Diagnostic Study of Apparent Heat Sources and Moisture Sinks in the South China Sea and Its Adjacent Areas during the Onset of 1998 SCS Monsoon①

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ABSTRACT

The apparent heat sources (⟨Q_1⟩) and moisture sinks (⟨Q_2⟩) are calculated based on the reanalyzed data of the South China Sea Monsoon Experiment (SCSMEX) from May 1 to August 31, 1998. It is found that the formation and distribution of the atmospheric heat sources are important for the monsoon onset. The earlier onset of the SCS monsoon is the result of enduring atmospheric heating in the Indo–China Peninsula and South China areas. The atmospheric heating firstly appears in the Indo–China Peninsula area and the sensible heat is the major one. The 30–50 day periodic oscillation of atmospheric heat sources between the SCS area and the western Pacific warm pool has a reverse phase distribution before the middle of July and the low frequency oscillation of heat sources in SCS area has an obvious longitudinal propagation. The 30–50 day low frequency oscillation has vital modificatory effects on the summer monsoon evolution during 1998.

Key words: Apparent heat sources, Apparent moisture sinks, The South China Sea monsoon, Diagnostic study

1. Introduction

It is well known that the South China Sea (SCS) monsoon is not only a major member of the East Asian monsoon, but also has an important function on the weather and climate in the South China Sea, the neighboring areas and the world. Many scholars at home and abroad have done various researches about it. Jiang et al. (1993a, 1993b) found that the tropospheric heating increases abruptly, and the heat sources and the moisture sinks become strong obviously in the southeastern Tibetan Plateau and the east plain of China when the South China Sea monsoon onsets. Additionally Jiang et al. (1995) found that the major 30–60 day oscillation propagation of the Summer monsoon in the western Pacific is westward. Yang et al. (1998) pointed out that the main heat source is located in the upper air of the Indo–China Peninsula after the onset of Southeast Asian monsoon and it is the major factor for the stability of the South Asia high. Luo and Yanai (1983, 1984) suggested that the onset of Asian monsoon is caused by the interaction between the vertical circulation induced by the thermal function in the upper air of the Tibetan Plateau and the northward monsoon circulation system. The emphases of most researches are on the thermal function of the Tibetan

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Plateau under the planetary scale circulation background. However, there are few researches about the distribution of regional heat sources and moisture sinks in the SCS and the neighboring Indo–China Peninsula, South China areas, and its possible effect on the onset of SCS monsoon. Most problems about the SCS monsoon cannot be further studied for lack of the observational data in the SCS region. The beginning of the South China Sea Monsoon Experiment (SCSMEX) from 1996 makes further researches about the SCS monsoon become possible, especially the SCSMEX regional experiment from April 15, 1998 to August 31, 1998 provides abundant data for the SCS monsoon research. The heat sources and moisture sinks are calculated using the above data. The possible effects on the SCS monsoon onset of the atmospheric heat source distributions in the SCS and its neighboring areas and the periodic oscillation characteristics of heat sources in the SCS region in active and break periods of the SCS monsoon are studied.

2. Data and method

The day–by–day reanalysis data of the SCSMEX from May 1 to August 31, 1998 are used in this paper. u, v, ω and T are at 12 levels (1000 hPa–100 hPa), while humidity q is only at 8 levels (1000 hPa–300 hPa). The heat sources Q_1 and moisture sinks Q_2 are calculated by using the above data. The time evolution of Q_1 and Q_2 in different latitudes and longitudes, the vertical time evolution and periodic oscillation of heat sources in different regions are analyzed. The vertical p–velocity ω of the surface boundary is obtained from the following equation:

$$\omega_s = \frac{u_s}{a\cos\varphi} \cdot \frac{\partial p_s}{\partial \lambda} + \frac{v_s}{a} \cdot \frac{\partial p_s}{\partial \varphi} + \frac{\partial p_s}{\partial t} , \tag{1}$$

where u_s and v_s are the zonal and meridional components of the surface horizontal wind, p_s is the surface pressure, a the mean earth radius, φ the latitude, λ the longitude.

According to the algorithm of Luo and Yanai (1983), the apparent heat source Q_1 and apparent moisture sinks Q_2 of the unit quality and unit vertical length of the atmosphere are calculated from

$$Q_1 = C_p\left[\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T + \omega\left(\frac{\partial T}{\partial P} - \kappa\frac{T}{p}\right)\right] , \tag{2}$$

$$Q_2 = -L\left(\frac{\partial q}{\partial t} + \vec{v} \cdot \nabla q + \omega\frac{\partial q}{\partial P}\right) , \tag{3}$$

where T is the temperature, q the mixing ratio of water vapor, $\vec{v}$ the horizontal wind, ω the vertical p–velocity, $\kappa = \frac{R}{C_p}$, R and C_p are the gas constant and the specific heat at constant pressure of dry air.

Multiplying (2) and (3) by the air density ρ, integrating them from the surface to 100 hPa or 300 hPa by using static relation, we get

$$\langle Q_1 \rangle \equiv \frac{1}{g}\int_{100\ \text{hPa}}^{p_s} Q_1 dp , \tag{4}$$

$$\langle Q_2 \rangle \equiv \frac{1}{g}\int_{300\ \text{hPa}}^{p_s} Q_2 dp . \tag{5}$$

Integrating Q_1 / C_p and Q_2 / C_p from surface to 100 hPa or 300 hPa and dividing by $p_s - 100$ or $p_s - 300$, the heating rate and drying rate are

$$\langle \hat{Q}_1 \rangle \equiv \frac{1}{P_s - 100} \int_{100\ \text{hPa}}^{p_s} Q_1 / C_p dp \ , \tag{6}$$

$$\langle \hat{Q}_2 \rangle \equiv \frac{1}{P_s - 300} \int_{300\ \text{hPa}}^{p_s} Q_2 / C_p dp \ . \tag{7}$$

3. Analyses of heat sources and moisture sinks in different time intervals

In order to analyze the distribution of heat sources and moisture sinks in different periods, the onset of the SCS monsoon is divided into 5 periods according to the characteristic of Meiyu in 1998: pre–onset of SCS monsoon (5.1–5.15), onset of SCS monsoon (5.16–5.25), prevailing period of SCS monsoon (5.26–6.10), Meiyu period (6.11–7.3) and the break period of Meiyu (7.4–7.15). The distributions of $\langle Q_1 \rangle$ (a–e) and $\langle Q_2 \rangle$ (f–j) in different periods are shown in Fig. 1. Seen from Fig. 1a, the heat source centers are located in the Indo–China Peninsula and the South China area, while heat sinks are located in the Bay of Bengal, the Arabian Sea and the desert area of the western Tibetan Plateau before the onset of SCS monsoon. This thermal distribution makes the SCS region and the adjacent areas become heat sources which are different from the thermal distribution of the Indian Peninsula and its neighboring areas, resulting in the SCS monsoon onset earliest. Seen from $\langle Q_2 \rangle$ in the pre–onset period (Fig. 1f), it has a positive attribution to the total heating from the Indian Peninsula to the southeastern China, but the values are less than $\langle Q_1 \rangle$, especially in the Indo–China Peninsula. Thereby the sensible heat has the major effect in this region. During the onset period of SCS monsoon (Fig. 1b), the heat source centers in the South China area gradually move into the SCS area, at the same time a heat sink is formed in the western Pacific. So there is a thermal contrast between the eastern plain of China and the western Pacific, which is maybe important for the occur of SCS monsoon. The heat sources of the Indo–China Peninsula move westward into the Bay of Bengal with the western extension of the rain belt, while heat sinks or small heat sources are located in the whole Indian Peninsula and the Arabian Sea. Murakami and Matsumoto (1994) found that the onsets of the East Asian monsoon and the South Asian monsoon are the response of atmosphere to the land–sea thermal contrast. But there is the similar zonal land–sea distribution in the Indian Peninsula and the Indo–China Peninsula, why does the monsoon onset in the SCS region first? Seen from the above analysis, the atmosphere is always heated in the Indo–China Peninsula, the SCS and its neighboring areas from higher latitudes to lower latitudes. It is this enduring thermal effect that triggers the first onset of SCS monsoon, whereas the atmosphere in the Indian Peninsula responses slowly to the land–sea thermal contrast. There are small value areas of heat sources and heat sinks in the Indian Peninsula until June 10. With the monsoon development (Fig. 1c), a heat source center is formed in the southeastern Tibetan Plateau, simultaneously the heat source in the northwestern Tibetan Plateau gradually becomes stronger. With the onset of Changjiang–Huaihe River Meiyu, westard moving of the Bay of Bengal rain belt and the southward extension of heat source in the northwestern Tibetan Plateau, the heat source in the south part of the Arabian Sea moves northward and eastward along the west coast of the Indian Peninsula, then they combine together, cover the whole Indian Peninsula and form a heat source in the east part of the Arabian Sea. The heat

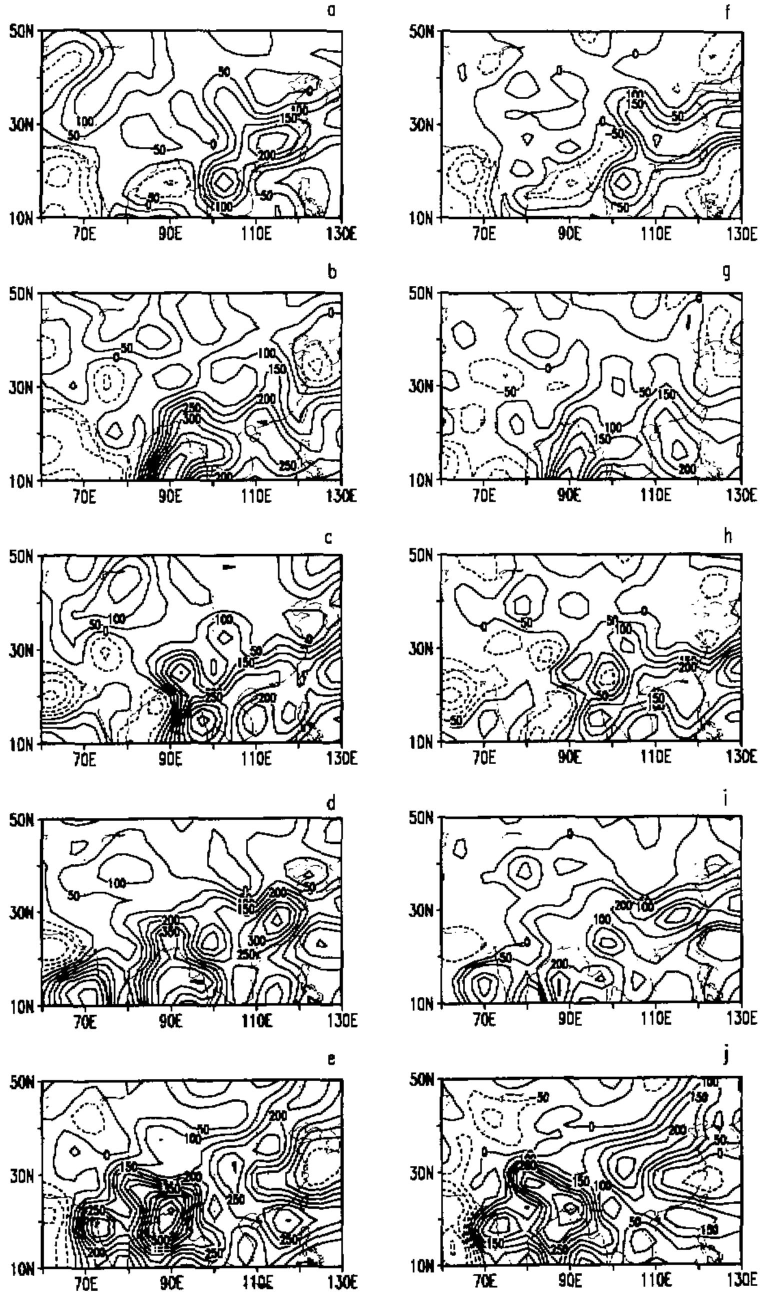

Fig. 1. Distributions of $\langle Q_1 \rangle$(a-e) and $\langle Q_2 \rangle$(f-j) in different periods of SCS monsoon, (a,f) pre-onset period (5.1-5.15), (b,g) onset period (5.16-5.25), (c,h) prevailing period (5.26-6.10), (d,i) Meiyu period (6.11-7.3), (e,j) break period of Meiyu (7.4-7.15), Unit: W/m^2.

source center of the southeast part of the Tibetan Plateau and the heat source area of the Bay of Bengal combine together and form a strong heat source, while a heat sink is located in the northern Arabian Sea. This distribution makes the zonal thermal contrast become stronger and triggers the onset of the Indian monsoon (Fig. 1d). During the prevailing period of the Indian monsoon (Fig. 1e), there are heat sources in the south part of the Indian Peninsula and the north part of the Bay of Bengal, especially the heat source center of the Bay of Bengal reaches 600 W/m^2 and there is less precipitation in the Changjiang River valley and South China because of the break of Meiyu, but there is still a heat source center in the northern SCS which reaches 300 W/m^2 and extends westward to the eastern Tibetan Plateau, because the water vapor is continuously transferred from the Bay of Bengal to South China and the SCS by the prevailing southwest wind. Seen from the above analysis, the formation and distribution of the atmospheric heat sources have a key function for the onset and maintenance of the SCS monsoon. The enduring atmospheric heating in the SCS region and the adjacent areas maybe can trigger the earliest onset of the SCS monsoon. From the analysis of moisture sink, it is found that the ratio of latent heat $\langle Q_2 \rangle$ in the whole heat $\langle Q_1 \rangle$ increases gradually with the onset of monsoon. The distribution of $\langle Q_2 \rangle$ is consistent with the distribution of precipitation in the Indo–China Peninsula and east of it, while in the Indian Peninsula and the Arabian Sea, $\langle Q_2 \rangle$ has a small value, even negative value before the onset of Indian monsoon, which indicates that the function of atmospheric evaporation is great in these areas.

In order to analyze where is the first formation of the atmospheric heat source, the evolutions of $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ at different latitudes and longitudes are analyzed in the following. The time evolutions of $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ along 15°N are given in Fig. 2. Seen from Fig. 2a, the heat source first appears in the Indo–China Peninsula, then moves to the Bay of Bengal gradually and reaches the west part of the Bay of Bengal about on May 16, after that it begins to retreat, simultaneously the heat sources in the middle and north part of SCS increase abruptly accompanying the onset of SCS monsoon. After the onset of SCS monsoon, the heat sources in the Bay of Bengal extend to the Indian Peninsula quickly preparing the thermal condition for the onset of Indian Peninsula. It is also found from Fig. 2a that the time evolution of heat sources in the SCS (110–120°E) is periodic, being about a month period. After the middle of July, the intensity of heat sources decreases obviously denoting the onset of SCS monsoon be periodic. The heat source center in the SCS has a slowly westward trend. It is found from the analysis of $\langle Q_2 \rangle$ that there exists one month periodic oscillation in the SCS and it has a slowly westward trend, too. During the active period of the SCS monsoon, the convective precipitation increases and moisture sinks form, while in the break period of the SCS monsoon, the evaporation is greater than the precipitation and $\langle Q_2 \rangle$ is of a small negative value.

From the above analysis, the heating function of the Indo–China Peninsula has an important effect on the onset of the SCS monsoon because the maximum value areas of the total heat $\langle Q_1 \rangle$ and latent heat $\langle Q_2 \rangle$ both first appear in the Indo–China Peninsula. In order to compare the heat source distributions in the Indo–China Peninsula and the Bay of Bengal and to analyze the effect of the Tibetan Plateau on heat source distributions in the neighboring areas, the time–latitude evolutions of the whole layer mean heating rate $\langle \hat{Q}_1 \rangle$ averaged in 98–108°E (a) and 80–100°E (b) are given in Fig. 3. Seen from the time evolution in the Indo–China Peninsula (Fig. 3a), a heating rate center of 3 K/d appears in the middle of May. The existence of the heating rate center is of important significance for the onset of the

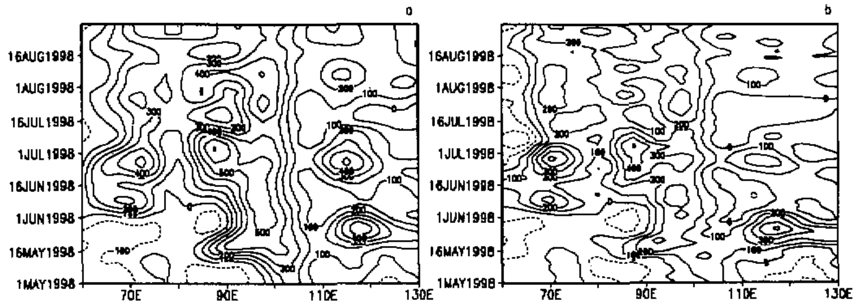

Fig. 2. The time evolutions of $\langle Q_1 \rangle$ (a) and $\langle Q_2 \rangle$ (b) along 15°N. Unit: W / m^2.

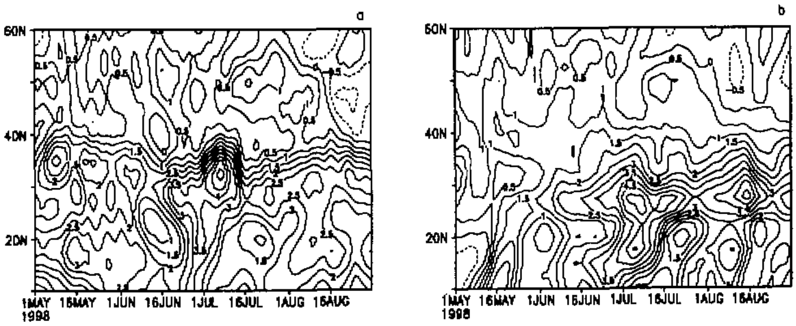

Fig. 3. The time–latitude evolutions of $\langle \hat{Q}_1 \rangle$ averaged over 98–108°E (a) and 80–100°E (b). Unit: K / d.

SCS monsoon. A greater heating rate center exists in the eastern Tibetan Plateau (30–40°N) from the beginning of May. In the Bay of Bengal between 80–100°E (Fig. 3b), although the heating begins from the middle of May, the value is smaller than that in the Indo–China Peninsula, until the beginning of June, the heating rates along 15°N and 25°N increase quickly, the strong heating rate center appears until the onset of the Indian monsoon in the middle of June and the greatest heating appears in the beginning of July. Comparing the appearing time of the heat source centers in the two areas, it is found that the onset of monsoon is closely related to the position of the neighboring area heat source centers and their formation time. The first formation of the heat source center in the Indo–China Peninsula maybe triggers the onset of the SCS monsoon. From the above two figures, it is found that the thermal contrast between the mountain and the plain caused by the Tibetan Plateau is very obvious. Seen from Fig. 3b, although the Tibetan Plateau is a heat source, the heating function of the main Plateau is not obvious, the strongest heat source center is not located in the center of the Plateau, it is located in the south part of the Plateau and the Bay of Bengal. The latitude of 35°N is the dividing line. To the south of the 35°N, $\langle \hat{Q}_1 \rangle$ has denser contour lines and two great centers, while to the north of the 35°N, $\langle \hat{Q}_1 \rangle$ decreases quickly and the contour lines are sparse. So the heat source center in the southeastern part Plateau caused by the thermal contrast between the mountain and the plain has an important function on the onset of the SCS monsoon.

4. The vertical time evolution of heating rate Q_1 / C_p and the time evolution of precipitation in different regions

From the above analysis, it is found that the distribution of heat source in the SCS and its neighboring areas is related to the periodic oscillation of the SCS monsoon. In order to analyze the low frequency oscillation(LFO) in the SCS and its neighboring areas and to study the relationship between the distribution of heat sources and the periodic oscillation of the SCS monsoon, we take four regions: (a) the Changjiang River valley (110–120°E, 24–34°N); (b) the SCS region (109–120°E, 10–20°N); (c) the northwestern Indo–China Peninsula (90–100°E, 17.5–27.5°N); (d) the Bay of Bengal (82.5–95°E, 10–20°N). Through the analysis of these four different regions, it is helpful for us to understand the thermal effect in different regions on the SCS monsoon onset and the monsoon periodic oscillation. Precipitation is an important characteristic of monsoon, it is easy to find the active and break periods of monsoon by analyzing the distribution of precipitation of different regions and the vertical distribution of the heat source. Because $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ only reflect the heat flux density in the whole atmosphere and the atmosphere has different thickness in a different area, therefore it is difficult to compare the real heating. Therefore, the vertical distribution of heating rate (Q_1 / C_p) and the time evolution of precipitation in these four regions are given in Fig. 4 (a–d) and Fig. 5 (a–d).

The Changjiang River valley includes the most part of the middle and the eastern plain and is the major region of Meiyu precipitation. 1998 is the second year of the strong El Nino starting from 1997. In that year the East Asian summer monsoon is obviously weakened because of the enduring high SST in the equatorial eastern Pacific and lower SST in the western Pacific. The abnormal activities of the middle–and high–latitude weather systems, such as polar vortex, make the subtropical high ridge line a little southward of the normal position, which causes the monsoon rain belt being located in the Changjiang River area and south of it in most of the time. Seen from Fig. 4a, the time section of Q_1 / C_p reflects the time variation of frontal precipitation, which corresponds with the time variation of Q_2 / C_p (figure omitted) and these two time series have very similar values and phases, which indicates that the major heat in that area is released by the condensed precipitation. It can also be seen from Fig. 4a and Fig. 5a that, the heating rate in the middle troposphere reaches 4–6 K / d during two Meiyu periods, corresponding with Q_2 / C_p reaching 3–4 K / d. The maximum values of Q_1 / C_p are located between 350–450 hPa, whereas the maximum values of Q_2 / C_p in lower levels. This implies that most of the precipitation is in the troposphere and the latent heat released by precipitation is upward transferred. At the same time the heat sources in the upper air have a 30–50 day periodic oscillation, which agrees with the periodic oscillation of precipitation.

The distributions of Q_1 / C_p (Fig. 4b) and precipitation rate (Fig. 5b) in the SCS region are different from that of the Changjiang River valley. There are three obvious precipitation processes in the SCS, while there are only two precipitation processes in the Changjiang River valley. The first two precipitation processes of the SCS region are 20 days earlier than the corresponding precipitation processes of the Changjiang River valley and there are less precipitation periods during these three precipitation processes. Seen from the vertical time–section

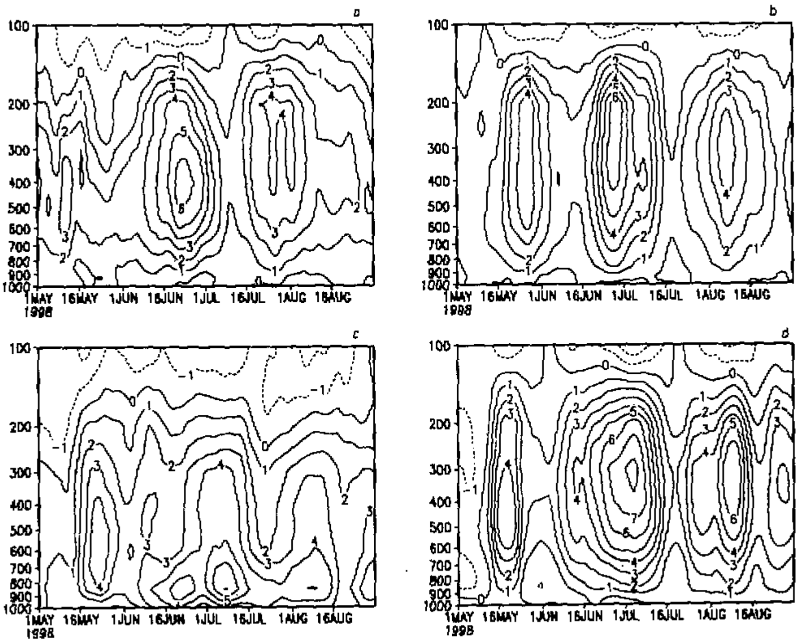

Fig. 4. The vertical time-section of Q_1 / C_p in different regions, (a) the Changjiang River valley, (b) the SCS region, (c) the northwestern Indo-China Peninsula, (d) the Bay of Bengal. Unit: K / d.

of ω (figure omitted), there is an obvious subsidence period between each two precipitation processes. Combining the vertical time-section of Q_1 / C_p, we find that the periodic oscillation is more obvious in the SCS region. There are heating rate centers on May 20, July 1 and August 5 and the period is between 30–50 days. In the Indo-China Peninsula (Fig. 4c and Fig. 5c), there is a similar oscillation period to that in the SCS, but the value of Q_1 / C_p is larger than that of Q_2 / C_p, which corresponds with the above analysis. It can be also seen from Fig. 4c that the great heating rate appears in lower levels, which indicates that the sensible heat is the major heat in the northwestern Indo-China Peninsula. Seen from Fig. 5c, the precipitation in the Indo-China Peninsula increases abruptly in the middle of May and is 1 pentad earlier than that in the SCS region. In the Bay of Bengal, the vertical time evolution of ω is analyzed. It is found that the large scale subsidence prevails in this region before the onset of the SCS monsoon and the precipitation is small, however, 5 days before the onset of the SCS monsoon, about from May 16 to May 20, the precipitation increases quickly, which bears a resemblance to that of the Indo-China Peninsula. It is also seen from the vertical time evolution of heating rate that there is a heat source center at 400 hPa on May 20, which reaches 4 K / d. While after the onset of the SCS monsoon, there is an about 20 days break period of heat source. From the precipitation distribution of the same region, it is found that the precipitation is small and the upward motion is weak before the onset of the Indian monsoon, while after the onset of the Indian monsoon, the precipitation increases quickly, which reaches 18 mm / d, and the upward motion reaches 6 hPa / h, which means that the cumulus convection is active during the monsoon onset, especially during the Indian monsoon, so the

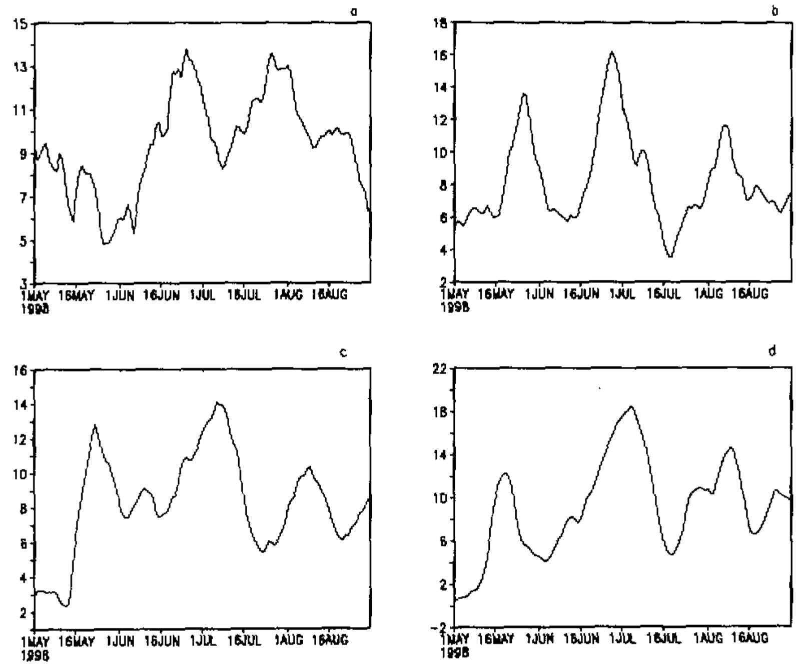

Fig. 5. The time evolution of precipitation in different regions, (a) the Changjiang River valley, (b) the SCS region, (c) the northwestern Indo–China Peninsula, (d) the Bay of Bengal. Unit: mm / d.

latent heat released by condensed precipitation is the major one. Seen from the above analysis, the Bay of Bengal and the Indo–China Peninsula are important for the onset of the SCS monsoon. The first formations of heat sources in these two regions maybe trigger the onset of the SCS monsoon.

Comparing the vertical distribution sections of Q_1 / C_p in the four regions, we find that there are similar oscillation periods except for the Changjiang River valley. The low frequency oscillation (LFO) in the Changjiang River valley has almost opposite phase to that in the other three regions and the appearing time of LFO in the Changjiang River valley is about a month later than that in the other three regions. Because of the latitude effect, the similar LFO is found in the Bay of Bengal, the Indo–China Peninsula and the SCS region, while the LFO in the SCS moves northward along the meridian, this also leads to the much later appearing of the LFO in the Changjiang River valley than in the other three regions, because the Changjiang River valley is located north of the SCS. Additionally, we also analyzed the Q_1 / C_p and the precipitation rate of the western Pacific warm pool (WPWP) (125–145°E, 0–15°N) (figures not presented here). The heating rate is obviously weaker than that in the above four regions and the precipitation has an opposite phase distribution to that in the Bay of Bengal, the SCS region and the Indo–China Peninsula, while it has a similar phase distribution to that in the Changjiang River valley. Before the onset of the SCS monsoon, the precipitation in this region is large, while during the period of the SCS monsoon, the precipitation decreases abruptly, so the atmospheric heat sources between the SCS and the WPWP are in the opposite phase. This distribution must affect the distribution of

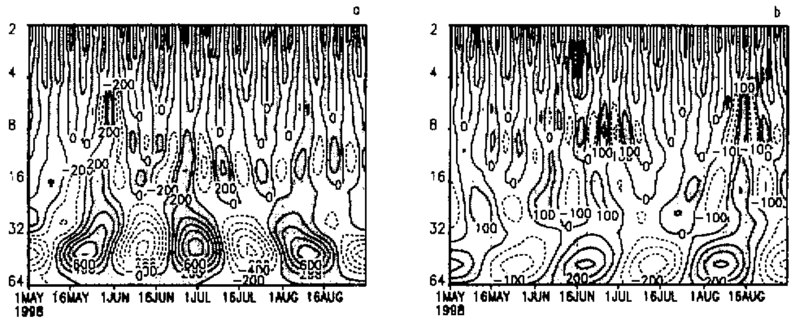

Fig. 6. The Morlet wavelet transfer section of heat sources in (a) SCS region and (b) the western Pacific warm pool.

convergence and divergence fields in the upper and lower layers. From the analysis of the divergence field, it is found that the whole SCS region has been a divergence field in the lower layers since early May and the convergence in the upper layers turns to the divergence field during the 4th pentad of May. Such a distribution of strong heat sources is helpful for the formation of the upper layer divergence, while the strong divergence is favorable for the upward motion necessary to the monsoon precipitation. When the precipitation is formed, the maintenance of the South Asia high in the upper layers of the SCS and the Indo–China Peninsula is strengthened by the feedback mechanism of latent heat, which is also useful for the stable development of the SCS monsoon.

In order to further analyze the oscillation mechanism of heat sources in the SCS and the WPWP, the period sections of the Morlet wavelet transfer of apparent heat source $\langle Q_1 \rangle$ in these two regions are given in Fig. 6.. From Fig. 6, it is found that there are 30–50 day periodic oscillations in both regions, the oscillation period in the SCS is a little shorter than that in the WPWP and they have the opposite phase distributions before the middle of July, while after then, have the same phase distribution. From the enduring time of every phase, it is found that the enduring time in the SCS is shorter than that in WPWP and the argument is larger than that of WPWP. It can also be seen from the energy density section of the two areas that the energy of 30–50 day period in the SCS is much larger than that of the WPWP. So this strong low frequency oscillation maybe triggers the onset of the SCS monsoon, and further analysis of the heat source distribution of the SCS is beneficial for understanding the periodic oscillation mechanism of the SCS heat sources.

5. Distribution of heat sources and moisture sinks during the active and break periods of the SCS monsoon

Seen from the above analysis, there exists a 30–50 day LFO in the SCS region. In order to further analyze the distribution of heat source and moisture sink in different periods of the SCS monsoon, according to the vertical time–section in the SCS (Fig. 4b), we divide the SCS monsoon period into active periods and break periods. Active periods are May 19 to May 31, June 19 to July 10 and August 1 to August 16, break periods are June 1 to June 18 and July 11 to July 31. The distributions of $\langle Q_1 \rangle$ (a–e) and $\langle Q_2 \rangle$ (f–j) in different periods are presented in Fig. 7. Seen from Fig. 7a, in the first active period, heat source centers exist in the Indo–China Peninsula and the middle SCS region, and another one forms in the western Pacific with the development of rain belt in the northeastern SCS region, whereas the moisture sink centers of $\langle Q_2 \rangle$ are only located in the SCS region and the western Pacific, not in the Indo–China Peninsula, which implies that the sensible heat is the major one in the Indo–China Peninsula while the latent heat is the major one in the SCS. In the whole active period, the heat sources distribute from west to east and cover the whole SCS monsoon trough area. In the following break period (Fig. 7b), the heat sources in the SCS move northward and reach the South China area, and the heat sources in the western Pacific also move to 20°N. The heating in the SCS region decreases quickly, but still has an east–west orientation, while to the south of the Changjiang River and the western Pacific there are strong latent heat areas (Fig. 7g). Seen from the precipitation distribution of the same period, the rain belt moves northward and two precipitation centers exist in the East China Sea. During the second active period (Fig. 7c), the western Pacific heat sources begin to retrieve to the Philippine areas, in the west, the heating areas extend to the eastern Tibetan Plateau and the Changjiang River valley from the northern Indo–China Peninsula and the distribution changes to south–north orientation. This period is the Meiyu period, so the precipitation is large in the Changjiang River valley and South China, while there is small precipitation in the western Pacific. The second break period (Fig. 7d) is similar to the first one, the heating area has an east–west distribution, but the heat center is located in a higher latitude than the first distribution. During the third active period (Fig. 7e), the monsoon is in the end and weak. The moisture sinks in the western Pacific extend to the Taiwan Strait and north of the SCS, while the heat source extends eastward and reaches the western Pacific warm pool. From the above analysis, it is found that the heat source reaches higher latitudes than in the former break period during every break period of the SCS monsoon, so the periodic oscillation of the SCS region heat source has an obvious characteristic of longitudinal propagation accompanying the movement of rain belt. From the heat source distributions of the three active periods, it is seen that there is an east–west oscillation between the SCS area and the western Pacific, the period is about 60 days which is longer than the south–north oscillation period.

6. Discussions and conclusions

The distributions of apparent heat sources and apparent moisture sinks and their oscillation characteristics are analyzed by using the NCEP reanalysis data from May to August, 1998. The results show:

(1) The distribution and formation of the atmospheric heat sources play a key function on the onset of the SCS monsoon. The enduring heating in the Indo–China Peninsula and South China makes the SCS monsoon break out first. The atmosphere in the Indian Peninsula and its neighboring areas responses slowly to the land–sea thermal contrast because of the existence of the Tibetan Plateau, so the onset of the Indian monsoon is later than that of the SCS monsoon.

(2) The atmospheric heating firstly appears in the Indo–China Peninsula and the sensible heat is the major one in the Indo–China Peninsula, while the latent heat is the major one in the Bay of Bengal, the SCS, the Changjiang River valley and South China.

(3) During the onset period of the SCS monsoon (Fig. 1b), the lower atmospheric layers in the Bay of Bengal and the Indian Peninsula are occupied by the low pressure centers because of the withdrawal of the western Pacific subtropical high and the deepening of low

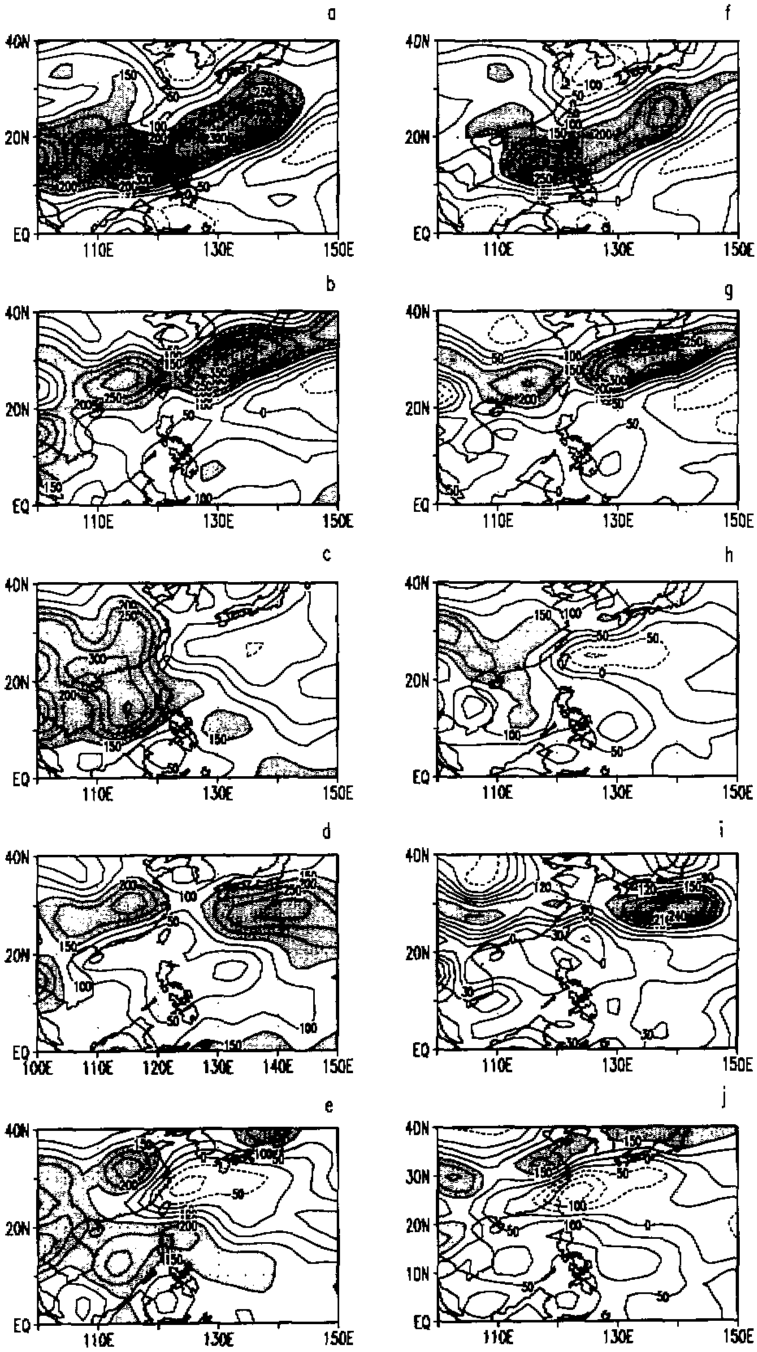

Fig. 7. The distribution of $\langle Q_1 \rangle$ (a–e) and $\langle Q_2 \rangle$ (f–j) in the active and break periods of SCS monsoon. Unit: W / m^2.

pressure centers in land and the Indian Ocean. It is found that there is a strong heat source from the Bay of Bengal to the Indo–China Peninsula, while a moisture sink is located in the Indian Peninsula, and the thermal gradient is from left to right, so the Bay of Bengal low pressure deepens and it is helpful for the formation of the north wind in the west of the Bay of Bengal. Although in the SCS there is a warm center, the center is weaker than that in the Bay of Bengal, so the Bay of Bengal low pressure is deeper than that in the SCS, and it is helpful for the formation of the south wind in the SCS, which makes the SCS region be controlled by the south wind. Because of the opposite phase distribution between the heat sources in the SCS region and the western Pacific, it is helpful for the formation of the south wind in the Philippines. Seen from the above analysis, the heat source center in the southern the Tibetan Plateau makes the south wind not easy to form in the Indian Peninsula, while it is easy to form in the SCS region, so the SCS monsoon onset is earlier than that of the Indian monsoon. This can be also seen from the heat source Morlet wavelet analysis in the Indo–China Peninsula and the western Pacific warm pool. There is a 30–50 day low frequency oscillation in both regions and it has opposite phase distribution before the middle of July. It is this opposite phase distribution that makes the formation of the south wind in the SCS region, so it is important for the onset of the SCS monsoon.

(4) Because of the latitude effect, the heat source distributions in the Bay of Bengal, the northwestern Indo–China Peninsula and the SCS region bear a resemblance to periodic oscillations and the low frequency oscillation in the SCS has a northward trend along the meridian. From the $\langle Q_1 \rangle$ latitude–time section by use of a 12.5–50 day band–pass filter (averaged between 110–120°E) (figure omitted), it is found that there are three oscillation processes in the SCS region, every oscillation has a northward propagation and in each process the oscillation reaches a higher latitude than the former one. The second one is the strongest, the oscillation center is located in 27°N, with the movement of the monsoon, the third oscillation center becomes weaker and reaches 30°N by the end of July, then retrieves slowly. Therefore, during the 1998 SCS summer monsoon evolution, the oscillation has an important effect not only on its local variation but also on its march to the eastern China.

All the above conclusions are obtained only from the analysis of the heat sources and the moisture sinks in 1998. Because of the interaction of the heating field with the atmospheric circulation field, the mechanism of mutual influences is not clear yet, so the above conclusions need to be further analyzed and verified by numerical experiments.

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