# THE VARIATION OF THE HEAT SOURCES IN EAST CHINA IN THE EARLY SUMMER OF 1984 AND THEIR EFFECTS ON THE LARGE-SCALE CIRCULATION IN EAST ASIA

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ABSTRACT

The distributions and daily variations of the apparent heat source ( $Q_1$ ) and the apparent moisture sink ( $Q$ ) in East China in the early summer of 1984 have been estimated with the budget calculation method. It has been found that during this time period, there occurred three significant episodes of strong heating that corresponded to the three events of heavy rainfalls prior to, during and post to the onset of mei-yu (plum rains). The peaks of $Q_1$ were generally found at 200 hPa, with the heating rate of 6°–10°C/day observed, while the peaks of $Q_2$ were located at about 700 hPa, with their magnitudes being 12°–20°C/day. The vertical distribution of $Q_1$ and $Q_2$ indicates the importance of eddy vertical flux. In other words, the convective activity plays a very important role in the processes of precipitation in East Asia in the early summer. This result is different from the finding obtained by Luo and Yanai (1984) in their calculation of the case of 1979. They pointed out that in the early summer of 1979 the continuous precipitation dominated the region of East China.

Among the three terms of $Q_1$ and $Q_2$, the maximum contribution was made from the adiabatic term, which was caused by strong ascending motion. The adiabatic cooling produced by this term may compensate for the heating created by the condensation process.

In addition, it has been revealed that the three significant heating processes were closely related to the seasonal transition from spring to summer in East China. One major synoptic event associated with it showed up in the sudden jump of the upper tropospheric, subtropical jet-stream from 30°N to 40°N. So did the planetary frontal zone in East China.

## I. INTRODUCTION

In the early summer of each year, the general circulation in East Asia undergoes a distinct seasonal change, characterized by the occurrence of the "mei-yu" (plum rains) over the middle and lower valley of the Yangtze River, the northward jump of the subtropical jet stream and the subtropical high, and the onset of the summer monsoon in East Asia. Many investigators (Flohn, 1960; Kuo and Qian, 1982) have argued that the variation in the heat sources in the early summer in East Asia may make a significant contribution to that of the large-scale circulation features in this region. The condensation heating produced by the large amount of precipitation during the mei-yu in the early summer is a major component of the heat sources in East Asia (Luo and Yanai, 1984). The present study has estimated the distributions and variation of the apparent heat source and the apparent moisture sink in the early summer of 1984 in order to illustrate the characteristics of the heating field caused by the mei-yu and its effect on the seasonal change in the general circulation in East Asia.

## II. DATA SET AND COMPUTATIONAL ASPECTS

Once daily grid point data (2.5° latitude/longitude horizontal resolution) from the European Center for Medium-Range Weather Forecasts (ECMWF) for the time period from May 16 to July 15 of 1984 were used in the present study. The data include zonal wind component (U) and meridional wind component (V), temperature (T), relative humidity (RH) and the geopotential height (Z) for 7 pressure levels (1000, 850, 700, 500, 300, 200, 100 hPa). All of the above fields are derived from uninitialized analyses obtained from the archives of ECMWF operational analysis system. Only the data for 12 GMT are used in the present study. This observation time corresponds to 2000 hour Beijing Local Time, i.e., early in the evening. Diurnal variations of heat and moisture budgets are not investigated here because of data limitations. The domain under study is the region of 22.5°-37.5°N, 102.5°-122.5°E.

The apparent heat source ($Q_1$) and apparent moisture sink ($Q_2$) were calculated by use of the data of large-scale variables according to the following equations (Yanai et al., 1973):

$$Q_1=\left(\frac{\partial\theta}{\partial t}+\vec{V}\cdot\nabla\theta+\omega\frac{\partial\theta}{\partial p}\right)\left(\frac{p}{p_0}\right)^k, \tag{1}$$

$$Q_2=-\frac{L}{C_p}\left(\frac{\partial q}{\partial t}+\vec{V}\cdot\nabla q+\omega\frac{\partial q}{\partial p}\right), \tag{2}$$

where $\theta$ is the potential temperature, $q$ the specific humidity, $\omega$ the vertical velocity in p-coordinates, $k=R/C_p$, $R$ and $C_p$ the gas constant and the specific heat at constant pressure of dry air, $L$ the latent heat of condensation, and $p_0=1000$ hPa.

The apparent heat source and the apparent moisture sink are interpreted as

$$Q_1=Q_R+L(C-e)-\frac{\partial}{\partial p}\overline{S'\omega'}, \tag{3}$$

$$Q_2=L(C-e)+L\frac{\partial}{\partial p}\overline{q'\omega'}, \tag{4}$$

where $S=C_pT+gz$ is the static energy, $C$ the rate of condensation per unit mass of air, and $e$ the rate of re-evaporation of cloud and rain water. The overbars denote running horizontal means, and the primes denote the deviations from the large-scale values due to small-scale eddies such as cumulus convection and turbulence.

Integrating (3) from $p_t$ (the pressure at which the eddy motion vanishes) to $p_s$ (the pressure at the ground surface) yields

$$\frac{1}{g}\int_{p_t}^{p_s}(Q_1-Q_R)\,dp=\frac{L}{g}\int_{p_t}^{p_s}(C-e)\,dp-\frac{1}{g}(\overline{S'\omega'})_{p=p_s}$$

$$\approx Lp+\rho_sC_p(\overline{T'W'})_{p=p_s}=Lp+S, \tag{5}$$

where $\rho_s$ is the density of surface air, $W$ the vertical velocity, $p$ and $S$ are the amount of precipitation and sensible heat flux per unit area at the surface, respectively.

Similarly, from (4) we obtain

$$\frac{1}{g}\int_{p_T}^{p_s} Q_2\,dp=\frac{1}{g}\int_{p_T}^{p_s}(C-e)\,dp-\frac{L}{g}\left(\overline{q'\omega'}\right)_{p=p_s}$$

$$\approx Lp-\rho_s L\left(\overline{q'W'}\right)_{p=p_s}=L(p-E), \tag{6}$$

where $E$ is the eddy moisture flux (evaporation) per unit area at the surface.

The vertical $p$-velocity, $\omega$, in equations (1) and (2), was calculated kinematically by integrating the mass continuity equation. The effect of terrain at the earth's surface, rather than at a pressure surface was incorporated by the estimate of the lifting of the sloping topography, i.e.,

$$\omega=-\frac{p_s}{RT_s}g\left(\frac{u_s}{a\cos\varphi}\frac{\partial h_m}{\partial\lambda}+\frac{v_s}{a}\frac{\partial h_m}{\partial\varphi}\right), \tag{7}$$

where $p_s$, $T_s$, $u_s$ and $v_s$ are the surface pressure, the surface temperature, the surface zonal wind component and the surface meridional wind component, respectively. The thus obtained vertical velocity is adjusted in the vertical based on the O'Brien scheme (O'Brien, 1970). In the adjustment process, we assumed that the $\omega$ at the top of the column (100 hPa) is given by

$$\omega_T=\left[\frac{\partial\theta}{\partial t}+\vec{V}\cdot\nabla\theta-\frac{(p_0/p)^k}{C_p}Q_R\right]\Big/-\frac{\partial\theta}{\partial p}, \tag{8}$$

where $Q_R$ is the radiative cooling rate computed by Dopplick (1972).

In this study, we attempt to use (1)-(6) to determine $Q_1$ and $Q_2$ and their individual components, and infer the nature of heating processes from the horizontal and vertical distributions of $Q_1$ and $Q_2$.

## III. THE HORIZONTAL AND VERTICAL DISTRIBUTIONS OF $Q_1$ AND $Q_2$

Fig. 1 (a) is the time variation of the profiles of the area-averaged $Q_1$ and $Q_2$ in the

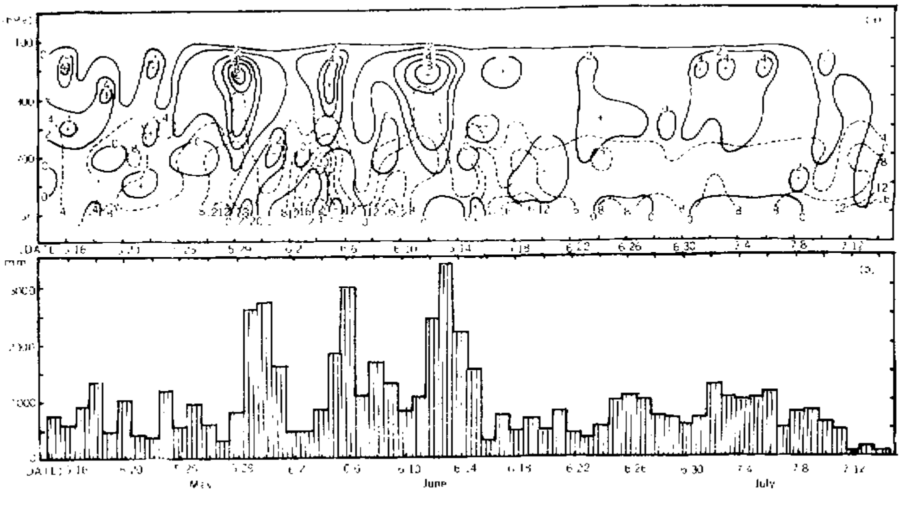

Fig. 1. (a) The time variation of the area-averaged profiles of $Q_1$ (solid lines) and $Q_2$ (dashed lines) in East China in the early summer of 1984. Unit: °C/day.
(b) Same as Fig. 1 (a), except for daily areal total rainfall amount, which is obtained by summing daily rainfall amounts at all grid points in the studied domain. Unit: mm/day.

early summer of 1984 in the eastern China. The distinct feature showed up in the presence of the three significant peaks of the positive $Q_1$ and $Q_2$ at upper level and below 700 hPa, respectively. The peaks of $Q_1$ were generally found at 200 hPa, with the heating rate of 6°–10 °C/day observed, while the peaks of $Q_2$ were located at about 700 hPa, with their magnitudes being 12°–20°C/day. The above mentioned three episodes of strong heating apparently correspond to the three events of heavy rainfalls prior to, during and post to the onset of mei-yu (June 7) (Fig-1(b)). The comparison made between the vertical distributions of $Q_1$ and $Q_2$ indicates the importance of cumulus vertical flux because the profiles of $Q_1$ and $Q_2$ differ from each other and there is a separation in the levels of peak values of $Q_1$ and $Q_2$ (Luo and Yanai, 1984). In other words, the convective activity plays a very important role in the process of precipitation in East Asia in the early summer. This result is different from the finding obtained by Luo and Yanai (1984) in their calculation of the case of 1979. They pointed out that in the early summer of 1979 the continuous precipitation dominated the region of East China. The different circulation conditions of 1979 and 1984 may be responsible for the differences in the nature of heating processes. In 1984, the summer monsoon in the eastern China is much stronger and set in much earlier (June 7) than in 1979 (June 19). The low level vorticities and lows, the major rain-bearing synoptic systems for 1984, frequently moved eastward through the eastern China. They may often initiate and enhance the convective precipitation as revealed by many observations.

In addition, the peaks of $Q_1$ for 1979 were found at about 400 hPa, whereas in 1984 the peaks of $Q_1$ were found at 200 hPa. This fact also reflects the obvious importance of convective activity for the precipitation of 1984. Fig. 2 (a)-(c) are the mean profiles of the area-averaged $Q_1$ and $Q_2$ for the different periods respectively. Prior to mei-yu (Fig. 2(a)), the heating ($Q_1$) was weak, with the maximum (2°C/day) found at 500 hPa. Another secondary maximum of heating was found at 850 hPa. The peaks of $Q_2$ were at 700 hPa and near the ground. During the major rainy episodes (Fig. 2 (b)), the heating significantly augmented,

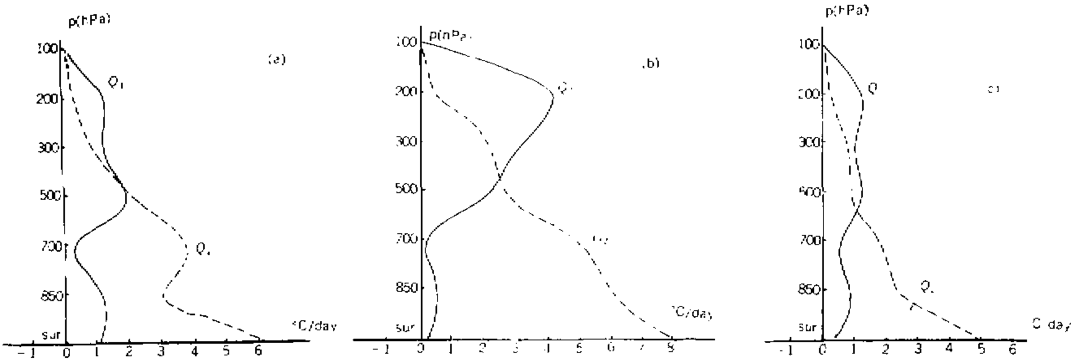

Fig. 2. (a) The mean profiles of the area-averaged $Q_1$ (solid lines) and $Q_2$ (dashed lines) for the time period from May 16 to May 28. Unit: °C/day.

(b) Same as Fig. 2 (a), except for the time period from May 29 to June 15.

(c) Same as Fig. 2 (a), except for the time period from June 16 to July 15.

with the maximum heating rate of 4°C/day going up to 200 hPa. As previously stated, this may indicate the dominating contribution of convective heating to $Q_1$ . The low level weak heating maximum (at 850 hPa) might suggest the presence of low clouds. $Q_2$ had the maximum near the surface and decreased upward. Post to mei-yu (Fig. 2(c)), the heating rapidly weakened, with the maximum heating rate being only 1.3°C/day in the upper troposphere. This profile may be associated with the situation of suppressed convective activity.

Fig. 3 is the horizontal pattern of total rainfall amount for mei-yu period from June 5 to June 16. Three major areas of large rainfall amount exceeding 200 mm may be noted in the middle and lower valley of the Yangtze River, with the maximum one in the lower valley. Comparing Fig. 3 with Fig. 4, one can find significant differences between the horizontal distributions of the vertically-integrated heat source and moisture sink, and between them and the observed precipitation amounts in the lower valley of the Yangtze River. Therefore, from Eqs. (5) and (6), it can be inferred that there exists a strong sensible heat flux or evaporation from the surface. But, in the middle valley of the Yangtze River the heating (other than the radiative heating $Q_R$ ) is primarily due to the condensation process, because the vertically integrated values of $Q_1 - Q_R$ and $Q_2$ are similar to each other and they also are close to the observed precipitation pattern in this area.

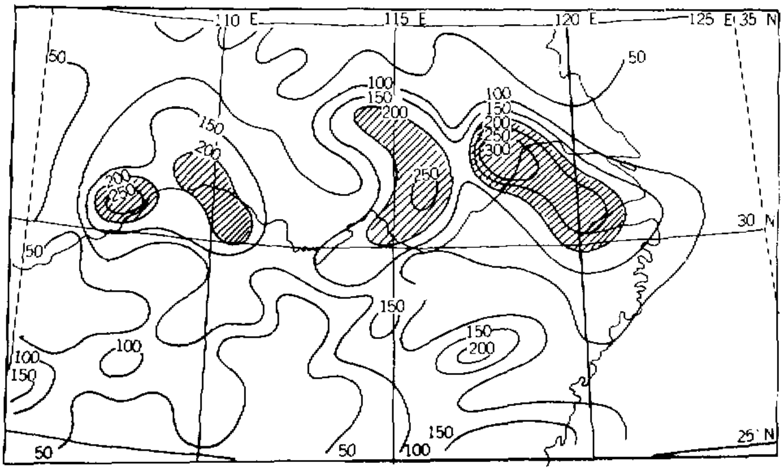

Fig. 3. The pattern of the total rainfall amount for the major rainy period from June 5 to June 16, 1984. Unit: mm.

## IV. THE CONTRIBUTIONS OF THE INDIVIDUAL COMPONENTS OF $Q_1$ AND $Q_2$

Figure 5 is the mean profiles of the individual components of $Q_1$ and $Q_2$ for the major rainy episode from May 28 to June 15. The maximum contribution to $Q_1$ (Fig. 5 (a)) has been made from the vertical advective term. The local change term is small throughout the layer of the troposphere. The horizontal advective term has made the significant contribution to $Q_1$ above 300 hPa and 700 hPa. For $Q_2$ profile, the three components have nearly the same order of the magnitude. The area-averaged vertical velocity for the different time periods are shown in Fig. 6. The strongest upward motion was observed at 300 hPa during the major

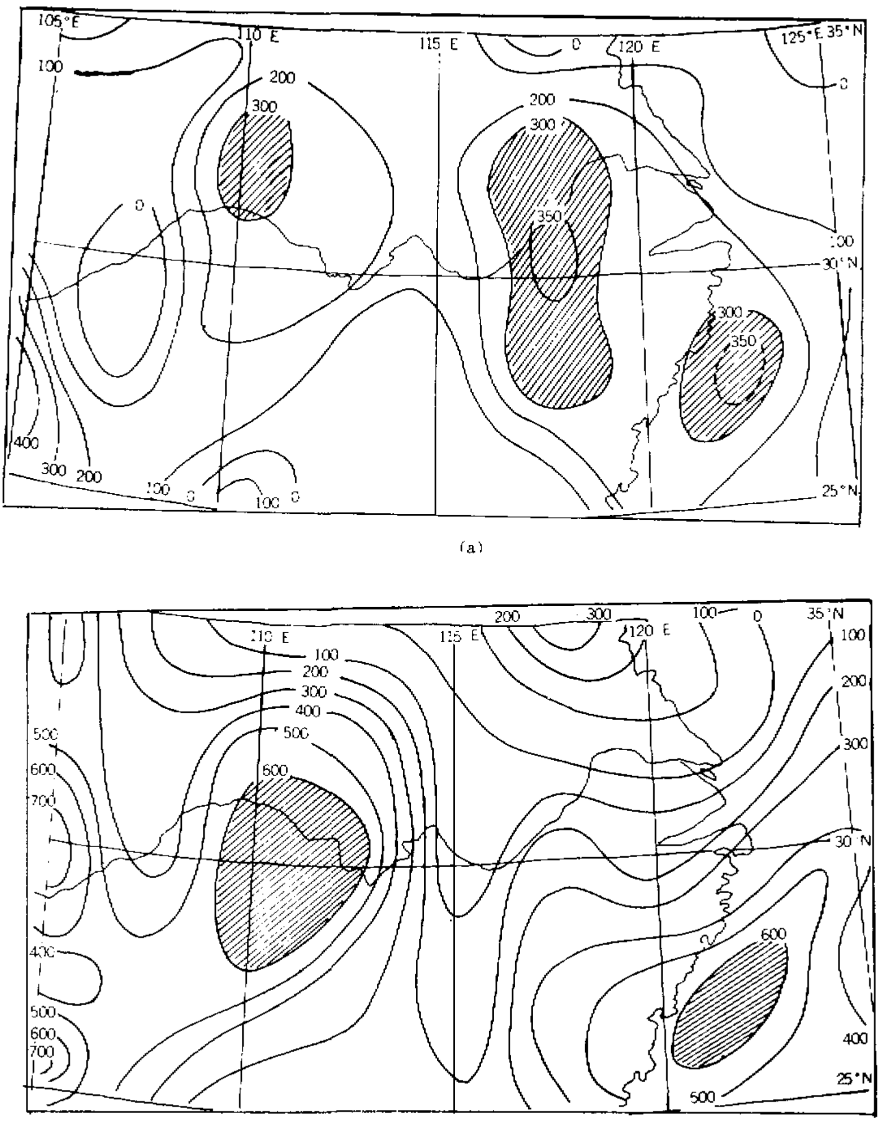

Fig. 4. (a) The mean horizontal distribution of the vertically-integrated $Q_1$ for the time period from June 5 to June 16. Unit: W/M$^2$.

(b) Same as Fig. 4 (a), except for the vertically-integrated $Q_2$.

rainy episode. This fact is consistent with the large positive value of the vertical advective term and $Q_1$. Fig. 7 further indicates the time variations of the vertical advective terms and the horizontal advective terms of $Q_1$ and $Q_2$, and area-averaged vertical velocity. They show the obvious mutual consistency. Generally, the contributions of the horizontal

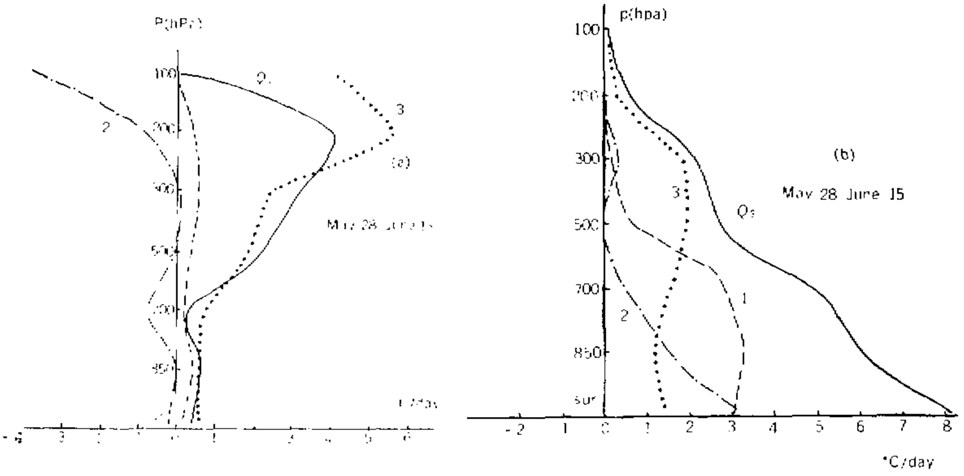

Fig. 5. (a) The mean profiles of the individual components of $Q_1$ for the major rainy episode from May 28 to June 15. Curve "1" denotes the local change term; Curve "2" the horizontal advective term; Curve "3" the vertical advective term. Unit: ℃/day.
(b) Same as Fig. 5 (b), except for the individual components of $Q_2$.

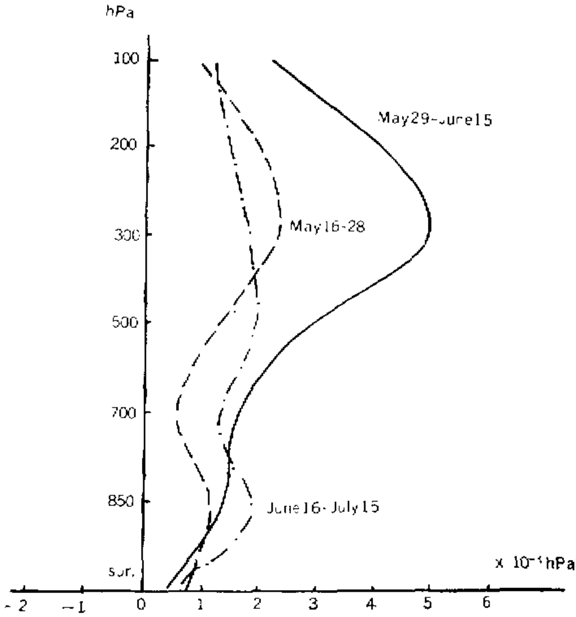

Fig 6. The mean profiles of the area-averaged vertical velocity ( $\omega = dp/dt$ ) for the different time periods. The dashed line denotes the period prior to mei-yu (from May 16 to May 28). The dashed-dotted line represents the major rainy period (from May 29 to June 15). The solid line denotes the time period post to the major rainy episode (from June 16 to July 15). Unit: $10^{-4}$ hPa/S.

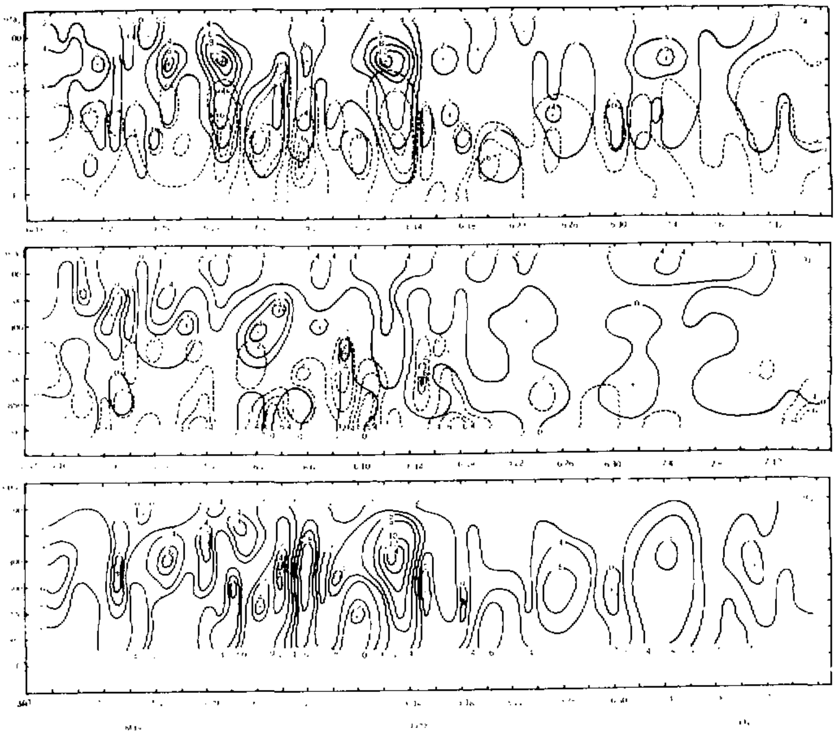

Fig. 7. (a) Same as Fig. 1 (a), except for the vertical advective terms of $Q_1$ (solid lines) and $Q_4$ (dashed lines).

(b) Same as Fig. 1 (a), except for the horizontal advective term.

(c) Same as Fig. 1 (a), except for the vertical velocity ($\omega$). Unit: $10^{-4}$ hPa/S.

and vertical advective terms are nearly opposite.

## V. THE POSSIBLE EFFECT OF HEAT SOURCES IN EAST CHINA ON THE SEASONAL CHANGE IN THE LARGE-SCALE CIRCULATION

It has been pointed out that the general circulation over East Asia undergoes a distinct seasonal change in the early summer (normally in June). One major event characterizing this change is the nearly simultaneous occurrence of the onset of the summer monsoon and the sudden northward shift of the subtropical westerly jet stream in East Asia, and the commencement of the mei-yu in the Yangtze River. This fact reflects the possible thermally-forced effect of the heat source caused by much precipitation around the onset of the mei-yu on the large-scale circulation in East Asia. From Fig. 8, the time variation of the vertically-integrated $Q$ along 30°N, it has been seen that the variation in the vertically-integrated apparent heat source was in good accordance with that of precipitation amounts shown in Fig. 1(b). The three episodes of the significant heating along 30°N occurred during the time period of the mei-yu of 1984.

After about two days of the termination of the first episode of significant heating (May 29-June 2), the maximum of the westerly winds at 200 hPa at and to the south of 30°N sud-

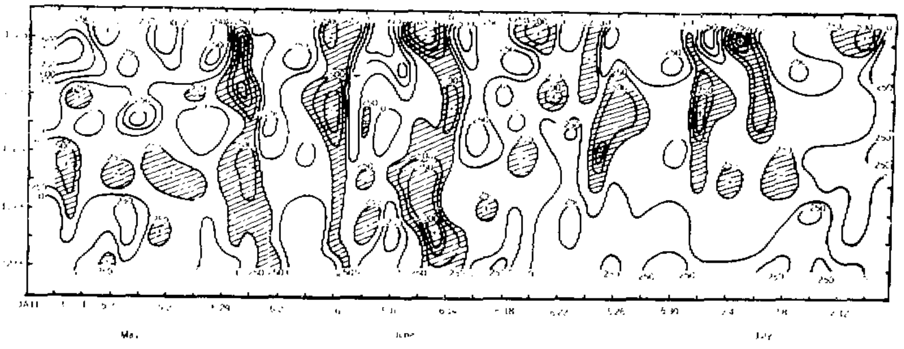

Fig. 8. The time-longitude section of the vertically-integrated $Q_1$ along 30°N. The areas with the values greater than 250 W/m² are shaded. Unit: W/m².

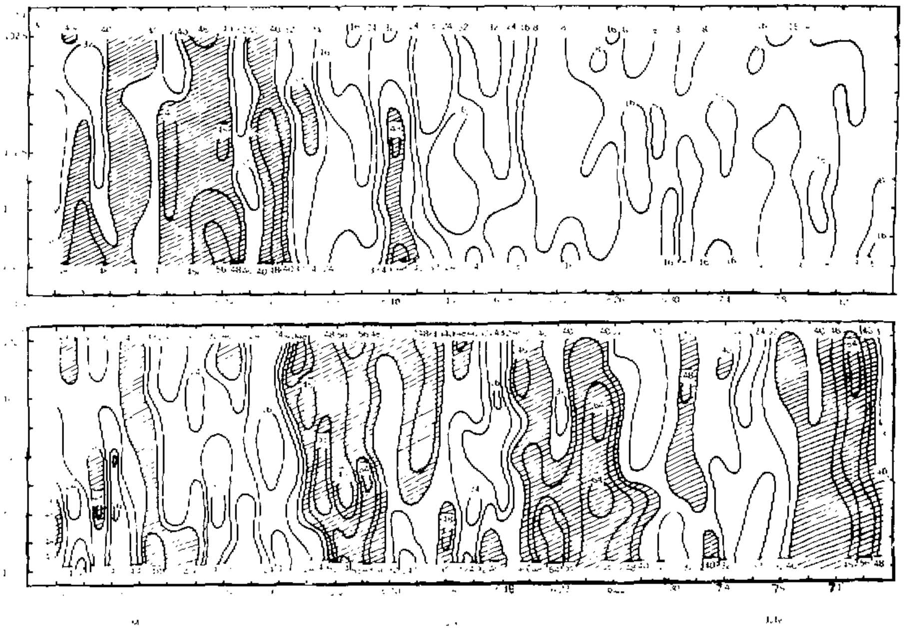

Fig. 9. (a) The time-longitude section of westerly wind speed at 200 hPa along 30°N in the early summer of 1984. Unit: m/s.

(b) Same as Fig. 9 (a), except for 40°N.

denly disappeared and rapidly jumped northward to about 40°N. From Fig. 9, one may see this out-phase variation in the westerly winds at 200 hPa at 30°N and 40°N, i.e., with the rapid decrease in westerly wind speed at 30°N from June 3 corresponding to concurrent increase in westerly wind speed at 40°N. The variations are obviously associated with the significant variation in heat sources at 30°N, as shown in Fig. 8. Especially, the northward shift of the position of the westerly jet stream most significantly occurred during the two major rainfall episodes of meiyu, i.e., from June 4 to June 10 and from June 12 to June 16. Due possibly to the thermal forcing caused by the successive three rainfalls during the mei-yu, the westerly jet stream at 30° N completely disappeared since June 12, and meanwhile the westerly jet stream was steadily established at 40° N.

The above-described variation may provide an evidence that the seasonal northward shift of the subtropical westerly jet stream from spring to summer is not only confined at the longitudinal range of the Tibetan Plateau, but also occurs in the other places where there exists the thermal forcing.

## VI. CONCLUDING REMARKS

The main findings of this study may be summarized as follows:

(1) For the period of the mei-yu of 1984, the convective precipitation has made the very significant contribution to the apparent heat source, with peak of the area-averaged $Q_1$ generally found at 200 hPa.

(2) Among the three terms of $Q$ and $Q_2$, the maximum contribution was made from the adiabatic term, which was caused by strong ascending motion. The adiabatic cooling produced by this term may considerably compensate for the heating created by the condensation process.

(3) The three significant heating processes during the major rainy episode in the early summer of 1984 were closely related to the seasonal transition from spring to summer in East China, which was mainly characterized by the sudden jump of the subtropical jet-stream from 30° N to 40° N.

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