Mechanism of Thermal Features over the Indo–China Peninsula and Possible Effects on the Onset of the South China Sea Monsoon

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ABSTRACT

The thermal characteristics during the South China Sea (SCS) summer monsoon onset period near the Indo–China Peninsula are analyzed by using the South China Sea Monsoon Experiment (SCSMEX) reanalysis data from 1 May to 31 August 1998 and the NCEP / NCAR pentad–mean reanalysis data from January 1980 to December 1995. The possible relationships between the anomaly of thermal features near the Indo–China Peninsula and the SCS monsoon onset are investigated, and the mechanism causing the SCS summer monsoon onset is also discussed. Results from the 1998 SCSMEX reanalysis data show that there exists a strong persistent surface sensible heating near the Indo–China Peninsula prior to the SCS monsoon onset, which has apparent low frequency oscillation features. This sensible heating leads to a warmer center in the lower atmosphere near the Indo–China Peninsula and strong local horizontal temperature and geopotential height gradients which are favorable to strengthening the southwest wind over the Indo–China Peninsula. It is also found that stronger convergent winds at lower levels and stronger divergent winds at high levels appear, which provide a favorable configuration for the development of vertical motion, enhancement of precipitation, and onset of the SCS monsoon. These results can be verified by analysis of the multi–year mean data. Additionally, it is found that the temperature at 850 hPa increases more rapidly over the Indo–China Peninsula than the South China Sea prior to the SCS monsoon onset, which leads to a strengthening of the temperature difference between the Indo–China Peninsula and the South China Sea. Moreover, results from the analysis of the longitudinal temperature and geopotential height differences show that the eastern retreat of the subtropical high over the Indo–China Peninsula during the period of SCS monsoon onset is associated with the temperature increase over the Indo–China Peninsula and the eastern extension of low trough over the Bay of Bengal.

Key words: Indo–China Peninsula, thermal feature, mechanism of SCS monsoon onset

1. Introduction

The onset of the South China Sea (SCS) summer monsoon marks the coming of the East Asia summer monsoon and the start of the rainy season in eastern China. The anomalies of the SCS monsoon activities have important impacts on the summer general circulation, weather, and climate, as well as influencing the movement of the rainbelt and the occurrence of flood and drought over eastern Asia (Gao and Xu 1962). Therefore, studies on the mechanism and features of SCS summer monsoon onset are very important for accurate prediction of summer precipitation over eastern Asia.

Many studies have shown that the Asian summer monsoon starts earliest in the northern South China Sea, then extends northward to mainland China and Japan as well as the western

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Pacific, and northwestward to the Bay of Bengal and India. Thus the SCS monsoon region is taken as the origin of the East Asian monsoon (Tao and Chen 1987). However, the mechanisms and reasons for SCS summer monsoon onset reported by different researchers are inconsistent with one another due to different data used, and years and areas chosen. From the analysis of the beginning of the rainy season in Asia, it is found that the rainy season starts earliest near the Indo–China Peninsula, though there is a slight regional difference (Lau and Yang 1997; Matsumoto 1997; Webster et al. 1998). Xie and Zhang (1994) found that the summer monsoon breaks out in the Indo–China Peninsula first, then moves northwestward; the summer monsoon onset occurs later over the South China Sea compared to the Indo–China Peninsula region. Observational studies have shown that the Asian summer monsoon breaks out first over the eastern coast of the Bay of Bengal, providing favorable background conditions for the subsequent SCS monsoon onset (Wu and Zhang 1998). He et al. have also found that the early precursors for the Asian summer monsoon establishment appear near the Indo–China Peninsula and the South China Sea; the monsoon then extends westward and eastward (He and Luo 1996; He et al. 2000).

Wang and Qian (2000) studied the effects of local land–sea thermal difference on SCS monsoon onset. They found from the analysis of regional heating field features during the period of SCS monsoon onset that the thermal difference between the Indo–China Peninsula and the South China Sea is an additional thermal heating in the background of large–scale land–sea thermal difference which can trigger SCS monsoon onset. On the other hand, the intraseasonal low frequency oscillation over the South China Sea can also trigger SCS monsoon onset (Mu and Li 2000; Li and Wu 2000; Jiang and Qian 2000), and the thermal anomalies near the South China Sea may be the heat source that trigger wave trains (Li and Zhang 1999; Fukutomi and Yasunari 1999). Therefore, the earlier onset of the Asian monsoon near the South China Sea may be related to the special land–sea distribution and topography, warm and moist land surface conditions and the shielding effect of the Tibetan plateau in the north side, in which the local interaction of the land–sea–atmosphere system plays an important role, and the Indo–China Peninsula becomes the key area triggering SCS summer monsoon onset. However, the mechanism and importance of the role of the local land–sea–atmosphere interaction is not yet clear.

In this paper, we present the results of research on the thermal features near the Indo–China Peninsula during the period of SCS monsoon onset by use of the South China Sea monsoon experiment data (SCSMEX) in 1998 and the multi–year NCEP/NCAR reanalysis pentad–mean data from 1980–1995. The possible relationships between the thermal anomaly near the Indo–China Peninsula and SCS summer monsoon onset and the mechanism of SCS summer monsoon onset are studied. It is important to analyze the valuable high resolution data obtained from the South China Sea monsoon experiment in order to further understand the SCS summer monsoon onset mechanism. The data and methods used in this paper are presented in section 2. The features of the South China Sea monsoon onset in 1998 and in multi–year mean data are analyzed in sections 3 and 4. Summary and discussion are given in section 5.

2. Data and methodology of analysis

Two kinds of data are used in this paper. The first is the South China Sea monsoon experiment (SCSMEX) data provided by the National Climate Center, covering the period from 1 May to 31 August 1998 at 6–hour intervals. The data have 18 variables, including geopotential height, temperature, wind speed, specific humidity, and surface pressure, with $1^\circ \times 1^\circ$ horizontal resolution and 17 vertical levels, spanning from 70°E to 150°E, 10°S to 40°N. The other data set is the NCEP / NCAR reanalysis data of pentad–mean geopotential height and temperature with $2.5^\circ \times 2.5^\circ$ horizontal resolution and 17 vertical levels, from January 1980 to December 1995.

We only focus on the variational characteristics of the meteorological variables during the onset period of the SCS monsoon because the main objective of this paper is to unveil the possible relationship between the thermal condition anomaly near the Indo–China Peninsula and the SCS summer monsoon onset, and to find the key or sensitive areas triggering the SCS summer monsoon onset. Generally speaking, there are discrepancies in determining the date of SCS monsoon onset due to the choice of meteorological variable index as the criterion. Recently, He et al. (2001) have conducted a detailed investigation on SCS monsoon onset dates and have provided more accurate dates than those in the past few decades. We adopt these dates in this paper while analyzing the multi–year mean data from 1980 to 1995. Yet, concerning the interannual variations in the SCS monsoon onset dates, we perform a composite analysis covering the two pentads before and after the SCS monsoon onset in order to emphasize the differences in the meteorological variables during the onset period. In the analysis of the 1998 SCSMEX data, we take the period from 16 to 20 May as the time of pre–monsoon onset, 25–29 May as the time after monsoon onset, and we only focus on the differences in meteorological variables of these two pentads.

3. The features of SCS monsoon onset in 1998

3.1 *Surface sensible heat flux*

In order to understand the thermal effects of the Indo–China Peninsula on the SCS monsoon onset in 1998, the temporal variations of surface sensible heat flux near the Indo–China Peninsula are analyzed first. Figure 1 gives (a) the time–longitude evolutions of the sensible heat flux averaged along 10°–25°N and (b) the time–latitude evolutions averaged along 95°–110°E. These show that surface sensible heat fluxes more than 60 W m^{-2} appear from the middle of February near the Indo–China Peninsula along 95°–110°E, and persist to the beginning of May, with a maximum moving northwestward from March to April, then diminishing and shrinking to the northeast of the Indo–China Peninsula and decreasing rapidly in the last ten days of May. The date on which the sensible heat flux diminishes in the Indo–China Peninsula corresponds to the SCS monsoon onset, which agrees well with the conclusion from the analysis of multi–year 10–day mean sensible heat flux by Zhang and Qian (1999a). It is also shown in Fig. 1b that persistent strong surface sensible heating exists in the Indo–China Peninsula along 12°–25°N before the beginning of May with maximum sensible heating from March to April, after which the strength of sensible heating decreases slightly but maintains a strength of 60 W m^{-2}. The surface sensible heat flux reduces rapidly in the last ten days of May. This may be related to the SCS monsoon onset because the increase of cloudiness and precipitation over the Indo–China Peninsula results in the reduction of solar radiation reaching the surface and a decrease of surface temperature which are known to accompany the SCS summer monsoon onset. Figure 2 gives (a) the time–longitude evolutions of the latent heat flux averaged along 10°–25°N and (b) the time–latitude evolutions averaged along 95°–110°E. These show that the surface latent heat fluxes are less before the SCS monsoon onset and increase afterwards, which also agrees well with the conclusion from the analysis of multi–year 10–day mean latent heat flux of Zhang and Qian (1999b). Therefore,

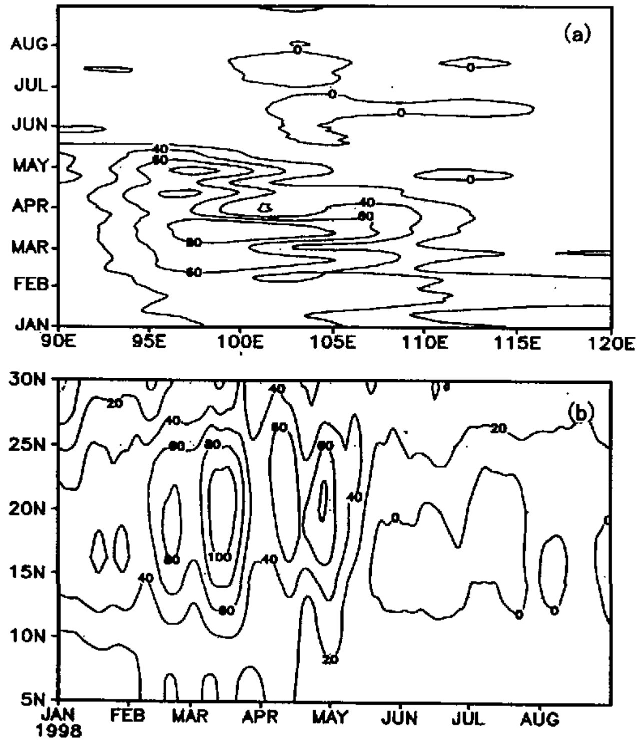

Fig. 1. (a) Time–longitude evolutions of the sensible heat flux averaged along 10°–25°N and (b) time–latitude evolutions averaged along 95°–110°E in 1998.

the surface sensible heating in the Indo–China Peninsula plays a triggering role in SCS monsoon onset, whereas the surface latent heating is an accompanying phenomena of the monsoon in its course of development.

There is also an obvious low frequency oscillation (LFO) feature in the sensible heat flux near the Indo–China Peninsula before the SCS monsoon onset, which intensifies after the middle of February and expands westward and northward and then disappears after the monsoon onset. On the other hand, the LFO feature in the heat flux over the oceans is apparent before the SCS monsoon onset, whereas there is a weak LFO in the latent heat flux near the Indo–China Peninsula at the same time, which enhances after the SCS monsoon onset. Thus the LFO in surface sensible heat flux in the Indo–China Peninsula plays a triggering role in SCS monsoon onset, whereas the LFO in surface latent heat flux influences the monsoon activity, intermittence, and maintenance. The LFO features in the surface sensible and latent heat flux cannot be found from the two analyses of Zhang and Qian (1999a, b).

3.2 *Temperature and geopotential height in the lower atmosphere*

Shao and Qian (2000) analyzed in detail the regional circulations during the period of SCS monsoon onset in 1998, but they did not study the relevant thermal features near the Indo–China Peninsula. In order to analyze the lower atmospheric features related to the

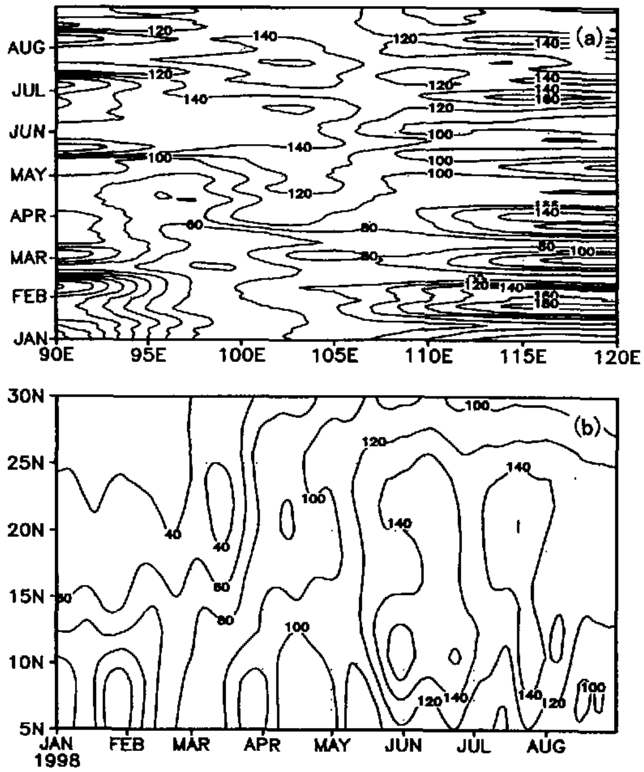

Fig. 2. (a) Time–longitude evolutions of the latent heat flux averaged along 10°–25°N and (b) time–latitude evolutions averaged along 95°–110°E in 1998.

surface sensible heat flux evolution, the temperature fields at 850 hPa before and after SCS monsoon onset are given in Fig. 3. It can be seen that there is a larger area with higher temperature at 850 hPa over the Indo–China Peninsula before the monsoon onset, in which the 22°C isotherm surrounds the entire Indo–China Peninsula with larger horizontal temperature gradients on the northeastern and eastern sides of the higher temperature area; after the monsoon onset, the higher temperature area at 850 hPa shrinks. These events suggest that the temperature increase of the lower atmosphere over the Indo–China Peninsula is related to the persistent sensible heating in this region, and the existence of a cold trough over southwestern China results in the enhancement of the horizontal temperature gradients on the northeastern and eastern sides of the higher temperature area.

Figure 4 presents the geopotential height fields at 850 hPa before and after the SCS monsoon onset. A ridge of the western Pacific subtropical high is over the Indo–China Peninsula prior to the monsoon onset, with a geopotential height gradient running from northwest to southeast. After the onset, the western Pacific subtropical high over the Indochina peninsula and the South China Sea retreats eastward with enhanced geopotential height gradients over the Indo–China Peninsula. We note that this result is consistent with other studies (He et al. 2000; Wang and Qian 2000; Li and Wu 2000), but the reason is unclear. In this study, we infer

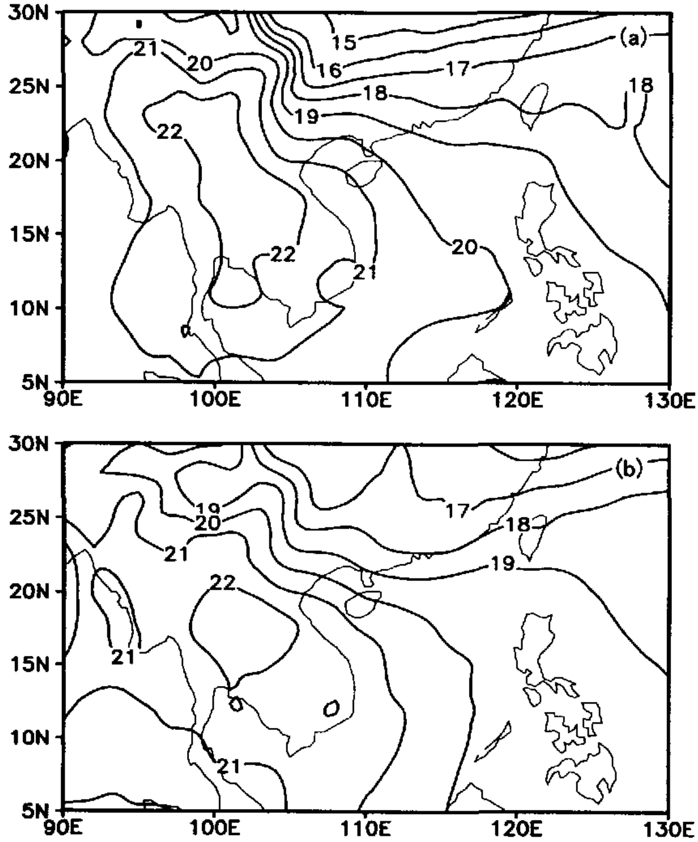

Fig. 3. Temperature fields at 850 hPa (a) before and (b) after SCS monsoon onset.

that the eastward retreat of the western Pacific subtropical high is probably associated with the surface sensible heating and temperature increase over the Indo–China Peninsula. Figures 3 and 4 also show that the area with larger horizontal temperature gradients corresponds to the area with stronger geopotential height gradients, which is favorable to the enhancement of the southwest winds and the triggering of the SCS monsoon onset as well as the maintenance of the southwest monsoon.

The u and v differences at 850 hPa after versus before the SCS monsoon onset are given in Fig. 5. It shows that the west winds strengthen after the SCS monsoon onset over the Indo–China Peninsula and the South China Sea, and the south winds are enhanced over southern Indo–China and weaken over the South China Sea due to the retreat of the western Pacific subtropical high.

3.3 *Divergent wind and velocity potential*

To analyze the convergence and divergence of the wind fields in upper and lower levels, Figs. 6 and 7 give the divergent wind and velocity potential as well as their differences after versus before SCS monsoon onset at 1000 hPa and 200 hPa. Figure 6 shows that strong

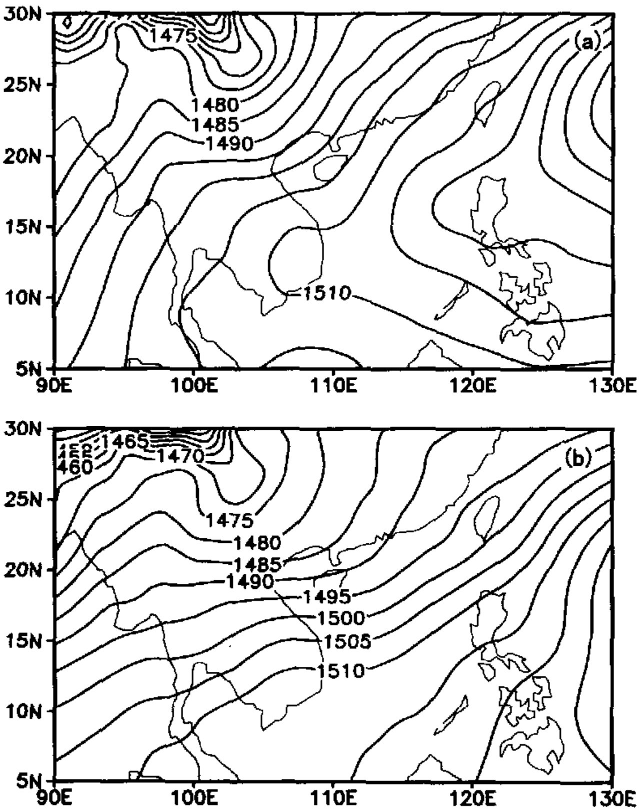

Fig. 4. Geopotential height fields at 850 hPa (a) before and (b) after SCS monsoon onset.

convergent winds at 1000 hPa and divergent winds at 200 hPa exist over the Indo–China Peninsula before the onset, which persist over the Indo–China Peninsula afterwards, but the strongest convergent and divergent centers appear over the Bay of Bengal. Figure 7 shows that small differences of the divergent winds at 1000 hPa exist over the Indo–China Peninsula, implying a weakening of convergence in this region after the SCS monsoon onset, whereas larger differences of the convergent winds at 200 hPa appear over the Indo–China Peninsula, suggesting a weakening of the divergence in this region after the monsoon onset. This pattern in the vertical direction also provides a favorable condition for the development of vertical motion, the intensification of precipitation, and for triggering the SCS monsoon onset.

4. The thermal features during the SCS monsoon onset period in multi–year mean data

In order to further understand the general features of the thermal differences near the Indo–China Peninsula before and after SCS monsoon onset, we perform a similar analysis on the NCEP / NCAR 16–year pentad–mean data from January 1980 to December 1995. Figure 8 presents the temperature field at 850 hPa before the SCS monsoon onset and the

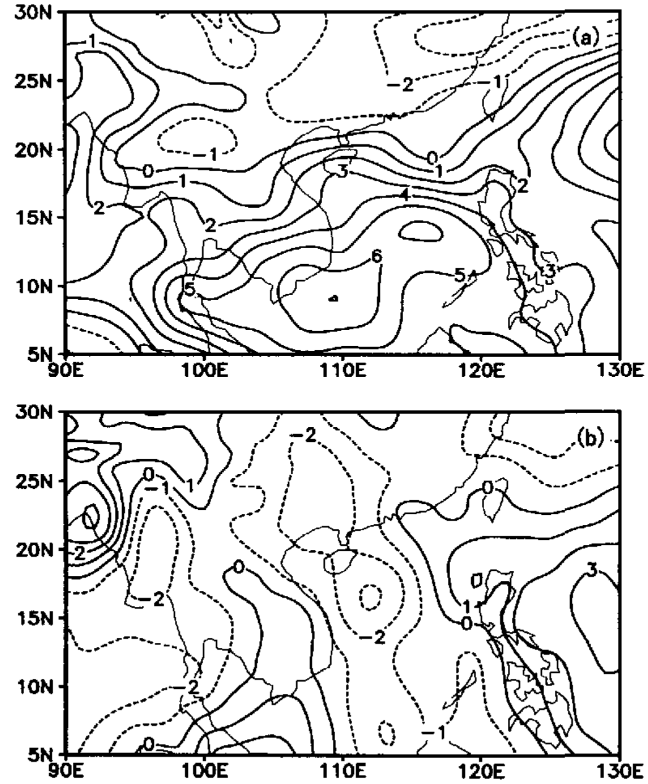

Fig. 5. Differences of (a) u and (b) v at 850 hPa after and before SCS monsoon onset.

temperature difference at 850 hPa after versus before SCS monsoon onset. It is found that there exists a warm ridge over the Indo–China Peninsula before SCS monsoon onset and a maximal temperature center of 18°C over the western Indo–China Peninsula, which weakens after the SCS monsoon onset with a temperature decrease of 0.9°C. These basic features in multi–year mean data are similar to those in 1998 and the difference between them is slight. Figure 9 gives the geopotential height fields at 850 hPa before and after SCS monsoon onset for the 16–year mean data. These show that a ridge of the western Pacific subtropical high occurs over the Indo–China Peninsula prior to SCS monsoon onset, with a geopotential height gradient running from northwest to southeast. After SCS monsoon onset, the western Pacific subtropical high over the Indo–China Peninsula and the South China Sea retreats eastward with decreased geopotential heights over the Indo–China Peninsula and the South China Sea, which is also similar to that in 1998.

To analyze the thermal features in the multi–year mean data over the Indo–China Peninsula and the South China Sea, we give the evolution of the regional mean temperature at 850 hPa over the Indo–China Peninsula (15°–25°N, 95°–105°E) and the South China Sea (10°N–20°N, 110°–120°E) and their difference in Fig. 10. The figure shows that the temperature at 850 hPa over the Indo–China Peninsula increases before the 24th pentad, with a larger range than that over the South China Sea, and changes in phase during 30th–57th pentad,

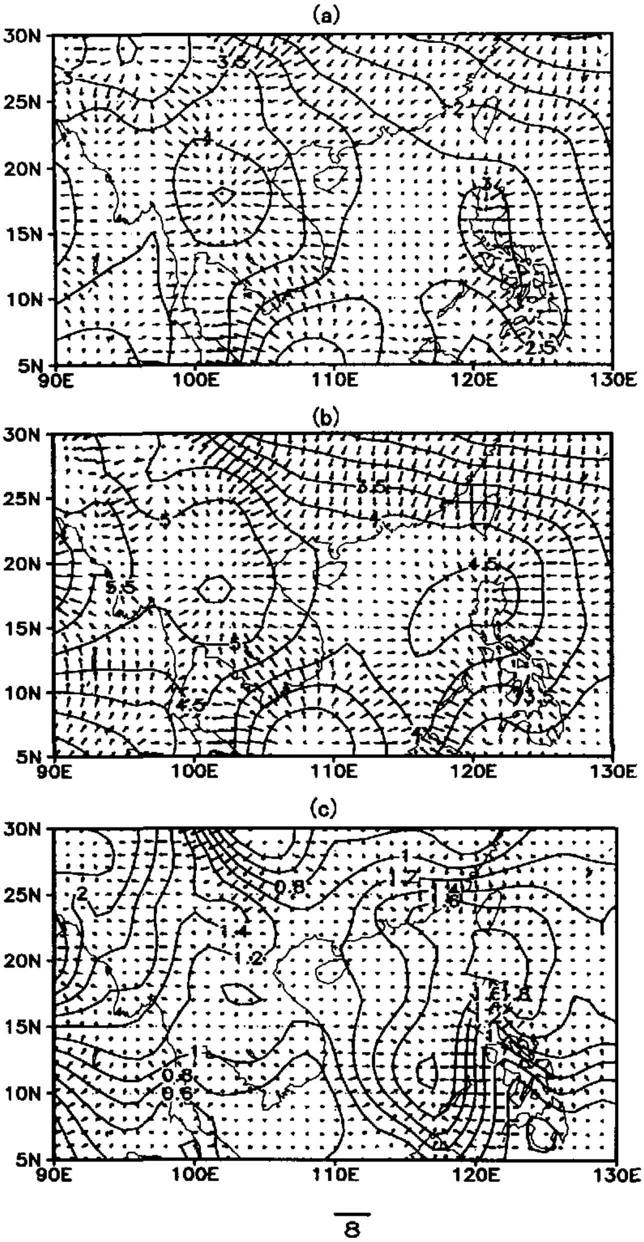

Fig. 6. Divergent wind and velocity potential at 1000 hPa (a) before and (b) after SCS monsoon onset and (c) their differences after versus before SCS monsoon onset.

then decreases with a larger range than that over the South China Sea. The evolution of the regional mean temperature difference between the Indo–China Peninsula and the South

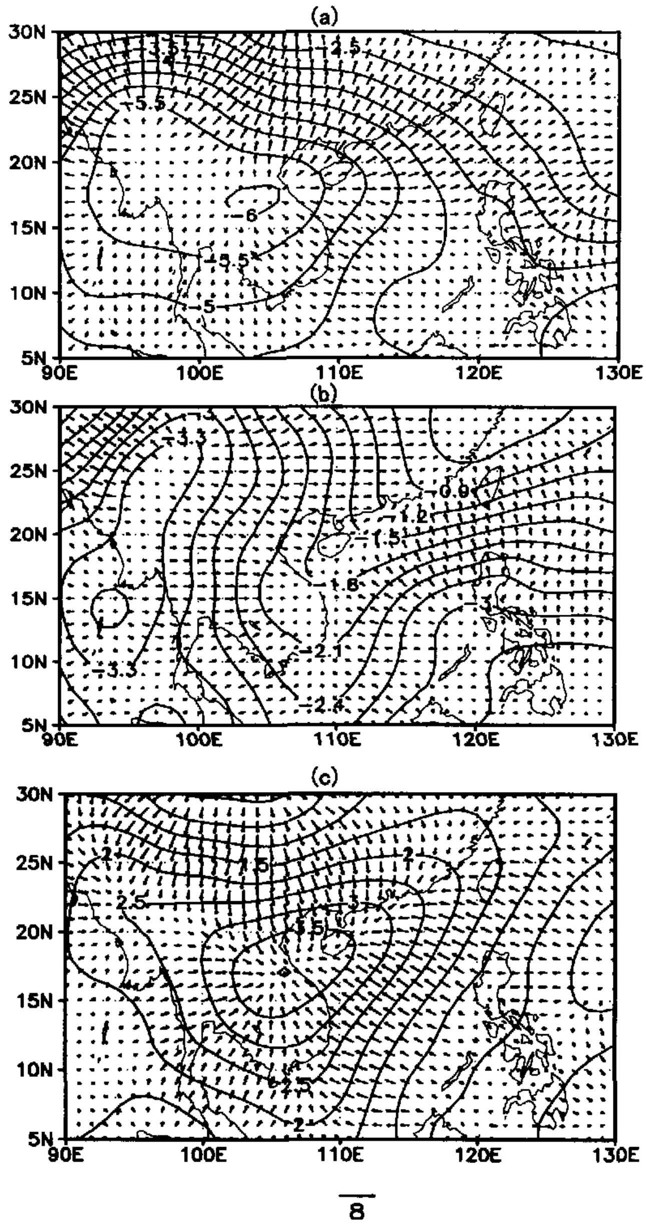

Fig. 7. Divergent wind and velocity potential at 200 hPa (a) before and (b) after SCS monsoon onset and (c) their differences after and before SCS monsoon onset.

China Sea shows that the temperature difference increases before SCS monsoon onset and decreases rapidly after the monsoon onset, implying that there exists an evident thermal

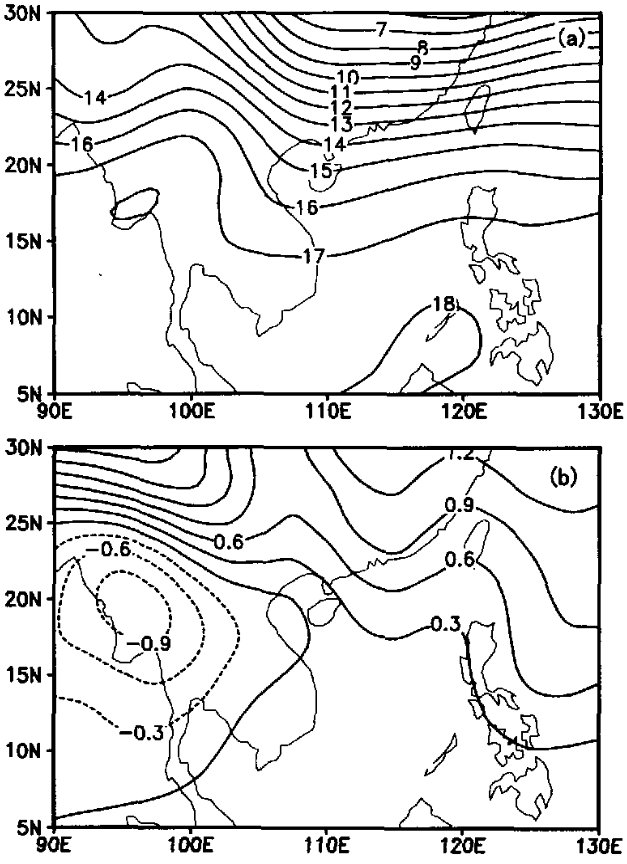

Fig. 8. (a) Temperature field at 850 hPa before SCS monsoon onset and (b) the temperature difference after versus before the SCS monsoon onset in 16–year mean data.

difference between the Indo–China Peninsula and the South China Sea before the SCS monsoon onset. This is an additional thermal effect overlapping the background of the large–scale land–sea thermal difference for triggering the onset (Wang and Qian 2000). Figure 11 gives the time–longitude evolution of the temperature and geopotential height deviations at 850 hPa relative to the average of 70°–130°E. The evolution of the longitudinal temperature deviation at 850 hPa indicate that the high temperature areas in the same latitude are located over the Indo–China Peninsula, India, and the Bay of Bengal before the 26th pentad, then the temperature deviations become negative over the Indo–China Peninsula, and the positive deviations persist and increase over India. Thus, the time of longitudinal deviation change corresponds to the climatic date of SCS monsoon onset. The evolution of the longitudinal geopotential height deviations at 850 hPa show that the low geopotential height areas in the same latitude are located over the Indo–China Peninsula and Bay of Bengal before the 26th pentad, then expand eastward, and the negative geopotential height deviations are situated over the western part of the Bay of Bengal and India and strengthen after 26th pentad.

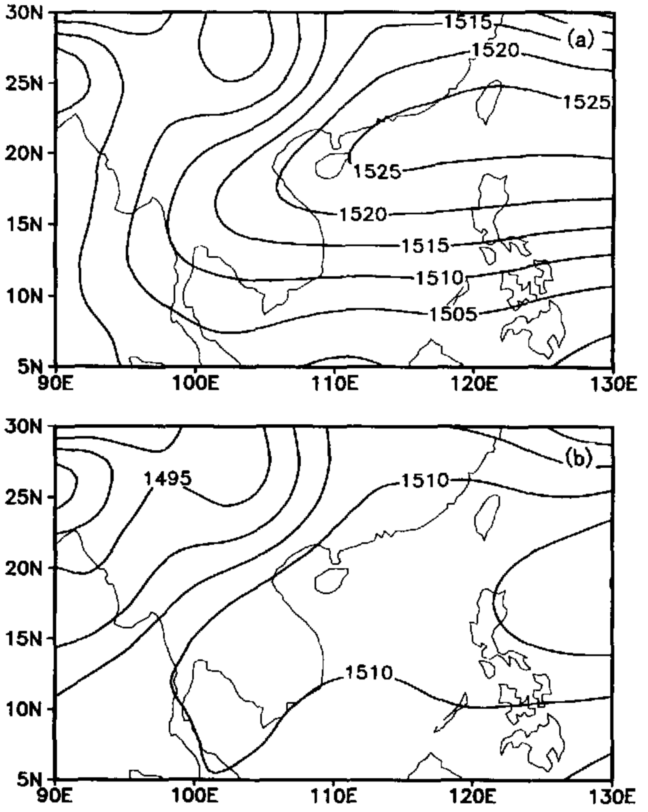

Fig. 9. Geopotential height fields at 850 hPa (a) before and (b) after SCS monsoon onset in 16-year mean data.

Combining the evolutions of temperature and geopotential height deviations, it is found that the trough over the Bay of Bengal extends eastward gradually before SCS monsoon onset, and moves over the Indo-China Peninsula when the SCS monsoon begins. Therefore, the retreat of the western Pacific subtropical high during the period of SCS monsoon onset is associated with a temperature increase over the Indo-China Peninsula and the eastern expansion of the trough of the Bay of Bengal.

5. Summary and discussion

In this paper, regional thermal features during the period of SCS monsoon onset and possible relationships between the anomaly of thermal features near the Indo-China Peninsula and the SCS monsoon onset are investigated, based on two datasets, viz. the SCSMEX data in 1998 and the NCEP/NCAR multi-year pentad mean data. Results from the 1998 SCSMEX reanalysis data show that there exists a strong persistent surface sensible heating near the Indo-China Peninsula prior to SCS monsoon onset, which has apparent low frequency oscillation features. This sensible heating leads to a warmer center in the lower atmosphere near the Indo-China Peninsula and strong local horizontal temperature and

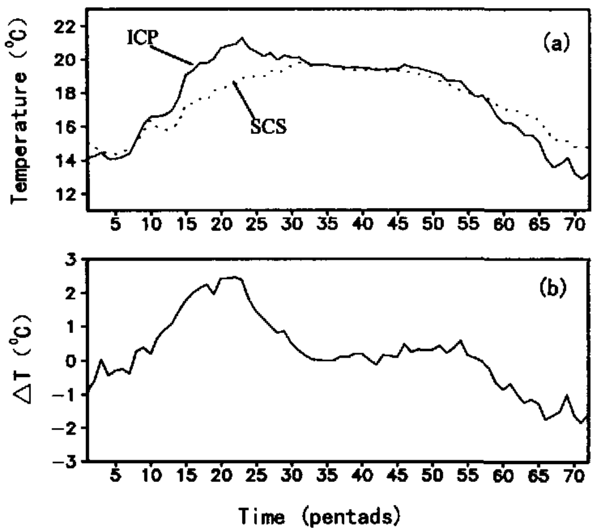

Fig. 10. (a) Evolution of regional mean temperature at 850 hPa over the Indo–China Peninsula (15°–25°N, 95°–105°E) and the South China Sea (10°–20°N, 110°–120°E) and (b) the difference bewteen them (ΔT).

geopotential height gradients which are favorable to strengthening the southwest wind over the Indo–China Peninsula. It is also found that stronger convergent winds at lower levels and stronger divergent winds at high levels appear, which provide a favorable configuration for the development of vertical motion, enhancement of precipitation, and onset of the SCS monsoon. These results are validated by the analysis of the multi–year mean data. Additionally, it is found that the temperature at 850 hPa increases more rapidly over the Indo–China Peninsula than the South China Sea prior to SCS monsoon onset, which leads to a strengthening of the temperature difference between the Indo–China Peninsula and the South China Sea. Moreover, results from the analysis of the longitudinal temperature and geopotential height deviations show that the eastern retreat of the subtropical high over the Indo–China Peninsula during the period of SCS monsoon onset is associated with the temperature increase over the Indo–China Peninsula and the eastern extension of the low trough of the Bay of Bengal.

Based on the above results, a possible mechanism for triggering the SCS monsoon onset is formulated. Due to the persistent sensible heating over the Indo–China Peninsula, the temperature at low levels near the ground increases and a strong horizontal temperature gradient appears over the northeastern side of the warm area, which leads to a strong horizontal geopotential height gradient and a favorable condition for strengthening the southwest wind over this area. At the same time, there exist strong convergent winds in the low levels and strong divergent winds in the high levels, which is favorable for the development of vertical motion, intensification of precipitation, and triggering the SCS monsoon onset. On the other hand, the persistent sensible heating over the Indo–China Peninsula results in breakup of the subtropical high and expansion of the trough of the Bay of Bengal before the SCS monsoon onset, which also provides a necessary circulation for the monsoon onset. In addition, the low frequency oscillation of the surface sensible and latent heat fluxes also has a triggering effect

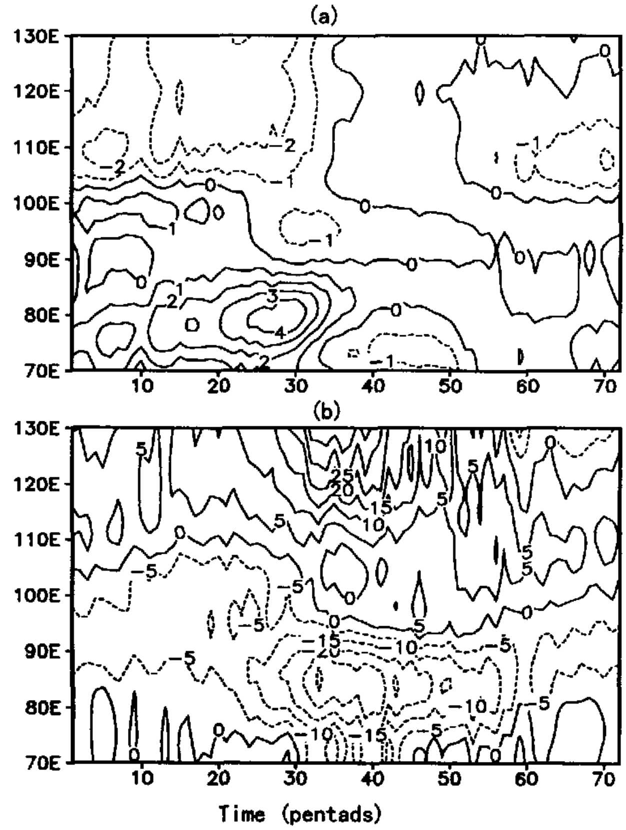

Fig. 11. (a) Time–longitude evolution of the temperature deviations (°C) and (b) geopotential height deviations gpm at 850 hPa relative to the average between 70°–130°E.

on the SCS monsoon onset.

Finally, it should be emphasized that we have only analyzed the regional thermal features during the period of SCS monsoon onset and possible relationships between the anomaly of thermal features near the Indo–China peninsula and the SCS monsoon onset, and focused on the triggering effects of the thermal features over the Indo–China Peninsula on the SCS monsoon onset. A complete understanding of these topics requires further study, especially numerical simulations. Moreover, the SCS summer monsoon onset is related to the interaction of the local land–ocean–atmosphere system. Clearly, the local interaction of the land–ocean–atmosphere system in the SCS monsoon region and its effect on the SCS summer monsoon onset needs further study in the future.

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中南半岛地区热力特征对南海季风爆发的可能影响及机理

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摘 要

利用 1998 年 5 月 1 日-8 月 31 日南海季风试验(SCSMEX)资料和 1980 年 1 月-1995 年 12 月 NCEP/NCAR 候平均再分析资料，分析 1998 年和多年平均情况下南海夏季风爆发期间中南半岛地区热力特征，揭示该地区热状况的异常与南海夏季风爆发之间的可能联系，从而讨论引起南海夏季风爆发的可能机制。结果发现，南海季风爆发前中南半岛附近地区存在较强的持续地面感热加热并具有显著的低频振荡特征，低层大气在中南半岛地区出现较强的暖中心，由此导致局地强的水平温度梯度和位势高度梯度，有利于加强该地区的西南风。南海季风爆发前中南半岛地区低层出现较强的辐合风，高层出现较强的辐散风，这种低层强的辐合，高层强的辐散配置有利于垂直运动的发展，降水的加强，进而触发南海季风的爆发。对多年平均资料的分析也证实了 1998 年南海季风爆发过程中所具有的特征，并进一步发现南海季风爆发前中南半岛地区 850 hPa 温度是逐渐增加的，且增温幅度大于南海地区上空，由此加强了中南半岛与南海之间的温差。另外，从纬圈温度偏差和位势高度偏差的分析中发现，南海季风爆发期间南海和中南半岛地区的副高东撤与中南半岛地区的增温和孟加拉湾低槽的向东扩展有关。

关键词：中南半岛，热力特征，南海季风爆发机制