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THERMAL INFLUENCES OF LAND-SEA CONTRAST AND TOPOGRAPHY ON SUMMER MONSOON IN 1998

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ABSTRACT: In this work, the SCSMEX data are used to diagnose and compare the local land-sea thermal conditions, with the focus of discussion on possible influences of thermal forcing of the western Pacific and the Tibetan Plateau on the onset and development of summer monsoon in 1998. Results show a close relationship between the distribution of the heat sources and the land-sea contrast. Due to the blocking effect of terrain, main maximum zones of the heat sources in areas with more evident north-south land-sea contrast are more obviously southward located than those exclusively with oceans. The surface heating is characterized with apparent seasonal variation and difference between land and sea. The relationship between the western Pacific and the onset of summer monsoon is reflected in the variations of the sea surface temperature (SST) and the latent heat. The influence mechanism of the Tibetan Plateau during the summer monsoon is different: it is dominated by sensible heating during the South China Sea monsoon and by condensed latent heating during the Indian monsoon.

Key words: summer monsoon; land-sea contrast; topography; thermal influences

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1 INTRODUCTION

As found in the observation and research in recent years, the Asian summer monsoon consists of two systems, the East Asia monsoon and the South Asian monsoon. Among the monsoon systems is an important sub-member, the South China Sea monsoon. Of the variation of monsoons in the Asian region, the South China Sea monsoon has the earliest onset with the average date in the middle of May while the Indian monsoon in the middle of June, about a month later than the former. The onset of the Indian monsoon strengthens the South China Sea monsoon, bringing about the onset of monsoon in Asia. The monsoon waits no time to advance northward to eastern China, Japan and Korean region[1, 2]. On the one hand, the onset of the South China Sea monsoon signals the start of the East Asia monsoon and raining season in China. On the other hand, it poses important influence on weather and climate over a wider region through the mechanism of teleconnection. It is therefore important to study the main characteristics and mechanisms during the establishment of the summer monsoon in the South China Sea[3, 4].

The land-sea thermal contrast is the ultimate cause for the onset of monsoon. For the study of the mechanism responsible for the onset of Asian summer monsoons, one must takes into account the thermal conditions of the ocean and land and resultant changes in land-sea contrast. There are

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some similarities in the South China Sea and Indian monsoons when judged from the geographic location of onset. The monsoon region is bordered by the Asian continent to the north and the Indian Ocean to the south. The South China Sea region, Bay of Bengal and Arabian Sea are all within the same latitudinal zone, with the Indochina Peninsula and Indian Peninsula separating in between. They are the major regional terrains affecting the monsoons. The difference is that the Indian monsoon is more subject to the African continent that stretches well into low latitudes while the South China Sea monsoon may be more closely linked with the western Pacific Ocean. Inevitably, such similarities and differences in land-sea distribution are leading to those in the distribution of cooling and heating sources over land and sea, having stage influence on the onset of summer monsoon in Asia. It is therefore of great importance to study and compare the thermal conditions during the onset of Asian summer monsoon using detailed data.

In 1998, the climate was in an abnormal state as a result of the El Niño and the subsequent La Niña effects. The Asian monsoon was then set against a wider background of abnormal general circulation. Using reliable observations obtained from the “South China Sea Monsoon Experiment” (SCSMEX), the current work presents an analysis and comparison of regional thermal conditions over land and sea, with emphasis on the Tibetan Plateau and the western Pacific area.

2 DATA AND METHODS OF COMPUTATION

What are used in the current work include the reanalyzed data (surface: January 1 ~ August 31, 1998; upper level: May 1 ~ August 31, 1998) and weekly mean SST by NCAR / NCEP, which are provided for SCSMEX, and day-to-day data of apparent atmospheric heat source (Q_1) and apparent moisture sink (Q_2) from May 1 to August 31, 1998.

The apparent atmospheric heat source and apparent moisture sink are computed as follows (Nitta[5]; Yanai, Esbensen, Townsend[6]):

$$Q_1 = c_p\left[\frac{\partial T}{\partial t} + \vec{V}\cdot\nabla T + \left(\frac{p}{p_0}\right)^k w\frac{\partial q}{\partial p}\right] \tag{1}$$

$$Q_2 = -L\left[\frac{\partial q}{\partial t} + \vec{V}\cdot\nabla q + w\frac{\partial q}{\partial p}\right] \tag{2}$$

Specifically, T is the temperature, q the geopotential temperature, q the mixing ratio of moisture, $\vec{V}$ the horizontal wind, $k = R/c_p$, R and C_p being the gas constant in dry air and specific heat ratio respectively, L the latent heat by condensation, $p_0 = 1000$, and w the velocity of p in the vertical, which is separately known by computing the continuous equation. Refer to [1] for the method. Following Yanai, et al.[6], the vertically integrated values of Eq.(1) and Eq.(2) can be written as:

$$\langle Q_1\rangle = LP + S + \langle Q_R\rangle \tag{3}$$

$$\langle Q_2\rangle = LP - LE \tag{4}$$

specifically,

$$\langle\ \rangle = \frac{1}{g}\int_{p_T}^{p_s}(\ )\mathrm{d}p \tag{5}$$

Q_R is the radiation heating rate, P and E are the rainfall rate per unit area and evaporation rate, S is the density of sensible heat flux, p_T and p_s are the tropopause and surface pressure respectively. The terms $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ represent respectively the relative importance of atmospheric heating, precipitation and evaporation caused by radiation, precipitation and sensible heat. For the derivation of $\langle Q_1 \rangle$, p_T takes 100 hPa; for the determination of $\langle Q_2 \rangle$, however, p_T takes 300 hPa due to limited availability of data.

Next is the individual spans of various regions defined in the work: South China Sea (7.5°N ~ 20°N, 110°E ~ 120°E), Bay of Bengal (7.5°N ~ 20°N, 82.5°E ~ 97.5°E), Arabian Sea (7.5°N ~ 20°N, 57.5°E ~ 72.5°E), western Pacific (0° ~ 20°N, 130°E ~ 150°E), northwestern Pacific (20°N ~ 30°N, 130°E ~ 150°E), Tibetan Plateau (27.5°N ~ 40°E, 70°E ~ 105°E).

3 ANALYSES AND COMPARISONS OF THERMAL CONDITIONS

3.1 *Heat sources and moisture sinks in the atmosphere*

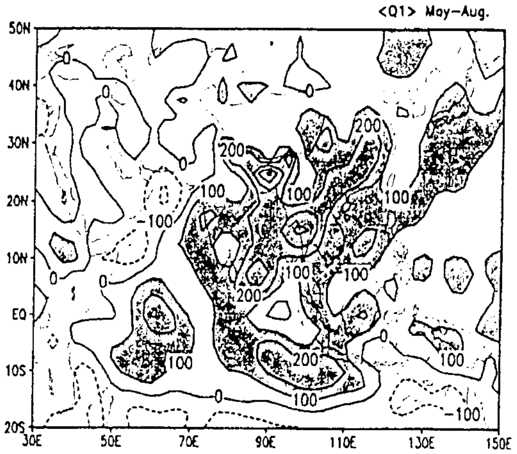

Fig.1 Horizontal distribution of the $\langle Q_1 \rangle$ averaged from May to August 1998

From the distribution of monthly mean $\langle Q_1 \rangle$ May through August (Fig.1), one knows that the heat sources are asymmetrically distributed across the Northern and Southern Hemispheres — it is generally in the zonal direction in the Southern Hemisphere with atmospheric heat sources concentrated in the region of equatorial Indian Ocean; the heat sources are oriented southwest – northeast in the Northern Hemisphere, with large-value areas (> 200 W/m^2) mainly in the Bay of Bengal, Indo-China Peninsula, areas to the south of the Plateau, eastern part of China, South China Sea and the region of Indian Peninsula. It is also clear that the atmospheric heat sinks are mainly dominating the areas along the coast of eastern Africa and south of 15°S. Because of the effect of monsoon propagation, the role of the cool source on the eastern coast of Africa and heat source over the Indian Peninsula and equatorial Indian Ocean is considered to be more essential in the evolution of the Indian monsoon system. In contrast, more factors can influence the monsoon in the South China Sea, such as the cool source in the region of Australia and the heat source over the Indian Ocean, Bay of Bengal and western Pacific, which are playing an important role. It is resulted from the fact that the southwesterly wind originates respectively from the westerly flow west of the subtropical high in the western Pacific, flows crossing the equator in Somali and the region of Kalimantan.

Examination of the distribution of $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ with time and latitude during the onset of monsoon gives one a clearer picture of how the atmospheric heat sources and sinks are distributed and how they vary with time. Fig.2 presents the distribution of $\langle Q_1 \rangle$ averaged over the latitude zones of 70°E ~ 105°E, 110°E ~ 120°E and 130°E ~ 150°E, respectively (the left panel)

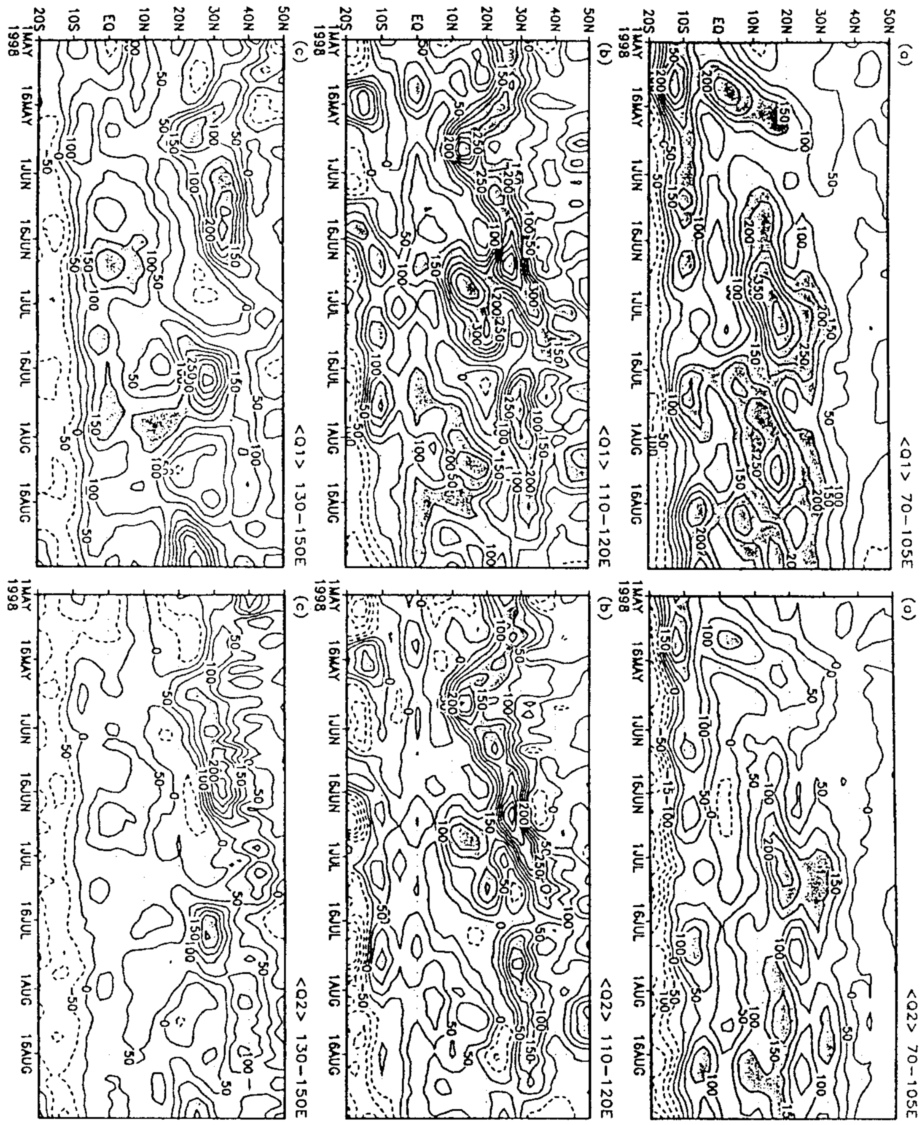

Fig.2 Time-latitude distributions of the mean $\langle Q_1 \rangle$ (left) and $\langle Q_2 \rangle$ (right) averaged for the latitude belts (a) 70~105°E; (b) 110°E ~ 120°E; (c) 130°E ~ 150°E (Unit: W/m^2).

and that of $\langle Q_2 \rangle$ for corresponding zones of longitude (the right panel). The 70°E ~ 105°E and 110°E ~ 120°E zones contain land-sea patterns, with the northern portion comprising the Tibetan Plateau and eastern China and the southern one corresponding to the Indian Peninsula-Indo-China Peninsula and the region of the South China Sea. The 130°E ~ 150°E zone mainly consists of the northwestern Pacific and western Pacific. As shown in the distribution of $\langle Q_1 \rangle$, the distribution of atmospheric heat source is closely related with land-sea distribution. With the presence of land (Fig.2a & 2b), large-value zones for the two heat sources in the north and south are gathering near 10°S in the Southern Hemisphere and the subtropics between 10°N and 30°N in the Northern Hemisphere. With the maritime environment (Fig.2c), however, the large-value zones are mainly seen in the equatorial area and between 20°N and 40°N in the Northern Hemisphere. The heat source changes insignificantly with time in the southern branch but with well-defined low-frequency oscillation in intensity in the northern one. The oscillations of heat sources are also quite substantial in the north-south direction.

Of the northern branch of heat sources, the low-frequency oscillation in the 110°E ~ 120°E zone is the most prominent. There were three major processes of intensification and northward propagation of $\langle Q_1 \rangle$, which took place in the late decades of May and June and at the end of July. According to relevant observation and diagnostic study[8], a number of important changes occurred during the onset of Asian monsoon in 1998. The monsoon first set off in May 17 in the northern part of the South China Sea and prevailed on a full scale in May 25 ~ 26. A break was observed from the end of May to June 10. Beginning from June 11 ~ 12, the Indian monsoon set off and made it possible to strengthen the South China Sea monsoon on a full scale. The Asian monsoons weakened on July 15 but reactivated on July 23 until a complete southward withdrawal on August 14. It is seen that the onset and strengthening of the South China Sea monsoon caused the oscillation and northward propagation of the atmospheric heat sources, reflecting phase-in features of these processes. It is comparable to $\langle Q_2 \rangle$ in intensity in the corresponding period. The atmospheric heating is mainly contributed by latent heat release from monsoonal precipitation.

Due to the presence of the Indo-China Peninsula and Indian Peninsula, the distribution of heat sources between 70°E and 105°E (Fig.2a) is different from the 110°E ~ 120°E longitudinal zone. Nonetheless, its low-frequency oscillation of north-south propagation is still significant, reflecting the phase-in features of monsoon onset. Fig.2a also shows that the region of Tibetan Plateau (27.5°N ~ 40°N) is acting as an independent heat source though with a smaller intensity. Referring to the distribution of $\langle Q_2 \rangle$, one found that the Plateau region basically displays surface heating prior to July but shows latent heat release by condensation after it when the region begins the raining season.

Over the ocean (Fig.2c), the northern heat-source branch is in the region of northwestern Pacific with well-defined oscillations in $\langle Q_1 \rangle$ as well. The heat sources and heat sinks appear in alternation, with the maxima in the early decades of June and July and the late decade of August, which is late as compared to the region of South China Sea. $\langle Q_1 \rangle$ varies in phase with $\langle Q_2 \rangle$, which reflects on the eastward propagation and northward shift of the South China Sea monsoon and the associated rain bands. The southern heat-source branch is in the warm pool of western Pacific with low-frequency oscillations in intensity, too. The contribution by the latent heat release from precipitation in the western Pacific region is relatively small and the atmospheric heating is mainly attributed by the underlying surface.

To have a fuller understanding of the variation and development of the northern branch of the heat source over the onset of monsoon, a time-longitude cross section (Fig.3) is given respectively along 30°N and 12.5°N. In the low latitudes (Fig.3a), a center of atmospheric heating occurred first in the Bay of Bengal area in the early decade of May and the heat source began to expand to the Indo-China Peninsula and the region of South China Sea. In the late decade of May a new center of atmospheric heating appeared in the latter region and another one in the Arabian Sea area in the early decade of June, which was expanding towards the Indian Peninsula. In the late decade of June, a steady atmospheric heat source was formed over the Indian Peninsula, Bay of Bengal and South China Sea. It weakened somewhat afterwards before intensifying once again in the late decade of July. In middle latitudes (Fig.3b), obviously subject to land-sea contrast, the heat source is not balanced in the east-west distribution with the eastern area having earlier heating in the atmosphere. One after the other, atmospheric heating centers appeared over the western Pacific region, Changjiang-Huaihe Rivers basins and southwestern Plateau. The bulk of the Plateau (80°E ~ 105°E) was acting as a heating source of weaker intensity. A conclusion that is the same as in Fig.2 can then be drawn, with reference to the

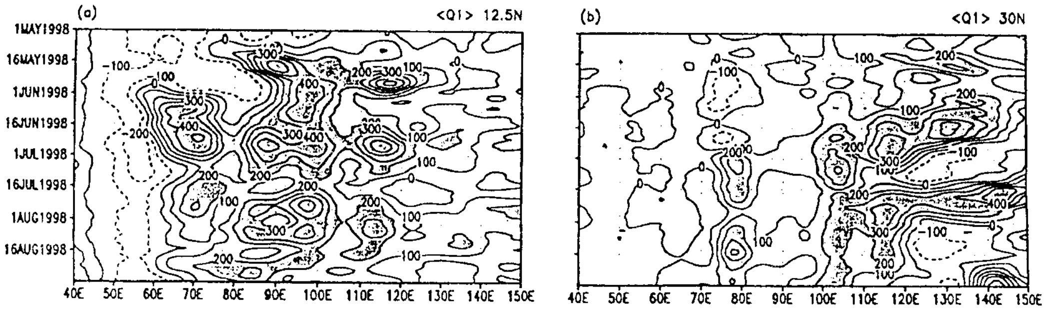

Fig.3 Time-longitude distribution of the <Q_1> along the latitude belts (a) 30°N and (b) 12.5°N(Unit: W/m^2).

distribution of $\langle Q_2 \rangle$ (figure omitted), that latent heating by condensation is generally a dominant process in areas of atmospheric heat source with oscillatory features, such as the Indian Ocean through the South China Sea, southwestern Plateau, eastern China and northwestern Pacific. In the northwestern Pacific, particularly, the maximum of $\langle Q_2 \rangle$ even exceeded that of $\langle Q_1 \rangle$ in some sections of time, which is just a good indicator that the maritime region is more important for its latent heating by condensation than its sensible heating.

It is found from the study above that the heat source is persistently active and relatively stable in the Tibetan Plateau and western Pacific regions, though with weaker intensity than that in the subtropics of the Northern Hemisphere. Being associated with the rainfall during the onset of the South China Sea monsoon, other regions have more intense temporal time and at phases simultaneous with or lagging behind those for the South China Sea monsoon. It can be drawn that, as far as the onset of monsoon is concerned, the Tibetan Plateau and western Pacific are the regions of greater importance while the heating over other regions are mainly resulted from air-sea and land-atmosphere interactions over the onset time of monsoon.

To compare the Tibetan Plateau, South China Sea and western Pacific areas in terms of the vertical distribution of atmospheric heating rate $\langle Q_1 / C_p \rangle$ and drying rate $\langle Q_2 / C_p \rangle$, the conditions of atmospheric heating were represented by averages over May 1 ~ 5, May 21 ~ 25 and June 11 ~ 15 for periods before and during the onset of monsoons in the South China Sea and India region (Fig.4). Just before and after the onset, there was always the diabatic heating in levels below 300 hPa in the troposphere over the Tibetan Plateau ($Q_1 / C_p \rangle 0$). The pre-onset situation is different from the Indian monsoon. The atmospheric heating that resulted from moisture condensation (Q_2 / C_p) was very weak and came near Q_1 / C_p in the distribution. It shows that the heating is fundamentally different over the Tibetan Plateau during the onset of Asian monsoon. Around the onset of the South China Sea monsoon, the near-surface layers in the Tibetan Plateau are heated mainly due to the sensible heating resulted from strong ground-air interactions over the underlying surface; the latent heat release by moisture condensation plays a major role in the onset of the Indian monsoon. Although the Tibetan Plateau is not a region of high heating values, regarding the vertical integration of the entire air column, the local diabatic heating is a factor that cannot be ignored, as judged from the same latitude, especially below the level of 300 hPa. The atmosphere remains cool in the region of South China Sea (Fig.4d ~ 4f) before the onset of monsoon; atmosphere at various levels have much higher heating as compared to the point around the onset, shifting the release of latent heat through condensation to a relatively weightier position. For the western Pacific region (Fig.4g ~ 4i), the atmospheric heating, mainly in the middle layer, is going on at a mild rate, with the intensity relatively stable.

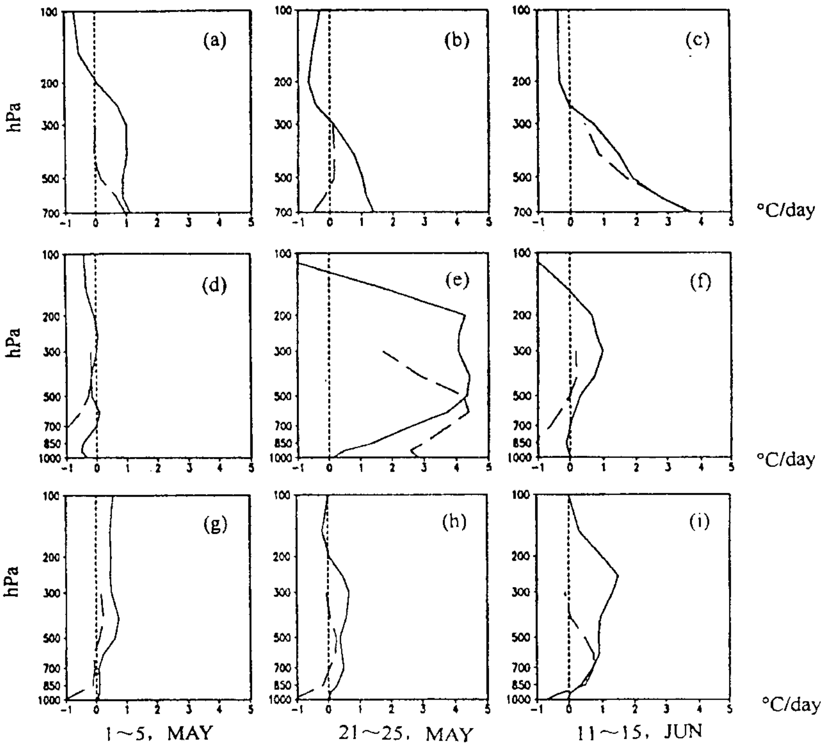

Fig.4 Vertical distribution of Q_1 / C_p (solid lines) and Q_2 / C_p (dashed lines) averaged over Tibetan Plateau (a ~ c), South China Sea (d ~ f) and western Pacific (g ~ i) before the onset of monsoon (left panel), during the SCS monsoon onset (middle panel) and during the Indian monsoon onset (right panel) (unit: °C / day).

3.2 *Sensible and latent heat at the surface*

With the sensible and latent heat data of NCEP / NCAR provided by SCSMEX, the following regions (figure omitted) are identified to have the relatively large values of sensible heat averaged over May ~ August 1998: northwestern and northern parts of China north of the Plateau, central Plateau at 80°E ~ 90°E, Iran Plateau west of the Plateau. In addition, the Indo-China Peninsula and Indian Peninsula are also the regions of large sensible heat but the intensity drops during the onset in both regions. There are large zones of latent heat by evaporation over the surface of the Indian Ocean and Pacific Ocean and significant temporal difference in the distribution of latent heat overland in southeastern and southwestern parts of China, eastern Tibetan Plateau, Indo-China Peninsula and Indian Peninsula. It is greatly related with the characteristics of the underlying surface and distribution of precipitation.

Fig.5 and Fig.6 give the time-longitude distribution of sensible and latent heat respectively along 30°N and 12.5°N. The seasonal changes and land-sea contrast for surface heating are clearly shown. The distribution of sensible heat (Fig.5) indicates that large sensible heat zones (Fig.5a) are principally in the northwestern Pacific for middle latitudes in the boreal winter (January), with the gradient pointing to the ocean from the land. Starting from February, the sensible heat slowly increases in the Tibetan Plateau itself and the region of Iran Plateau west of it while it gradually decreases over the western Pacific. By the late decade of March, the gradient of sensible heat has turned in direction, pointing to the land from the ocean, though the maximum sensible heating does not take place right over the Tibetan Plateau. For the low latitudes (Fig.5b), the land-sea thermal difference is relatively large and the ocean is always small concerning the value of sensible heat. The flux of sensible heat is large in the Indo-China Peninsula, Indian Peninsula and African continent but increases and then decreases, with significant amplitude, in the Indian Peninsula and Indo-China Peninsula. It will be described further in the text below.

The distribution of latent heat in the middle latitudes (Fig.6) also shows how the gradient reverses for land-sea heating. The latent heat significantly reduces in April ~ June in the northwestern Pacific region but strengthens again after July. Over land surface, it increases with time, with the maximum in the Changjiang-Huaihe Rivers basins relatively weak intensity over the Plateau. The low-latitude latent heat is concentrated over the western Pacific, South China Sea, Bay of Bengal and Arabian Sea. In April and May, the latent heat is being shrunk over the Arabian Sea and Bay of Bengal region but increases in the late decade of May while decreasing rapidly in western Pacific.

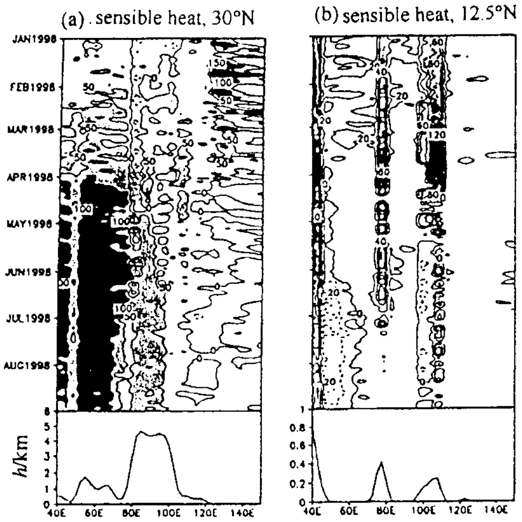

Fig.5 Time-longitude distribution of sensible heat (unit: W / m^2) along the latitude belts of 30°N (a) and 12.5°N (b) and corresponding topography height (unit: km)

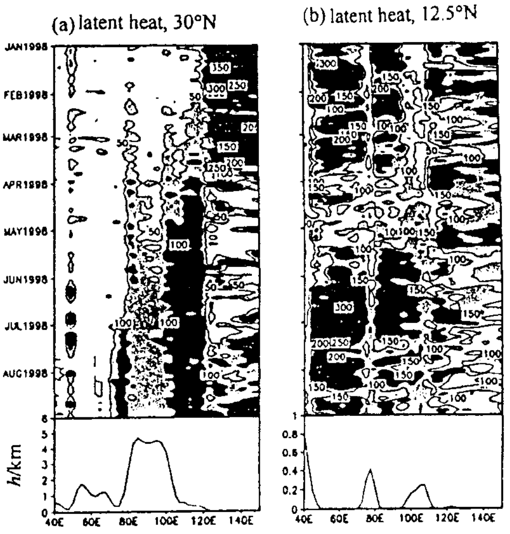

Fig.6 Same as Fig.5 except for latent heat.

4 ONSET OF SUMMER MONSOON AND THERMAL DIFFERENCE AMONG WATERS

The ENSO was weakening during the onset of the 1998 monsoon. Studying the variation of sea surface temperature (SST) reveals the forcing effect of the ocean on the atmosphere on the one hand, and shows the effect of ENSO cycle on the onset of monsoon on the other. Fig.7a gives the temporal evolution of mean SST over different waters. Starting from early May, the SST keeps decreasing in NINO3, suggesting the decay of ENSO cycle and the occurrence of La Niña phenomena. For the Asian monsoon region, the SST increases in both the South China Sea and western Pacific, though more rapidly in the former region. In the middle decade of May, it

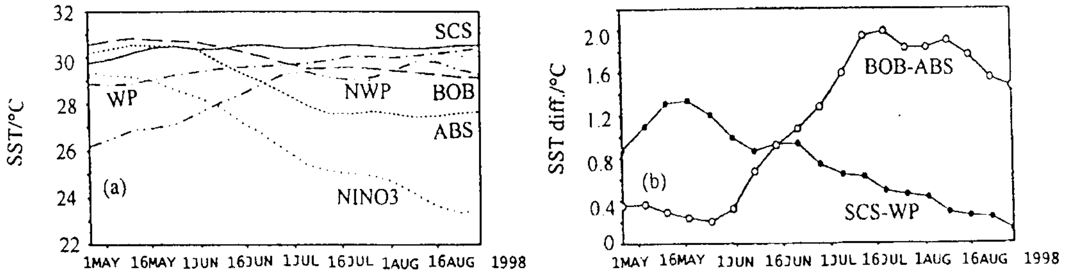

Fig.7 Evolutions of the mean SST averaged over (a) South China Sea (SCS), Bay of Bengal (BOB), Arabian Sea(ABS), western Pacific(WP), northwestern Pacific (NWP) and Area Nino3 and (b) the difference of SST between SCS and WP and between BOB and ABS (unit:°C).

reaches the stable state (above 30°C) in the region while having slowly changing variation in the western Pacific and reaching 30°C in August. Before the onset of the South China Sea monsoon (in the middle decade of May), the SST is higher in the Bay of Bengal and Arabian Sea than in the South China Sea and western Pacific. Afterwards, it begins to decrease in the former regions, more rapidly in June.

With the difference in SST variation over varied waters, there are changes in the difference of SST for the same latitude. Fig.7b is the evolution of SST difference with time for the waters of South China Sea-western Pacific and Bay of Bengal-Arabian Sea region. It is found that the two sets of SST vary in just the opposite phase. In the former region, the longitudinal difference in temperature increase results in a maximal SST difference in the middle decade of May, which decreases slowly before regaining some increase in the middle decade of June. The SST in the latter region does not have a significant difference before June, but it starts to grow in early June and acquires the maximum around the middle of July but begins declining after August. Comparisons of the difference in the two SST sets lead to the discovery of maximum period of SST difference around the onset of monsoon in the South China Sea (during the middle decade of May) and the western Pacific region with the minimum period for the Bay of Bengal-Arabian Sea region. When the SST difference increases to as much as about 1°C (in the middle decade of June), monsoon sets off in the Indian region. The inhomogeneous longitudinal distribution and temporal variation of SST are interacting with atmospheric sensible and latent heating and transport of moisture such that they have feedback to each other and result in corresponding changes in local thermal circulation.

Over the ocean, the flux of surface latent heat, with obvious seasonal variation, is far larger than that of sensible heat. The months April and May are the transitory season in the variation of latent heat, as found in the study of Fig.6. Before April, the flux of latent heat is generally large, having a similar distribution over a number of major waters. When it comes to April, the latent heat reduces significantly over the Arabian Sea and Bay of Bengal while keeping in a largely stable state over the western Pacific and South China Sea regions. At the beginning of May, the Bay of Bengal region first witnesses the growth of latent heat and by the middle decade of May the Arabian Sea and Bay of Bengal has once again become a zone of high latent heat. In the meantime, it rapidly weakens in the southern part of western Pacific, contributing to a strong contrast between the South China Sea and the western Pacific region. The changes in oceanic latent heat inevitably affects the way in which atmospheric circulation is adjusting and removes the source of South China Sea moisture to the Indian Ocean-Bay of Bengal region during the onset from the western Pacific region before it.

5 SUMMER MONSOON ONSET AND THERMAL EFFECT OF TIBETAN PLATEAU

Analyzing Section 3 of the current work, we know that the Plateau region is a stable atmospheric and surface heat source during the onset of Asian monsoons, though not being a center of maximum heat source. The region heats up the atmosphere differently for the onset of the South China Sea and Indian monsoons. Fig.8 gives the day-to-day variation of 300-hPa temperature, 500 hPa -250 hPa thickness and sensible heat, on the surface of the Tibetan Plateau. It is found that there is a rapidly warming process in the tropospheric atmosphere over the Plateau (Fig.8a & 8b) —two well-defined jumps occur after May, one in the middle decade of May and other in early June. There is another minor step in the end of April and the beginning of May. Such step-by-step warming in the atmosphere over the Plateau is well corresponding with monsoon onsets in Asia. With regard to the changes in the flux of sensible heat (Fig.8c), there is significant intensification in the sensible heat of the Plateau from the early decade of April to the middle decade of May, which then stays stable. It is obvious that the sensible heating of the Tibetan Plateau is linked with early onset of monsoon, which maintains the monsoon in periods afterwards.

The changes in the sensible heating of the Plateau invariably result in similar responses in the field of atmospheric circulation. Take the 200-hPa level for example. Fig.9 gives the distribution of difference in mean sensible heat, temperature and flow field during the onset of the South China Sea monsoon (May 21 ~ 25) and Indian monsoon (June 11 ~ 15) and the period leading up to it (May 1 ~ 5). During the onset of the former monsoon (Fig.9a & 9c), sensible heating increases near 90°E in the southern part of the Plateau, which in turn increases the atmospheric heating rate Q_1 / C_D (Fig.4) and consequently causes the temperature to rise above the Plateau. The warming is especially so at the upper layer of the troposphere (200hPa). Variations in the temperature field bring about corresponding responses in the flow field. An asymmetric situation appears on both sides of the warming center —an anticyclonic disturbance to the southeast of the Plateau is accompanied by a cyclonic disturbance to the north. During the onset of the Indian monsoon (Fig.9b and 9d), the sensible heating becomes more significant in

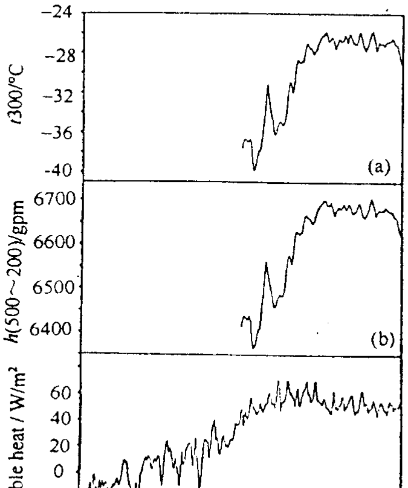

Fig.8 Evolutions of (a) the temperature at 300 hPa (unit: °C), (b) the height between 500 ~ 200 hPa (unit: gpm) and (c) the surface sensible heat (unit:W/m^2) over the Tibetan Plateau.

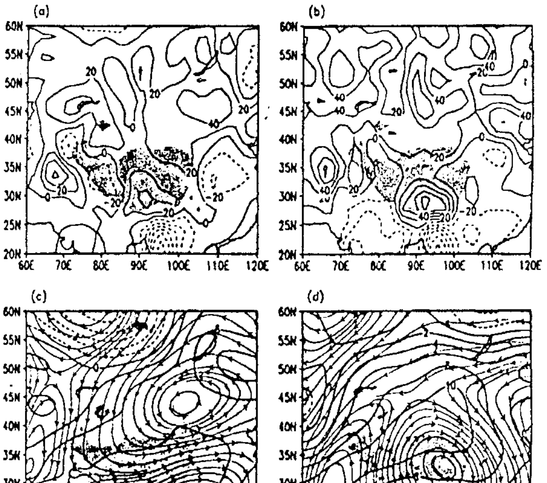

Fig.9 Differences of (a, b) the sensible heat (W/m^2), (c, d) the temperature (°C) at 200 hPa and the stream lines during and after the onset of monsoon in the SCS (left panel) and the Indian region (right Panel)

the south of the Plateau. The warming center moves towards northwest and together with it goes the anticyclonic disturbance to the eastern Plateau and the cyclonic disturbance moves out of the Plateau and nearby areas. The local circulation of thermal disturbance set off by the Plateau heating increases the easterly but decreases the westerly in the southern Plateau while strengthening the westerly but weakening the easterly in the northern Plateau. As a result, the easterly jet stream is established in the troposphere in the southern Plateau and the westerly jet stream jumps northward in the northern Plateau. Studying the horizontal distribution of 200 hPa (figure omitted) gives a consistent phase between the variation of atmospheric circulation disturbance resulted from such thermal action and the northward movement of South Asian high. The latter is obviously steered by thermodynamics of the Plateau during the northward shift and establishment over it. In addition, before the onset of monsoon in the South China Sea, the circulation disturbance arising from the thermal action first forms in the northern Bay of Bengal south of the Plateau, which is corresponding to the center of sensible heating. It then gradually moves to the north and west. The change of gradient direction in the latitudinal temperature in the middle and upper layers of the troposphere, which is caused by thermodynamic variation, is also propagating from east to west. It might be having an important role in the westward advancement of the Asian monsoons.

To have more comparison of sensible heating over various land areas, the work studies the variation of mean sensible heat for a number of important terrain. Fig.10 gives the curves of variation with time regarding the anomalies of sensible heat (obtained by subtracting the mean sensible heat over January ~ August from day-to-day values). It is apparent that the sensible heat has been increasing steadily from January until it reaches the maximum in the middle decade of March. It then drops rapidly and the anomaly turns from positive to negative at the end of April. The sensible heat varies in the Plateau in almost the opposite trend to that with the Indo-China Peninsula regions. The negative anomaly of sensible heat has been growing from January to the end of April but descends rapidly at the end of May. It becomes a negative anomaly in the early decade of June. The Indo-China Peninsula is similar with the Indian Peninsula in terms of the geographic location they are exposed to. The sensible heat changes from positive anomalies to negative anomalies at the time corresponding to the onset of monsoons in the South China Sea and India while being persistently increasing over the Plateau region. It shows that as local topographic features, the Indo-China Peninsula and Indian Peninsula are pre-heating the South China Sea and Indian Ocean regions. Once the heating weakens, land-sea thermal contrast caused by broader-scale sensible heating will cause the onset of monsoon in a corresponding stage.

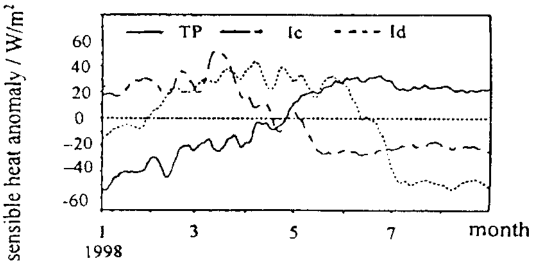

Fig.10 Evolutions of the anomaly of the surface sensible heat averaged over the Tibetan Plateau (TP), the Indochina peninsula (Ic) and the Indian peninsula (Id) (Unit: W/m^2).

6 CONCLUSIONS AND DISCUSSIONS

a. For the region where the Asian monsoons have the onset, the atmospheric heating source is divided into two main zones of large values asymmetrically located in the north and south. In the region of Southern Hemisphere, the heat source is basically structured zonally while aligning southwest-northeast in the region of Northern Hemisphere. It is characteristic of significant low-frequency oscillation, especially in the Northern Hemisphere. The heat source oscillates quite dramatically in the north-south direction, reflecting on the stage characteristics of the onset of Asian summer monsoons.

The distribution of atmospheric heat sources is closely related with land-sea distribution. Due to the blocking effect of terrain, the large-value zones of heat source are much more southward located in areas of land-sea difference in the meridional direction than in areas of entire oceanic coverage. Compared to other regions, the Tibetan Plateau and western Pacific regions are weak but steady sources of heating, which rely less on the onset of monsoon. It is therefore inferred that the thermal variation of the two regions is of significant physical implication in the onset and maintenance of summer monsoon.

b. There is obvious seasonal difference and contrast between land and sea in the surface heating. Around the point of monsoon onset in the South China Sea, large changes are noted in the direction of land-sea thermal gradient concerning both sensible heating and latent heating at the surface. The changes are important for the onset of monsoons.

c. The oceanic thermal difference interacts and interrelates with the onset of summer monsoon. During the onset of the South China Sea monsoon, the ENSO is weakening, the SST is gradually increasing in the South China Sea and western Pacific regions but decreasing in the Bay of Bengal and Arabian Sea regions. The variation of sea temperature in the latter is related with the up turning of seawater. In addition, the zonal and temporal difference in the variation also results in a reversed change in the difference of sea temperature in the regions of South China Sea-western Pacific and Bay of Bengal-Arabian Sea. It is around the onset of the South China Sea monsoon that the sea temperature differs by the most margins between the sea and the western Pacific Ocean in contrast to relatively small difference in sea temperature. After this point, the two sets of difference begin reducing and enlarging, respectively. When the difference in both sets increases to about 1°C, the monsoon sets off in the Indian region. Such inhomogeneous nature of the sea temperature difference inevitably affects the oceanic heating of the atmosphere through sensible and latent forms and transportation of moisture. April and May are the transitory season of latent heat variation in the tropical ocean. It alters the source of moisture for the region of South China Sea around the onset of the monsoon on the one hand and affects the adjustment of local atmospheric circulation on the other.

d. The Plateau contributes to the onset of Asian summer monsoons in different mechanisms. The sensible heat is the dominant factor during the onset of the South China Sea monsoon while the latent heat released from moisture condensation plays the decisive role during the onset of the Indian monsoon. Studying the effect of Plateau sensible heat on the general circulation is, therefore, helpful in having more understanding of the onset mechanism of the South China Sea monsoon as it is affected by surface heating over massive terrain.

With the sensible heating over the Plateau, variations occur in corresponding fields of temperature and flow in the tropospheric atmosphere around the onset of the South China Sea monsoon. The tropospheric atmosphere gets warm rapidly, the gradient of longitudinal temperature reverses and an anticyclone disturbance forms in the southern part of the warming center. They are favorable for the northward shift of the westerly jet stream and the setting-up of the easterly jet stream at the upper levels of the troposphere. Obviously subject to the thermal steering of the Plateau, the South Asia high moves to the north and settles down over the Plateau eventually. It shows that the variation of sensible heating over the Plateau is indeed important for the onset of the South China Sea monsoon. In contrast to other topographic features, the Tibetan Plateau heats up the spring atmosphere all the time. The sensible heat over the Indo-China Peninsula and Indian Peninsula is warming it in the preceding period. Once the heating reduces, land-sea thermal contrast resulted from broader scale Plateau heating will lead to the onset of monsoon in corresponding stages.

e. From the study above, it can be summarized that the Plateau and land-sea distribution and their thermal difference, especially the longitudinal difference over the ocean and latitudinal difference over the land, constitute to earlier onset of monsoon in the South China Sea than in the Indian region.

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REFERENCES:

[1] TAO S Y, CHEN L X. A review of recent research on the East Asian summer monsoon in China [A]. C P Chang, T N krishnamurti. Monsoon Meteorology [M]. Oxford University Press, 1987. 60-92.

[2] DING Yi-hui, WANG Qi-yi, YAN Jun-yue. Some aspects of climatology of the summer monsoon over the South China Sea —From atmospheric circulation to global change [M]. China Meteorological Press, 1996. 289-313.

[3] WANG Bin, WU Reng-nang. Peculiar temporal structure of the South China Sea summer monsoon [J]. *Advances in Atmospheric Sciences*, 1997, **14**: 177-194.

[4] LUO Hui-bang. Characteristics of summer monsoon onset in the South China Sea and the evolution of associated rain bands —Onset of South China Sea monsoon and evolution and interactions with the ocean [M]. Beijing: China Meteorological Press, 1999. 25-29.

[5] NITTA T. Energy budget of wave disturbances over the Marshall Islands during the year of 1956 and 1958 [J]. *Journal of Meteorological Society of Japan*, 1972, **50**: 71-84.

[6] YANAI M, ESBENSEN S, TOWSEND R D. Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets [J]. *Journal of Atmospheric Sciences*, 1973, **30**: 611-627.

[7] ZHANG Qiong, QIAN Yong-fu, ZHANG Xue-hong. Interannual and interdecadal variations of the South Asia high [J]. *Scientia Atmospherica Sinica*, 2000, **24**: 67-78.

[8] SHAO Hui, QIAN Yong-fu. Main features of regional circulation variation during onset of the South China Sea monsoon in 1998 [J]. *Advances in Atmospheric Sciences*, 2000, **17**: 322-338.