FIRST TRANSITION OF THE CIRCULATIONS IN ASIA AROUND MID-MAY FROM 7-YEAR MEAN ECMWF DATA①

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ABSTRACT

The time evolution of the general circulation over the South China Sea and surrounding areas during the period from April to June is studied using ECMWF data of 1980—1986. The first transition from the second (6—10 May) to the third (11—15 May) pentads is characterized by the distinct change of low-level (850 hPa) winds from southeasterlies to southwesterlies along 15°N over the South China Sea, and by the sudden movement of the center of South Asian high in the upper troposphere (200 hPa) from 10—15°N to 15—20°N over Southeast Asia. Corresponding to the abrupt change in circulations, the gradients of the temperature and humidity intensity along latitudes center on 30°N over East Asia at 850 hPa. The time sequence of the 850—200 hPa layer thickness shows that the layer-mean temperature over the southeastern Tibetan Plateau-East China Plain region increases abruptly at the same time. The corresponding sudden increase of the vertically integrated heat source $\langle Q_1 \rangle$over the warming areas reveals that the heat source plays an evident role in the drastic changes. The time series of $\langle Q_1 \rangle$ over the northern part of the South China Sea shows that the drastic increase of the area-mean $\langle Q_1 \rangle$ is also found but it is 5—10 days late than the change of corresponding wind fields. The time series of Xisha SST shows a continuous increase to about 29. 5° until May 10 when the abrupt changes in circulation occur.

Key words: summer monsoon onset, East Asia, circulation evolution

Ⅰ. INTRODUCTION

The establishment and maintenance of the East Asian summer monsoon (also referred to as the South China Sea monsoon) has been discussed by many authors (e. g. Tao and Chen, 1975, Tao et al. , 1983, Xie and Zhu, 1981, Chen et al. , 1991). Their results show that the East Asian monsoon and its time evolution play considerable roles in the atmospheric circulation system over Asia, and even exert profound influences on the global general circulation. However, research work is needed on the detailed process of the abrupt transition of the atmospheric circulation which leads to the onset of the East Asian summer monsoon, in order to further understand the monsoon phenomenon and to improve the medium range weather forecasting.

Based on the synoptic analysis of wind fields and flow patterns , Shen et al. (1983)

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found that the establishment of the South China Sea monsoon is accompanied by an abrupt change of the atmospheric circulation in the low latitude regions in both hemispheres. Using FGGE Ⅱ-b (He et al. ,1987, Yanai et al. ,1992) and QXPMEX 79 data sets (Yanai et al. , 1992), it was pointed out that during the onset of the Southeast Asian summer monsoon in 1979 there was: 1) a drastic transition period in circulations over Asia and the surrounding areas [similar to the results by Shen et al. (1983)], 2) an " explosive " warming in the troposphere from the eastern Tibetan Plateau to the South China plain (east of 85°E), and 3) a remarkable strengthening of the atmospheric heat sources which are mainly controlled by sensible heating over the southeastern plateau or by latent heat release in other areas. They thereby stressed the important role of the outbreak of the monsoon in the warming of the plateau. In addition, using the data of 1981, Ju et al. (1986) found that there also existed an obvious increase of the atmospheric heat source over the South China Sea area, with the latent heat of condensation as the main contributing factor.

Generally speaking, the previous studies were mostly based on data of uniform nature or relatively short periods. The purpose of this paper is, using the much longer period data ranging from 1980 to 1986, to discuss in detail the 7-year mean (or, climatological) features of the drastic transition of the atmospheric circulation over Asia during the onset period of the East Asian summer monsoon.

Ⅱ. DATA AND ANALYSIS PROCEDURES

The primary data used in this study are the ECMWF data of 1980—1986 including the daily temperature, humidity, geopotential height and wind fields on a grid mesh of 2.5°×2.5°, and the vertically integrated values of the apparent heat source $\langle Q_1 \rangle$ and apparent moisture sink $\langle Q_2 \rangle$, which were computed with the data using the residual method (e.g. Luo, 1990).

In the following sections of discussion, serials of 18 pentads averaged over the 7 years were used for the the period from April 1 to June 29 within a central domain of 70—140°E, 5—40°N. The grid mesh chosen for the wind, geopotental height, temperature and humidity fields is 5°×5°, but that for the atmospheric heat sources and moisture sinks is 2.5°×2.5°. In addition, daily sea surface temperature data from the Xisha station (located in the South China Sea region) is also employed for the same period.

Ⅲ. RESULTS AND ANALYSES

In this section we describe the drastic changes in the mean flow pattern, temperature and humidity distribution, and height field around the onset of the East Asian summer monsoon.

1. *Abrupt changes in the mean flow features*

Fig. 1 exhibits a significant change of Asian atmospheric circulation from Pentads 2 to 3 which corresponded to around the outbreak of the East Asian summer monsoon on May 10. In the upper troposphere (200 hPa, Figs. 1a,b), remarkable changes in circulations were clearly represented by the intensification of the South Asian anticyclone and the obvious movement of its center from 10—15°N to 15—20°N, the transition from the westerlies to easterlies over the northern South China Sea, the weakening and northward withdrawal of the westerly zone above the ground, and the strengthening and spreading of the easterlies at low latitudes. Corresponding to the abrupt changes at 200 hPa, the low-level circulation also underwent drastic changes. Figs. 1c, d show that the southwesterlies in the Bay of Bengal-Indochina region also intensified and extended eastward so that the southwesterlies replaced the southeasterlies over the northern part of the South China Sea. In the meantime, the northwesterlies over mid-latitude region of East Asia also intensified but extended southward to form low-pressure circulation along 30°N in 85—110°E (southwestern China). Results by He and Yanai et al. with 1979 data were basically consistent with the present mean results.

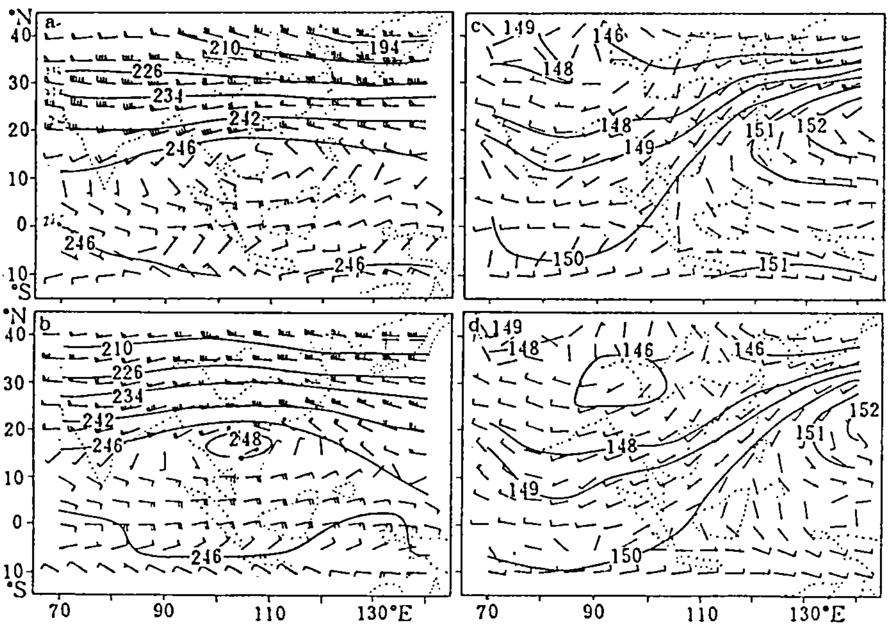

Fig. 1. Five-day mean heights and winds at 850 hPa (right) and 200 hPa (left) for (a) (c) the pre-onset pentad (6—10 May) and (b) (d) the post-onset pentad (11—15 May).

The drastic changes in the mean flow were also clearly recognized in the longitude-time cross-sections of wind along 15°N at both 200 hPa and 850 hPa (Fig. 2a, b). At 850 hPa, it is noted that the boundary separating the southwesterlies from the southeasterlies was located around 110°E until Pentad 2 in May and the southeasterlies dominated the northern part of the sea; as it was moved to around 130°E in Pentad 3 the organized southwesterlies prevailed over the area. In the upper layer (200 hPa) , before Pentad 2, the westerlies prevailed through the whole longitudinal domain of the South China Sea, but strong easterlies dominated almost the whole domain (including the South China Sea region) after the onset of the southwesterlies at low levels after Pentad 3.

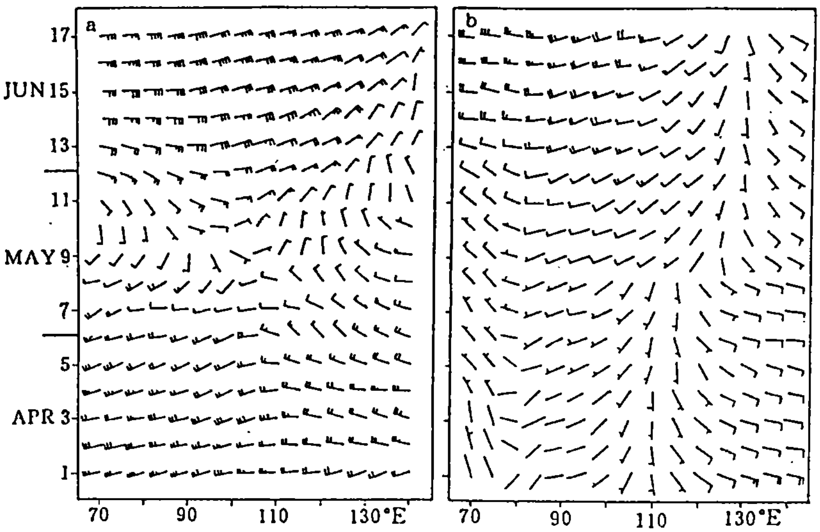

Fig. 2. Longitude-time cross-sections of 5-day mean winds at (a) 200 hpa, (b) 850 hPa, along 15°N from April to June.

2. *Changes of temperature and humidity at* 850 *hPa and significant warming of the tropospheric atmosphere*

To reveal more clearly the changes in the low-level circulation, we present pentad-mean composite maps of the temperature and humidity field at 850 hPa around the onset period (Fig. 3).

Fig. 3a exhibits that, by Pentad 2 of May, there had already existed a large humidity center over Indochina Peninsula and relatively strong gradient of humidity over the Yangtze River Valley centered around 30°N. Distribution of temperature in this period were marked by warmer air over the Indochina Peninsula and warm ridge extending from southern China to areas around 40°N via the Yantze River, which was flanked by rela-

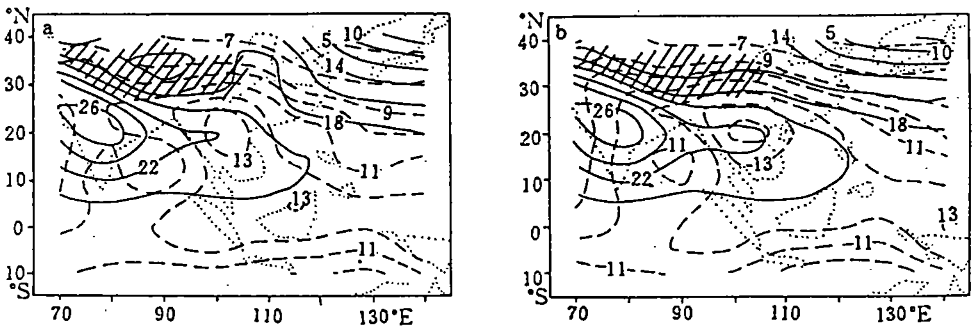

Fig. 3. Five-day mean temperature (°C, solid) and humidity (g/kg, dashed) at 850 hPa for (a) the pre-onset pentad (6—10 May) and (b) the post-onset pentad (11—15 May).

tively cool areas to the east and west.

By Pentad 3 (Fig. 3b), the air got warmer and the center of humidity stronger over the Indochina Peninsula and Southwest China regions with the coverage enlarging eastward. These changes in temperature and humidity fields were consistent with the strengthening of the low-level warm and humid southwesterlies over the Bay of Bengal, Indochina Peninsula and South China Sea regions, as shown in Fig. 1d. On the other hand, the above-mentioned warm ridge withdrew to the south so that isotherms in mid-latitudes changed the orientation to west-east and the corresponding north-south temperature gradients intensified, distributing in a much similar manner as those of the isohume. The changes in temperature in mid-latitudes were associated with the southward movement of the cold air mass (Fig. 1d).

Responding to the change in low-level temperature and humidity, drastic warming occurred in the whole tropospheric atmosphere. Fig. 4 (a, b) gives a time-longitude cross-sections of the 850—200 hPa layer along 30°N and 20°N. At 30°N (Fig. 4a) it is seen that there was a remarkable temperature increase in the layer from Pentad 2 to Pentad 3 in May, though the warming mainly took place in 90°E—115°E, i. e. from the southeastern Tibetan Plateau to the East China plain. In contrast, no significant warming was evident over the sea east of 125°E.

The drastic changes of the mean tropospheric thickness (temperature) along 30°N were contrasted to the much weaker temperature changes along 20°N (Fig. 4b). Around 100°E the temperature increase was the most rapid over the land surface of northern Indochina (being consistent with the northward "jump" of the South Asia high) but in less extent than that along 30°N. The warming over the ocean to the east of the peninsula was still slower. Taking an overall view, from May to June the

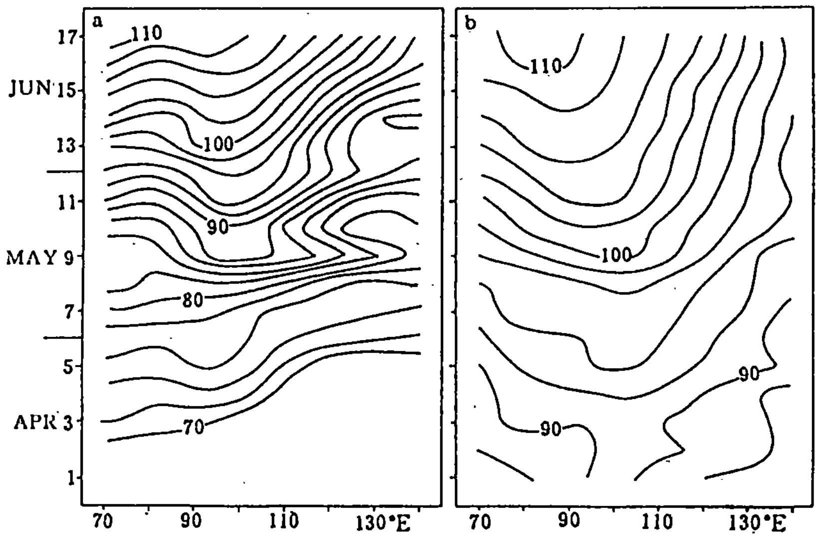

Fig. 4. Longitude-time (pentads) cross-sections of the 200—850 hPa layer thickness along (a) 30°N, (b) 20°N, Pentad 1 of April through Pentad 5 of June.

"warming" center moved westward from North Indochina to the Bay of Bengal coast, which might be related to the movement of the atmospheric heat source center in summer. It is tempted to argue that the spatial difference of the atmospheric warming may be closely linked to the land-ocean contrast in geographic distribution. To sum up, we see that during the onset of the East Asian summer monsoon the abrupt tropospheric warming was mainly located over the southeastern Tibetan Plateau and the East China plain, which was very close to the large gradients of temperature and humidity at lower levels (850 hPa). In fact, the warming was also obvious in the temperature field at 500 hPa (Figure not shown). It was just because of the warming that the temperature gradient was changed south of 30°N, resulting in corresponding adjustment of the pressure-wind field.

IV. EVOLUTION OF ATMOSPHERIC HEAT SOURCES AND MOISTURE SINKS

In this section the time evolution and regional differences of the heating process in relation to the onset of the East Asian summer monsoon circulation is revealed by examining the time sequences and the horizontal distributions of the vertically integrated heat source $\langle Q_1 \rangle$ and moisture sink $\langle Q_2 \rangle$.

1. *Horizontal distributions of heat sources and moisture sinks*

The pentad-mean horizontal distributions of the vertically integrated heat source

$\langle Q_1 \rangle$ and moisture sink $\langle Q_2 \rangle$ for pentads 2 and 3 in May are shown in Fig. 5.

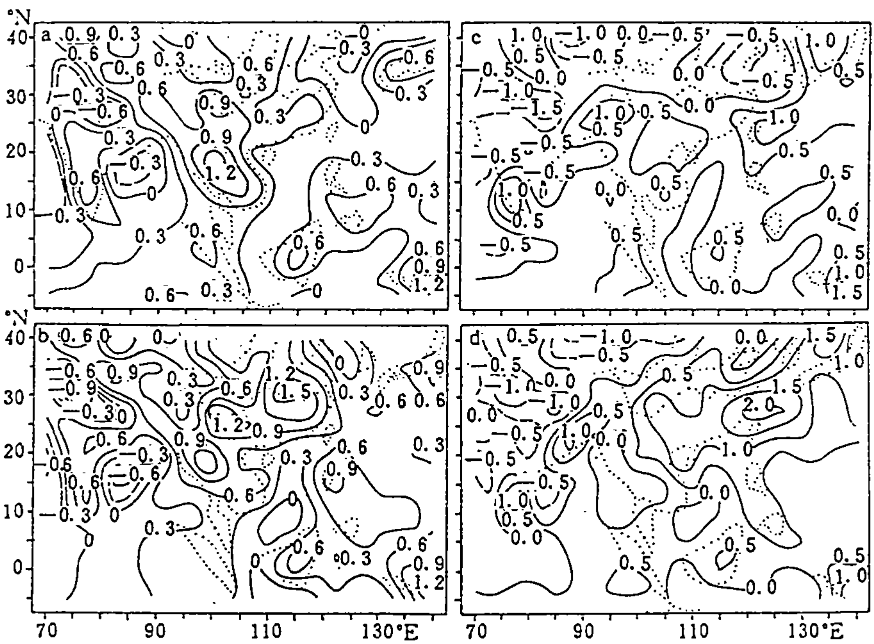

Fig. 5. Five-day mean values of vertically integrated apparent heat source $\langle Q_1 \rangle$ (left) and apparent moisture sink $\langle Q_2 \rangle$ (right) in units of 100 W/m^2 for (a) (c) the pre-onset pentad (6—10 May) and (b) (d) the post-onset pentad (11—15 May).

Around the onset period of the East Asian summer monsoon, large positive $\langle Q_1 \rangle$ areas were mainly situated over land mass, but the increase was significant after the outbreak. From Pentad 2 to Pentad 3 in May, the most pronounced increase of heat sources occurred over the southeastern plateau, the middle and lower reaches of the Yangtze River Valley and regions to its south. There was also a distinct increase of $\langle Q_1 \rangle$ over the oceanic region east of the Philippines. It should also be noted, however, that a heat source center persisted over the Burma-Thailand region, but with little change in intensity. The corresponding distributions of $\langle Q_2 \rangle$ showed that the release of latent heat of condensation also underwent remarkable intensification. The increase of $\langle Q_2 \rangle$ occurred mainly over the coastal region of Southeast China. The center of large $\langle Q_2 \rangle$ was slightly to the south of the large increase area of $\langle Q_1 \rangle$, but almost coincided with the position of the monsoon rainfall belt.

Comparisons of $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ suggested the importance of the release of latent heat of condensation in relation to the heat source increase over the central and eastern China plain, which was consistent with the aforementioned intensification and eastward extension of warm and humid air (southwesterlies) over the low latitude area, and the southward movement of the cold air mass in the mid-latitudes (shown in Fig. 1). On the other hand, the sensible heat flux from the surface over the southeastern plateau dominantly contributes to the heating intensification there. Another fact is that, over the western and coastal areas of the Indochina Peninsula $\langle Q_2 \rangle$ was smaller or even negative, which was contrasted to $\langle Q_1 \rangle$, indicating the significance of sensible heating there.

2. *Time sequences of the heat sources and moisture sinks*

Remarkable changes of the vertically integrated heat sources and moisture sinks can also be clearly recongnized in the longitude-time cross-sections of $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$, respectively. Comparisons of the sections along 20°N, 25°N, 30° N and 32. 5°N (Figures not shown) exhibited that, from Pentads 2 to 3 in May when the low-level southwesterlies commenced over the northern part of the South China Sea, strong heat source increase occurred abruptly and mainly over the southeastern slope of the plateau and the central and eastern China plain (95°E—120°E).

It should be pointed out that, just before the onset of the East Asian summer monsoon, i. e. for Pentads 1 and 2 in May, a conspicuous weakening process of the heat sources and moisture sinks was found. This phenomenon occurred not only on the 7-year mean maps but on those for individual years as well (Figure not shown).

3. *Time series of heat sources and moisture sinks over the South China Sea*

Using data of 1981, Ju et al. (1986) pointed out that the atmospheric heat sources over the South China Sea exhibited remarkable increase corresponding to the East Asian summer monsoon onset of 1981. In this subsection, in order to reveal the 7-year mean features of the time evolution of the heating over this region, we examine the 7-year mean day-to-day time series of the vertically integrated heat source $\langle Q_1 \rangle$ and moisture sink $\langle Q_2 \rangle$ averaged over the northern part of the South China Sea area (10—115°E, 10—20°N), and that of the sea surface temperature (SST) over Xisha Islands (Fig. 6).

The results showed that the abrupt change of $\langle Q_1 \rangle$ occurred around May 20 due to condensation heating. It is about 5—10 days late than the commencement of southwesterlies over the northern part of South China Sea. We noted that the small values of $\langle Q_1 \rangle$ persisted from April 1 until the occurrence of the significant increase. After the obvious increase in $\langle Q_1 \rangle$, however, the values of both $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ kept relatively large, with a manifestation of the modulation of a bi-weekly period oscillation.

On the other hand, the Xisha SST showed a continuous increase to about 29. 5°C until May 10, when the abrupt changes in circulations occurred. After the monsoon onset, the SST fluctuated around 29. 5°C, with a magnitude of deviation of about 0. 5°C.

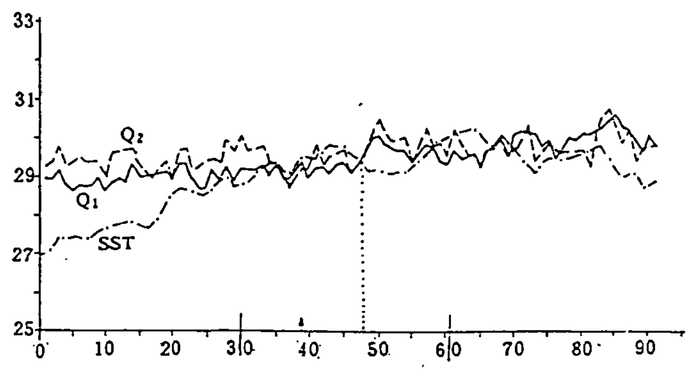

Fig. 6. Seven-year mean time series of the vertically integrated daily apparent heat source ⟨ Q_1 ⟩ (solid line), the apparent moisture sink ⟨ Q_2 ⟩ (100 W/m^2, dashed line), and the sea surface temperature (°C, dotted line) over Xisha Islands. [Subtraction of 29 from values in the figure is needed.]

We found that this feature of changes in Xisha SST occurred in each analyzed year. It may suggest that to some extent the onset of southwesterlies is closely related to the variation of the Xisha SST.

4. *Vertical distributions of the heating over the Tibetan Plateau*

As mentioned above, noticeable increase of the vertically integrated heat sources commenced over the southeastern Tibetan Plateau, mainly due to the sensible heat flux from the surface. Here, we examined the vertical distribution of heating in the atmosphere to discuss the orographic effects.

Fig. 7 shows the longitude-height cross-sections of the monthly mean values of the atmospheric heat source Q_1 and moisture sink Q_2 along 25°N in May. The remarkable feature was that the centers of large values of Q_1 and Q_2 existed above the Tibetan Plateau, with the axis of large values tilting eastward with the increase of height. The features of vertical distribution were similar in April and June, only with different intensity of heating.

From the results discussed above, i. e. there was close relationship between the heating field and the change of the 850-200 hPa layer thickness associated with the onset of the South China Sea monsoon, and the orographic effects of the Plateau was evident on the horizontal and vertical distributions and time evolution of the heating field, we may suggest that heating over the southeastern slope of the plateau might be important to the South China Sea monsoon.

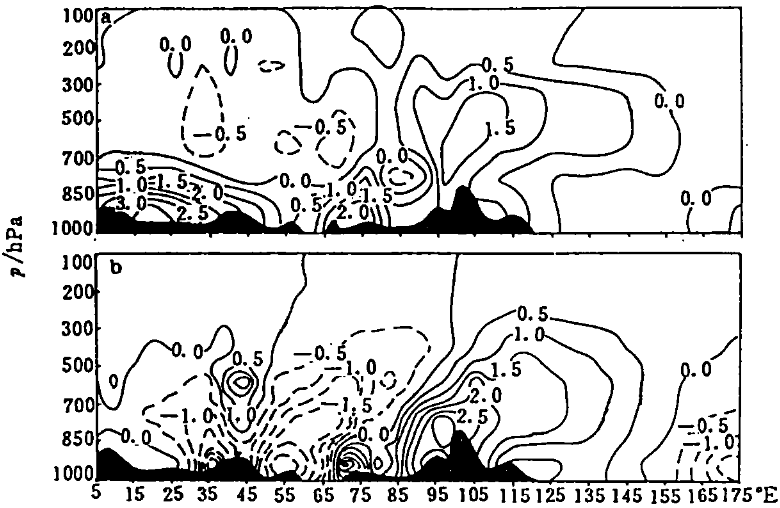

Fig. 7. Longitude-height cross-sections of the monthly mean values of May along 25°N for (a) the heating rate and (b) the drying rate (°K/day).

V. SUMMARY AND CONCLUSIONS

We have described the 7-year mean features of the abrupt changes in the large-scale circulations and those of the heat sources and moisture sinks over Asia around mid-May, in relation to the onset of the South China Sea summer monsoon, using the 7-year ECMWF (1980—1986) data from April to June and the SST at Xisha during the same period.

The major results of this work may be summarized as follows:

a. It was during Pentads 2—3 of May that the first transition of the circulation in Asia occurred in the years analysed, which lead to the onset of the East Asian summer monsoon.

In the upper troposphere, during the onset period mentioned above, abrupt changes in circulations were most clearly recognized by the drastic movement of the South Asian anticyclone center (200 hPa) over Southeast Asia from 10—15°N to 15—20°N, while the easterlies over the low-latitude region intensified and extended northward with the commencement of easterlies over the South China Sea in replacement for the westerlies, and the mid-latitude westerly belt weakened.

At the same time, in the low-level troposphere (850 hPa), drastic changes were characterized by the enhancement of activities of the warm and humid air over the low latitudes, with southwesterlies intensifying and extending eastward to cover the northern part of the South China Sea. On the other hand, the mid-latitude cold air behaved more actively so that the northwesterlies enhanced itself and intruded southward. It was around 30°N that the cold and warm air masses converged, forming quite strong gradients of temperature and humidity over the region from the southeastern periphery of the Tibetan Plateau to the middle and lower reaches of the Yangtze River Valley, and a depression over Southwest China region.

b. Drastic warming of the tropospheric air occurred during the onset of the East Asian summer monsoon over the southeastern plateau / East China plain region. The major warming area almost coincided with the area of strong gradient areas of temperature and humidity in the lower troposphere mentioned above. The warming lead to the change of meridional temperature gradients south of 30°N, causing the adjustment of the pressure wind field.

c. The atmospheric heat sources over the warming regions also showed a distinct increase accompanying the monsoon onset. The sensible heat flux from the ground surface was the dominant factor in the enhancement of heat sources over the southeastern plateau, while the heating increase over the central and eastern China plain was mainly due to the release of the latent heat of condensation, which was related to the activity of the cold and warm air masses.

The weakening of the heat sources and moisture sinks during the pre - onset period (pentads 1—2 of May) needs further research work.

d. The abrupt increase of the area-mean $\langle Q_1 \rangle$ over the northern part of the South China Sea was also found but with delay of 5—10 days as compared to the change in wind fields there. The Xisha SST, however, showed a continuous increase up to about 29. 5°C until May 10, when the southwesterlies developed greatly. After the onset of East Asian monsoon, the SST values kept fluctuating around 29. 5°C with a deviation of about 0. 5°C.

e. There existed orographic effects of the plateau on the distribution of the atmospheric heat sources. It was suggested that the sensible heat flux from the ground surface of the southeastern slope of the Tibetan Plateau might be a key factor to the onset of the East Asian summer monsoon.

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