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REASONS FOR THE LATE ONSET AND ANOMALOUS SOUTHWARD PERSISTENCE OF THE SOUTH CHINA SEA SUMMER MONSOON IN 2005

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Abstract: Features of atmospheric circulation and thermal structures are discussed using the NCAR/NCEP data to reveal the reasons for the late onset and anomalous southward persistence of the South China Sea Summer Monsoon (SCSSM) in 2005. The results show that three factors are crucial. First, a strong Arabian High overlaps with a high-latitude blocking high and channels strong cold air to southern Asia. Second, the Tibetan Plateau has a bigger snow cover than usual in spring and the melting of snow cools down the surface. Third, the Somali Jet breaks out at a much later date, being not conducive to convection over Indochina. The former two factors restrict atmospheric sensible heating over the Tibetan Plateau and nearby regions while the third one limits latent heating over Indochina. All of the factors slow down atmospheric warming and postpone the onset of SCSSM. Long after the onset of SCSSM, strong cold air over India advances the Southwest Monsoon northward slowly, resulting in weaker convection and latent heating over the Tibetan Plateau and nearby areas. The negative feedback conversely inhibits further northward movement of Southwest Monsoon.

Key words: South China Sea summer monsoon; Arabian High; Somali Jet; snow cover

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1 INTRODUCTION

Asian summer monsoon is the most prominent one in the world. It can be divided into two relatively independent members: South Asia summer monsoon and East Asia summer monsoon [1, 2]. The South China Sea (SCS) becomes an important area for the two interacting members due to its particular geographic location. Since 1980, much progress has been achieved about the onset of SCSSM and the mechanisms with winds, convection and other kinds of indexes used as signals [3-8]. The studies show that the mean onset time of SCSSM is the 4th pentad of May and has prominent inter-annual variations. The thermal difference between land and sea plays an important role on the onset and persistence of Asian summer monsoon [9, 10]. As a huge up-lifting heat source, the Tibetan Plateau has gained extensive attention for its thermal effect [11-12]. The snow cover is undoubtedly a significant factor affecting thermal intensity [13, 14].

In 2005, SCSSM broke out during the 6th pentad in May, two pentads later than the climatological mean and remained southward near the south of China until June 24. This led to two serious consequences: on the one hand, the Pearl River Delta saw the largest amount of precipitation since 1951 and devastating floods; on the other hand, heat waves and serious droughts appeared in the Yangtze River valley, which should generally have been in the Mei-yu season. What caused the late onset of SCSSM? Why did the extensive Southwest Monsoon spread straightly eastward to the SCS instead of propagating northeastward to eastern Tibetan Plateau and Indochina as usual? Here are some analyses of the atmospheric circulation, dynamical and thermal mechanisms for the investigation.

2 DATA AND CALCULATION

The datasets include National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis daily means of geopotential height, winds, humidity,

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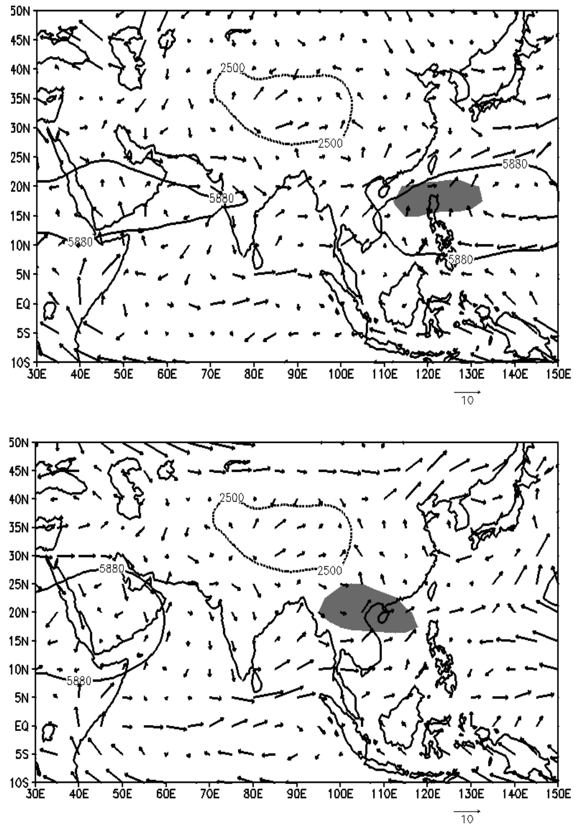
temperatures on pressure levels from May to June in 2005 and their long term means with a resolution of 2.5°×2.5°. The vertical integrated atmospheric heat source $\langle Q_1 \rangle$ and moisture sink $\langle Q_2 \rangle$ are calculated using the formula by Yanai et al[15].

3 FACTS OF LATE ONSET AND SOUTHWARD PERSISTENCE OF SCSSM

Until the 5th pentad in May, South Asia High lies from northern SCS to Luzon of the Philippines while West Pacific Subtropical High (WPSH) controls SCS and SCSSM did not break out (Fig. 1a). During the 6th pentad, South Asia High jumps to northern Indochina, WPSH subsides eastward. At the same time an equatorial westerly associated with an increasing Somali Jet merges with the westerly from the middle latitudes and flows across Indochina to SCS. Meanwhile a cross-equatorial southerly transforms from southeast trade winds along 110°E and flows to SCS. SCS is therefore controlled by obvious southwest winds and SCSSM bursts out (Fig. 1b). However, during the long time from June 1 to 24, though equatorial westerly related to a strong Somali Jet is much stronger than the multi-year average, it does not flow northeastward to India and northern Indochina extensively as the multi-year average does, but spreads directly eastward to SCS. Therefore the strong SCSSM can just reach 25°N in China, much more southward than the multi-year average (30°N) (Fig. 1c & 1d).



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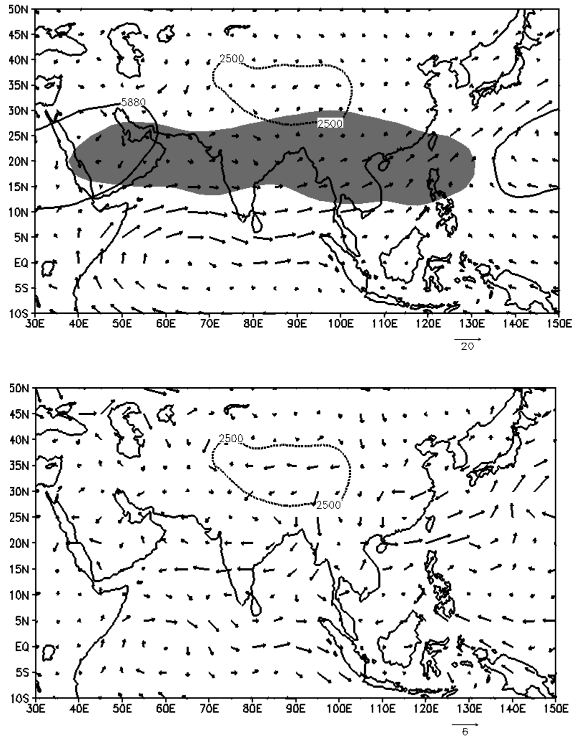


(c)

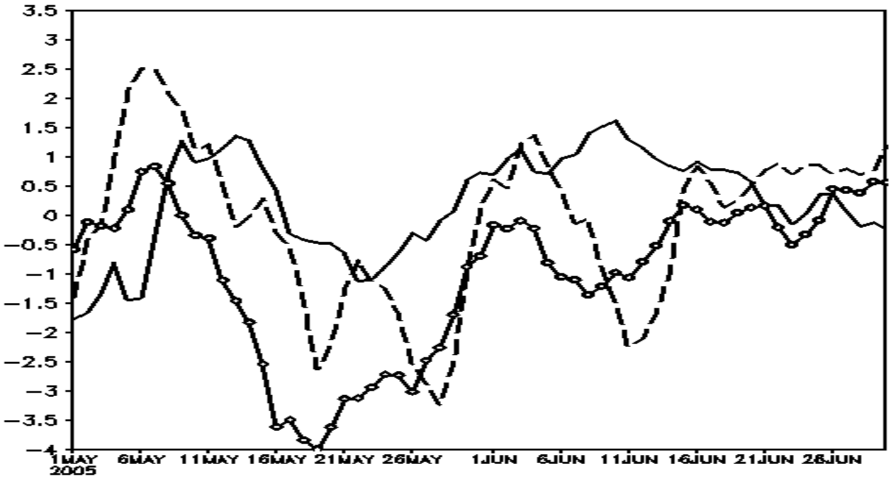
(d)

Fig.1 Mean 850 hPa winds during the 5th (a), the 6th (b) pentad in May, during the period of June 1–24 (c) and the anomalies (d) in 2005. (Shaded areas indicate geopotential heights of more than 12500 gpm at 200 hPa; solid lines indicate the contours of 5880 gpm at 500 hPa; dotted lines are the 2500 m terrain.)

4 REASONS FOR LATE ONSET AND ANOMALOUS SOUTHWARD PERSISTENCE OF SCSSM

4.1 *Features of atmospheric thermal structure*

Figure 2a gives the daily evolution of mean atmospheric temperature anomalies over Indochina (12.5°N－22.5°N, 95°E－107.5°E), Tibetan Plateau (27.5°N － 37.5°N, 75°E － 100°E) and Indian Peninsula (15°N－30°N, 72.5°E－85°E) at the middle and upper levels of the troposphere (500－300 hPa) from May to June. The temperature of Indochina is about 1°C lower than the multi-year average from May 16 to 24 and approaches the latter at the end of May. The Tibetan Plateau is also significantly cooler during the long period from May 10 to June 15, especially from the 4th to the 5th pentad of May, with high negative temperature anomalies of more than 3°C. Fig. 2b shows that the north-south temperature difference at the middle and upper levels (mean temperature of 17.5°N－27.5°N minus that of 2.5°S－2.5°N, 500－300 hPa) from the Tibetan Plateau, Indochina to SCS turns positive until May 24, almost 15 days later than the multi-year average (figure omitted). It is just the slow warming process that inhibits the onset of SCSSM.



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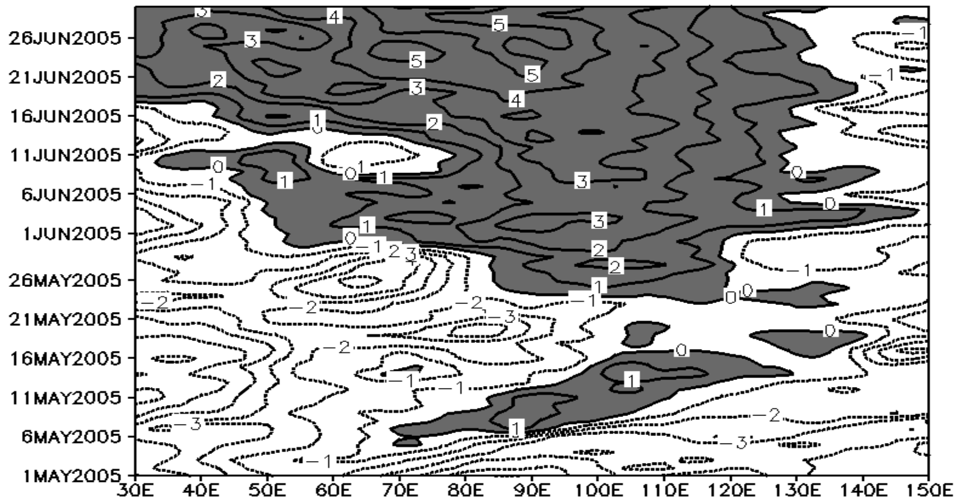


(b)

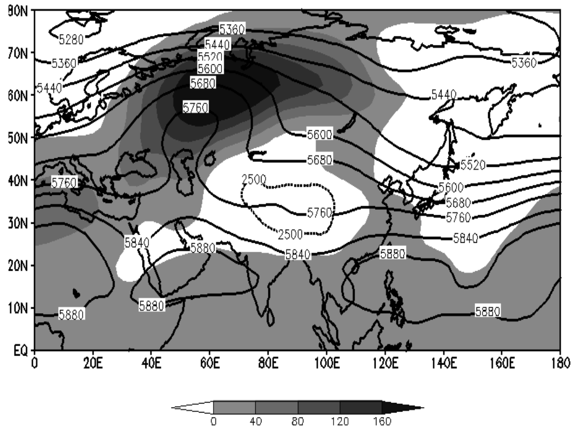
Fig.2 Daily evolution of mean temperature anomalies over Indochina (solid line), Tibetan Plateau (solid line with circles) and Indian Peninsula (dotted line) (a); North-south temperature difference (b) at the middle and upper levels of troposphere from May to June, 2005. (Unit: °C)

In the Indian Peninsula, the mean temperature from June 6 to 16 is about 2°C lower than the multi-year average. Along the longitudes of this area, positive north-south temperature differences appear at the end of May, similar to the multi-year average. But this situation is interrupted from June 9 to 14 by negative differences. Continuous strong positive north-south temperature differences don't occur until June 18. Such anomalous features of atmospheric warming are certainly not conducive to the normal northward advancement of Southwest Monsoon. What factors have delayed the atmospheric warming process in southern Asia? We'll reveal them by analyzing the atmospheric circulation, water vapor transmission and thermal mechanisms.

4.2 *Characteristics of middle and high latitude circulation*

Studies by Sikka [16] show that when a blocking high prevails in Europe during the transition season, the westerly splits into two branches and the southern one flows through the south of the Himalayas, causing cold air to penetrate the northern and central India, thus being not conducive to the outbreak of the Indian monsoon. Figure 3a shows that there exists a blocking high at 500 hPa in western Asia from May 11 to 25, while the Arabian High is also abnormally strong. The two highs overlap with the same phase and a strong ridge is formed north through south, continuously guiding high-latitude cold air down to the Tibetan Plateau and southern Asia by westerly transmission. The cold air restrains atmospheric warming there and delays the onset of SCSSM.

During the 6th pentad of May (Fig. 3b), the blocking high collapses and the Arabian High recedes westward to the Arabian Peninsula. Meanwhile the geopotential heights over the eastern Tibetan Plateau and northern Indochina increase and the atmosphere there becomes warmer rapidly, resulting in the burst-out of SCSSM. Nevertheless there is still strong cold air affecting the northern India and the western Tibetan Plateau where the height anomalies are still negative while the strong Arabian High still overlaps with a ridge over the Caspian Sea. From June 1 to 24, the distribution of geopotential heights and anomalies at 500 hPa (Fig. 3c) remains favorable for cold air to migrate to the western Tibetan Plateau and northern India, which inhibits further northward advancement of Southwest Monsoon.



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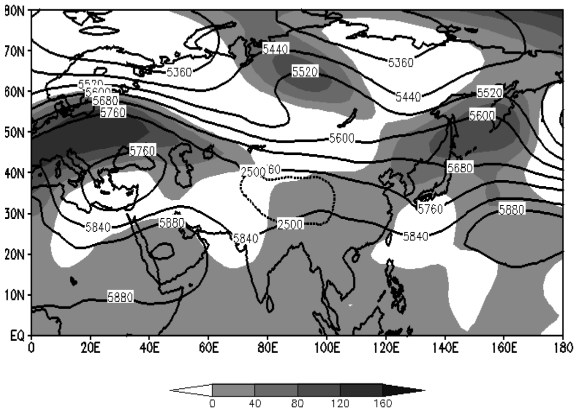

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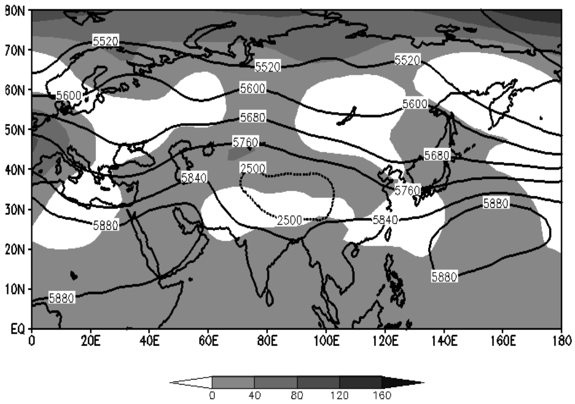
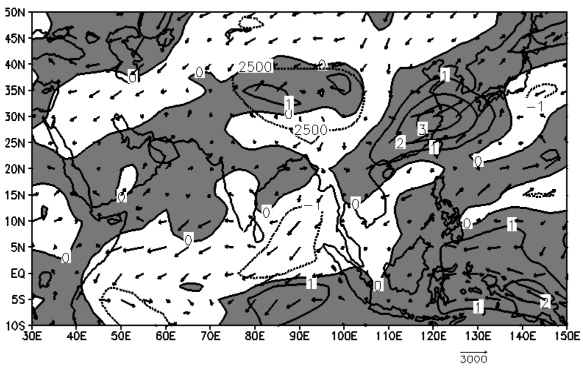


(c)

Fig.3 Geopotential heights at 500 hPa during the period from May 11 to 25 (a), the 6th pentad in May (b) and the period from June 1 to 24 (c) in the unit of gpm. The shaded areas indicate positive anomalies.

4.3 *Water vapor transmission*

Figure 4a – 4c shows the anomalies of water vapor fluxes integrated vertically from 1000 hPa to 300 hPa during the 5th and 6th pentad of May and during the period from June 1 to 24, 2005**.** With winds mainly coming from mid-latitudes (Fig. 1a), water vapor fluxes over most areas in South Asia, Southeast Asia and northern Indian Ocean are substantially weaker than the multi-year average during the 5th pentad of May. During the 6th pentad, water vapor fluxes over northern equatorial Indian Ocean, Southeast Asia and SCS increase in some way with some contribution from the Somali Jet (Fig. 1b), but are still weaker than the multi-year average except in northern SCS. During the period from June 1 to 24, due to tremendous surges of Somali Jet (Fig. 1c) there is a strong southwest-northeast transporting band of water vapor from the equatorial Indian Ocean to SCS, but it is apparently more southward as compared to that of the multi-year average (figure omitted). The water vapor transportation is still weaker over northern India, the southern Tibetan Plateau and northern Indochina.



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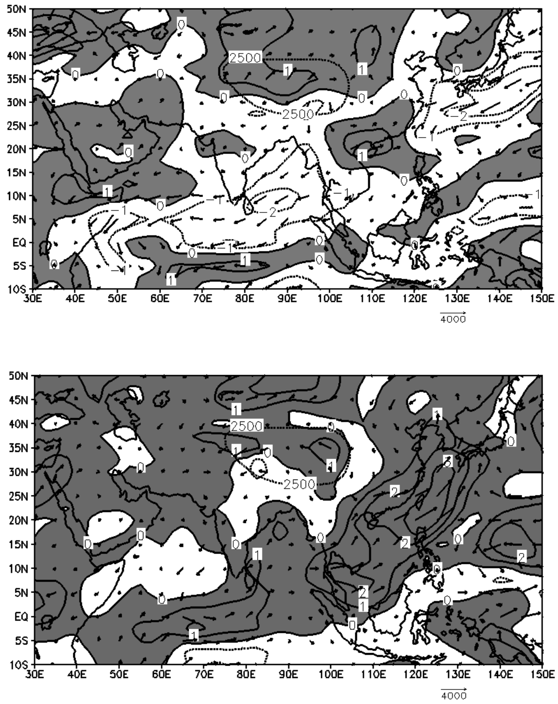


(b)

(c)

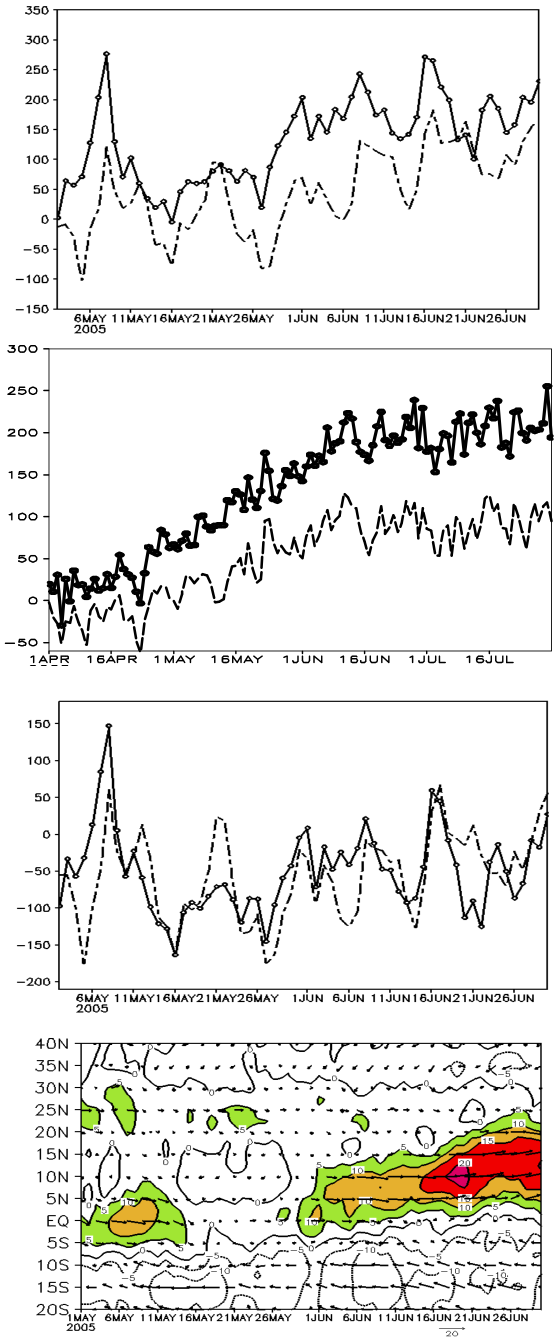
Fig.4 Anomalies of vertically integrated water vapor fluxes during the 5th (a), the 6th (b) pentad in May, and that during the period of June 1 – 24 (c) in 2005. (Unit: 10^3g•cm^{-1}•s^{-1})

4.4 *The heat source*

4.4.1 Indochina heat source anomalies and late onset of SCSSM

Figure 5a-5c gives the daily evolution of heat source <Q_1> and moisture sink <Q_2> over Indochina from May to June in 2005, the multi-year average, and the anomalies in 2005. In 2005, there are two increasing processes for <Q_1>, the second one being at the end of May and coinciding with the onset of SCSSM very well. During the period from the middle to the end of May, the heat source over Indochina is significantly lower than the multi-year average. It is exactly the weak heat source that affects the atmospheric warming and results in the reverse of north-south temperature difference.

For the multi-year average, since the beginning of May, the heat source <Q_1> evolves with almost the same steps with but is much stronger than the moisture sink <Q_2>, indicating that sensible heating plays a key role in the heat source while condensation latent heating cannot be neglected. In 2005, both of the two enhancing processes of the heat source from May to the beginning of June were accompanied with the increase of the moisture sink and were related closely to the strengthening of Somali Jet (Fig. 5d). From the middle to the end of May, Somali Jet disappeared and there was even a weak easterly over the equatorial Indian Ocean instead of a significant westerly as in the multi-year average (figure omitted); the mid-latitude westerly controlled almost all Indochina, which was unfavorable for convection as a result of the absence of southwest water vapor transport, leading to prevalent negative moisture sinks. Apart from weak condensation latent heat, strong air forces mentioned previously also cooled down the surface and restricted the growth of sensible heat. Due to these two factors, the heat source was obviously weaker than the multi-year averages, which slowed down atmospheric warming and the onset of SCSSM.



(a)

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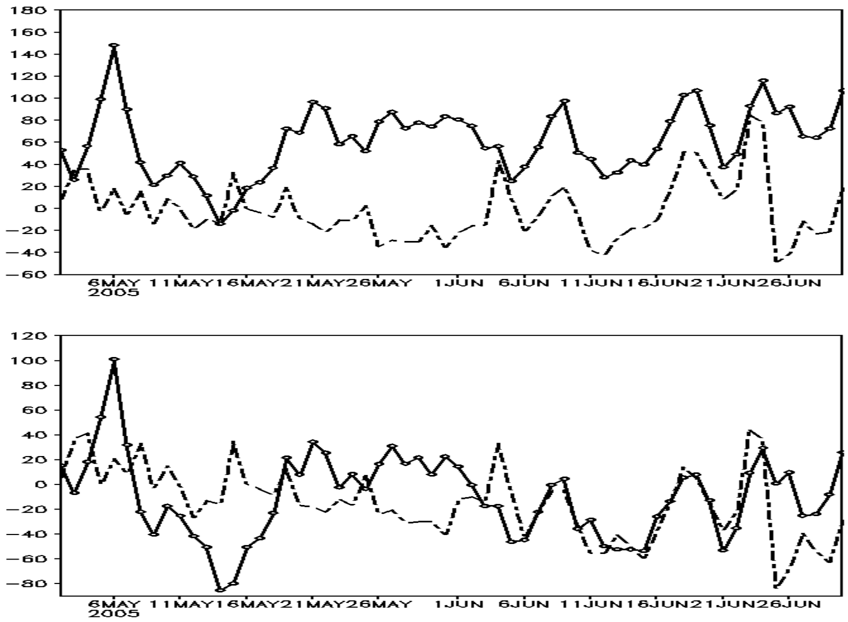
Fig.5 Daily evolution of <Q_1> and <Q_2> over Indochina from May to June in 2005 (a, the solid line with circles indicates <Q_1>, the dotted line indicates <Q_2>; unit: W.m^{-2}; same below), that of the multi-year average (b) and the anomalies in 2005 (c), and mean u winds along 50°E – 70°E at 850 hPa in 2005 (d).

4.4.2 TIBETAN PLATEAU HEAT SOURCES ANOMALIES AND MONSOON

Studies by Ding [17] show that an anomalously weak heat source over the Tibetan Plateau causes weak inflows to it and is an important cause for later onset and weaker northward advancement of the summer monsoon in 1999. The daily evolution of the heat source, moisture sink and their anomalies over the Tibetan Plateau (Fig. 6) shows that the heat source decreases abruptly to be much weaker than usual from May 7 to 19, being undoubtedly unbeneficial for the onset of SCSSM. Around May 20, the heat source $<Q_1>$ increased abruptly to approach the multi-year average and kept a similar value until the end of May while the moisture sink $<Q_2>$ decreased to be significantly negative at the same time. This means that the growth of the heat source is owing to sensible heating. The increasing process of the heat source is fairly consistent to the reverse of north-south temperature difference and the onset of SCSSM. Since then, in most of the time from the beginning of June to June 16, the heat source over the Tibetan Plateau is weaker than the multi-year average. In the multi-year average, the moisture sink over the Tibetan Plateau becomes positive around June 8 and has strengthened gradually since then, showing more and more prominent contribution from latent heat (figure omitted). Nevertheless in 2005, a negative moisture sink lasted until June 18. Therefore the weaker heat source over the Tibetan Plateau from the beginning of June to June 16 is closely related to anomalous weaker convection.



(a)

(b)

Fig.6 Daily evolution of $<Q_1>$ and $<Q_2>$ over the Tibetan Plateau from May to June, 2005 (a) and the anomalies (b).

Fig.7a shows that from June 1 to 18 the heat source over the Tibetan Plateau, South Asia, the Bay of Bengal and Indochina is weaker than the multi-year average, and so is the moisture sink (figure omitted). Northeastward winds anomalies are prevalent in these areas at 850 hPa. The weakness of the heat source is relevant either to strong cold air forces or to weak convection caused by weaker southwesterly water vapor transmission. Conversely the weak heat source is unbeneficial for further northward advancement of Southwest Monsoon. From June 19 to 23, the cold air over South Asia subsided, Somali Jet marched northward rapidly, Southwest Monsoon burst out from south to north along the western coast of India, and a huge heat source was formed by condensation latent heat (Fig. 7b). Since June 24, as Indian Monsoon broke out on a full scale, the India-Burma monsoon trough moved northward, the heat source from the southern Tibetan Plateau to the Bay of Bengal increased remarkably. As a result, the powerful Southwest Monsoon surged to the southeastern Tibetan Plateau and northern Indochina and advanced northeastward to China, ending the southward stagnation of SCSSM (Fig. 7c).

5 INFLUENCE OF SNOW COVER ON MONSOON

In 2005, the snow coverage over the Tibetan Plateau was apparently larger than usual from January to April and declined rapidly to be much smaller than usual in May (figure omitted). In comparing this variation process with that of the heat source and moisture sink over the Tibetan Plateau, it can be deduced clearly that the melting of snow suppresses surface warming from May 7 to 19 and leads to less sensible heating and a weak heat source. During the following days of May the snow cover melted and got smaller than usual while the heat source increased immediately by sensible heating. As a result, South Asia High leapt to northern Indochina while SCSSM broke out. Since the beginning of June, the snow cover does not have any direct effects. However, the negative feedback, which is caused by its earlier effect on the late onset of summer monsoon, once again inhibits the northward movement of Southwest Monsoon.

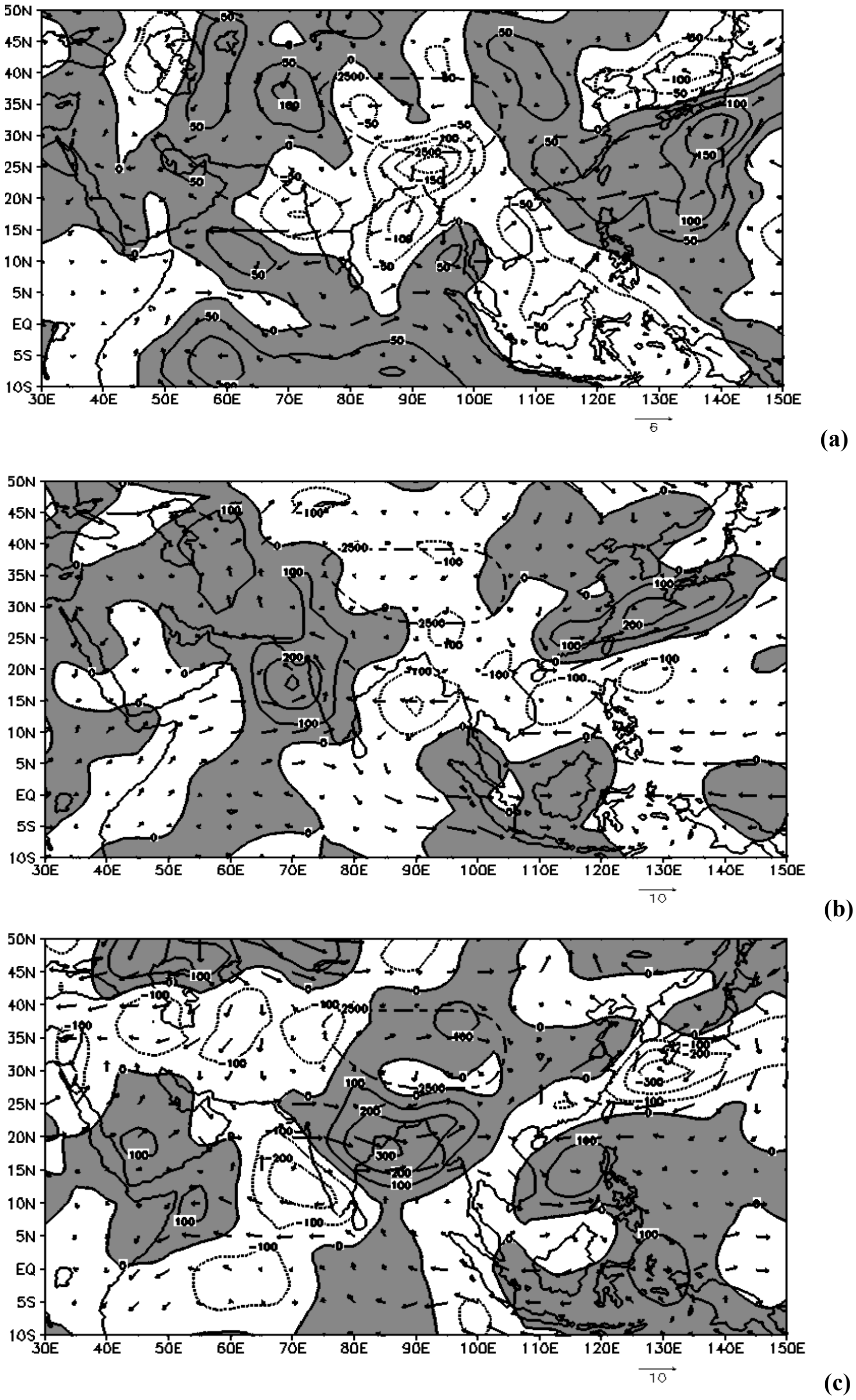


Fig.7 Mean anomalies of the heat source <Q_1> and 850-hPa winds over Asia during the period of June 1 – 18 (a), June 19 – 23 (b), the difference of the heat source <Q_1> and winds at 850 hPa between the period of June 24 – 28 and that of June 19 – 23 (c), 2005.

6 CONCLUSION

(1) From the late spring to the early summer in 2005, the reverse of north-south temperature gradients at the middle and upper levels along the latitudes of Indochina and nearby areas occurred about 15 days

later than usual, resulting in the late onset of SCSSM. Then Southwest Monsoon advanced northward slowly in South Asia where there was no continuous atmospheric heating.

(2) A strong ridge, formed by the in-phase overlapping of a strong Arabian High with a strong blocking high, ran through the middle and high latitudes in western Asia and caused strong cold air to travel to southern Asia, which suppressed atmospheric warming there and restricted the onset of SCSSM and northward advancement of Southwest Monsoon.

(3) As Somali Jet and the equatorial westerly burst out at the end of May, substantially later than the multi-year average, the heat source was quite weak over Indochina due to the lack of southwest water vapor transport and convection, being not conducive to atmosphere warming and the onset of SCSSM.

(4) Tibetan Plateau had a bigger snow cover than usual in the spring. The melting process cooled down the surface and restrained the evolution of the heat source, which was another important factor for the late onset of SCSSM.

(5) Before mid-June, stronger cold air inhibited atmosphere heating over India and therefore Southwest Monsoon advanced slowly and the monsoon trough stayed southward, leading to less water vapor transport, convection and a weaker heat source over the Tibetan Plateau and nearby areas. The negative feedback suppressed further northward advancement of Southwest Monsoon and guided it to spread southward, being a significant factor for the long southward persistence of SCSSM.

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