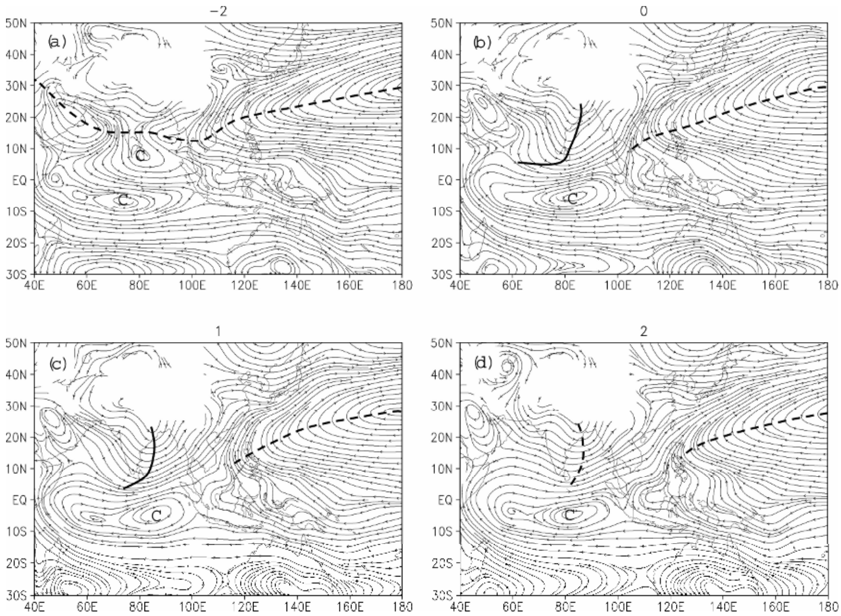


Fig. 1.6 Composite circulation fields at 850 hPa with the splitting dates of the subtropical high belt as reference point. (a) Pentad −2, (b) Pentad 0, (c) Pentad +1, and (d) Pentad +2. The dashed line is the ridgeline of the subtropical high, and the solid line is the trough line.

The composite time sections of the zonal wind at 850 hPa and OLR with the onset date of SCS summer monsoon as reference point are computed (not shown, He et al., 2003). Before (after) the onset of monsoon, the SCS is controlled by the easterly (westerly) and high (low) OLR, exactly accordant with the onset characteristics of summer monsoon. In addition, the westerly and low OLR propagate from the equatorial Indian Ocean (80ºE) 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) have 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 for the southward movement of the South China stationary front. In a word, the interactions between mid-latitude and low latitude during the onset of SCS summer monsoon also attribute to the abrupt features in the SCS summer