Heat and Moisture Budgets over China during the Early Summer Monsoon

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Abstract

Synoptic sounding and surface data are used to calculate heat sources and moisture sinks over China during the pre-Meiyu and Meiyu periods of 1987, 1988 and 1989.

The horizontal distributions of the vertically integrated heat source $<Q_1>$ and moisture sink $<Q_2>$ show that during the pre-Meiyu, the maximum heating is located in southern China in a band parallel to the coastline with a secondary maximum over the Yangtze Valley. When the Meiyu sets in, there is an increase in the heating in the Yangtze region; however, a band of heating continues over southern China during the Meiyu. In 1988 there is a prominent third band of heating over northern China. There is pronounced diurnal variation in rainfall during both the pre-Meiyu and Meiyu periods due to land/sea and mountain/valley breezes. At night, maximum rainfall occurs at lower elevations in the prominent basins of interior China. During the day, rainfall maxima shift to the region between the coast and the coastal mountain ranges and other areas favored by upslope flow.

The vertical profiles of the heat source Q_1 and moisture sink Q_2 averaged over subregions of China show that during both the pre-Meiyu and Meiyu, the precipitation type over the Yangtze region is a mixture of convective and stratiform, whereas over southern China deep cumulus convection predominates. The heating and drying in southern China occur throughout the whole troposphere, but low-level moistening occurs in the Yangtze region. The pattern in southern China resembles that observed in the deep tropics, whereas that in the Yangtze region is similar to that observed with midlatitude mesoscale convective systems where low-level evaporation is important.

1. Introduction

Over east Asia, the transition period from the northeast winter monsoon to the southwest summer monsoon begins in May. From early May to mid-June, precipitation is concentrated in southern China. Following this period, there is an abrupt shift in the zone of maximum rainfall to the Yangtze River region (Tao and Ding, 1981), making the onset of what is termed the *Meiyu* in China and the *Baiu* in Japan.[1] After mid-July, northern China has its maximum precipitation. The precipitation and circulation characteristics of the Meiyu and Baiu have been reviewed by Tao and Chen (1987), Ninomiya and Murakami (1987) and Ding (1992).

Heavy rainfall during the May–July period occurs pimarily along the Meiyu front. In contrast to the polar front, the Meiyu front is characterized by a weak temperature gradient, although the moisture gradient is pronounced. A strong southwesterly low-level jet is associated with the Meiyu front (Matsumoto *et al.*, 1971; Akiyama, 1973) as is a lower-tropospheric trough extending from the Sea of Japan to central China (Chen and Chang, 1980; Lau and Li, 1984; Ninomiya and Muraki, 1986). The north-

[1]Since precipitation over China is the focus of this study, the term *Meiyu* will be used here.

ward advance of the heavy rainfall is controlled by marked changes in the large-scale circulation from May through July over both Eurasia (Murakami and Ding, 1982) and east Asia (Akiyama, 1973; Luo and Yanai, 1983; Murakami and Huang, 1984; Kato, 1985 and 1989; Ninomiya and Muraki, 1986).

The heavy rainfall along the Meiyu front typically occurs within medium-scale disturbances, which have been studied extensively in the vicinity of the Japan Islands using satellite and radar data (Ninomiya and Akiyama, 1971, 1972 and 1973; Yoshizumi, 1977; Akiyama, 1978). Meso-α scale cloud clusters, with embedded meso-β scale features, are a common feature of these disturbances as they pass from the China mainland to the Japan Islands (Ninomiya *et al.*, 1981; Akiyama, 1984a and b). Akiyama (1984a and b) found that a very large cloud cluster that occurred in 1979 consisted primarily of deep convection over China, but develped into a combined convective-stratiform structure over the Japan Islands. It also exhibited a pronounced diurnal variation with a maximum intensity during the early morning hours.

Several recent studies have explored the cloud structure of the Meiyu front in yet greater detail. Akiyama (1989) examined the characteristics of the convection and circulation along the Meiyu front that occurred during July 1982 and found significant differences between the China continent, the Japan Islands and the NW Pacific areas. Over the continent, GMS IR data revealed mesoscale cloud clusters having diameters ~500 km consisting of primarily convective clouds. A strong diurnal cycle was evident with pronounced topographic effects: convective development was preferred in the basin areas in the early morning and at the higher elevations in the evening. Over the NW Pacific the cloud systems were larger (~1000 km), having periods of a few days and consisting of narrow convective bands and wide stratiform clouds. The structure over the Japan Islands showed characteristics intermediate to those over the continent and the NW Pacific.

Ninomiya (1989) has investigated cloud distributions over east Asia and the NW Pacific for the Meiyu period of 1979 using GMS nephanalysis charts. The Meiyu was divided into four periods and clouds were classified into four categories based on the horizontal scale of the cloud systems and their vertical development (convective or stratiform). He obtained the following results for eastern China.

Pre-Baiu (1–20 May): Convective clouds over extreme southern China with stratiform clouds to the north extending into the Yangtze Valley.

Early Baiu (21 May–10 June): Convective clouds over southern China and the northern Yangtze Valley with stratiform clouds between.

Peak Baiu (11 June–20 July): Convective clouds over the Yangtze Valley and parts of southern China.

Post-Baiu (21 July–10 August): Convective clouds over northern China and near the southeast China coast.

Radar data were not available to confirm the satellite-based inferences concerning the nature of the precipitation systems. It is therefore useful to attempt to confirm these results by other methods. In particular, we will use synoptic-scale heat and moisture budgets to infer the structure of the precipitation systems over China during the Meiyu period.

In an earlier study of this nature, Luo and Yanai (1984) computed daily and 40-day mean heat sources and moisture sinks over the Tibetan Plateau and surrounding area (including the Yangtze region and southern China) using the FGGE II-b data for the period 26 May to 4 July, 1979. They pointed out that there is a predominance of stratiform rainfall over the entire southern China and Yangtze regions during the Meiyu season, although precipitation becomes more convective toward the latter part of June and during July. In a related study, Kato (1985) detected an abrupt change in the thermal structure of the Meiyu front along with associated changes in the vertical heating distributions during late May of the FGGE year. The change in frontal structure was attributed to the onset of strong sensible heating over northern China during late spring. Nitta (1983) also computed heat and moisture budgets over China for the FGGE year, concentrating on results over the eastern portion of the Tibetan Plateau.

In a more recent study, Ding and Wang (1988) have computed heat and moisture budgets over the Yangtze River region for the 1983 Meiyu. Based on the vertical distributions of heating and moistening, they found that prior to and during the Meiyu, there was a predominance of continuous or stratiform precipitation over the Yangtze Valley. However, quite different results were obtained for the 1984 Meiyu, when precipitation was fount to be mainly convective in nature (Ding and Hu, 1988). Ding (1992) points out that these findings indicate a pronounced interannual variability of the heat sources and sinks over the Yangtze region during the Meiyu.

Recently, Johnson and Bresch (1991) studied the characteristics of Meiyu precipitation systems over Taiwan using the TAMEX (Taiwan Area Mesoscale Experiment, 1987) sounding the radar data. They found that major rainfall events in Taiwan were linked to the passage of midlatitude disturbances and typically consisted of both deep convection and stratiform precipitation. Deep convection was primarily pre-frontal or frontal, while the stratiform precipitation was post-frontal, presumably in association with overrunning and orographic lifting. Their results were supported by observational studies based on the May–June 1977–1982 Heavy Rain-

fall Experiment over southern China during the pre-Meiyu period (Huang *et al.*, 1986). The Heavy Rainfall Experiment indicated that most of the heavy monsoon precipitation over southern China appears in pre-frontal warm zone conditions (eleven of twelve cases of heavy rainfall over southern China in 1977, 1978, 1979 were mainly or partly warm zone precipitation).

The heat and moisture budget studies of Nitta (1983), Luo and Yanai (1984) and Kato (1985) were conducted for the FGGE year and those by Ding and Wang (1988) and Ding and Hu (1988) for 1983 and 1984, respectively. The Johnson and Bresch (1991) study was for the 1987 TAMEX year and covered a limited area. It is important to establish the representativeness of these previous findings by investigating heat and moisture budgets over China and the surrounding region over a several-year period. In addition, it is important to understand regional differeces in precipitation systems within China. Considering that several years of analysis are required, we must rely on the routine sounding data for our study.

In this paper, spatial and temporal variation of heat sources and moisture sinks over China are determined using routine sounding data. Due to data gaps and the limited vertical resolution of many of the soundings, the main emphasis will be on long-period (pre-Meiyu and Meiyu) characteristics of heating and moistening distributions rather than their structure for individual convective events.

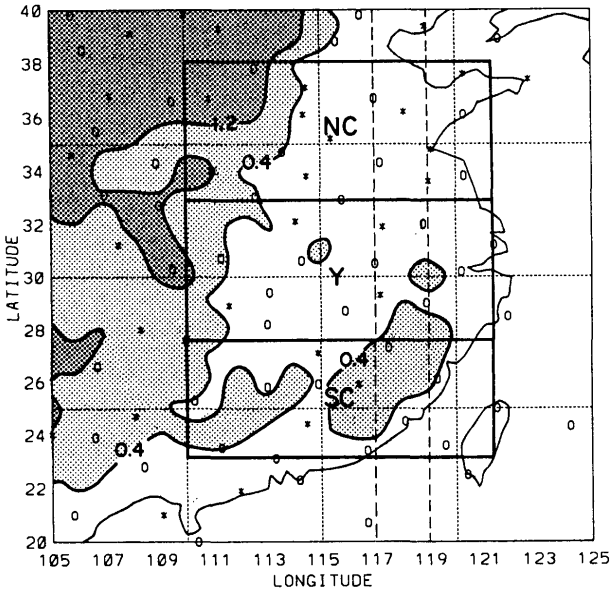

Fig. 1. Rawinsonde stations used in the analysis. Asterisks refer to stations having an average of less than five levels of data. The subregions SC, Y and NC represent Southern China, the Yangtze River region and Northern China, respectively. Dashed lines along 117 and 119°E enclose boundary for vertical cross-sections in Figs. 15 and 16. Elevations >0.4 km (light shading) and >1.2 km (dark shading) are indicated.

2. Data nad analysis procedures

The data used in this study are sounding and surface data (including daily precipitation amount) from 1 May to 31 July during 1987 to 1989 in an area covering from 20 to 40°N and 105 to 125°E. All data were obtained from the National Center for Atmospheric Research (NCAR). Figure 1 shows the distribution of the approximately 90 rawinsonde stations in the analysis domain. Some stations typically only report a few vertical levels. Stations with an average of less than five levels of data are indicated by an asterisk in Fig. 1. Few observations are located in the oceanic area near the south and east boundaries; consequently, results in these areas are considered not reliable. We divide the entire analysis domain into three subregions: region SC (24 to 28°N), representing southern China; region Y (28 to 33°N), representing the Yangtze River region; and region NC (32 to 38°N), representing northern China. Cross sections in our study are along 119°E (dashed line in Fig. 1).

Twice-daily (0000 and 1200 UTC) wind, temperature, geopotential height and moisture data at the ground and at reported pressure levels are first vertically interpolated to 25-hPa levels. The original sounding data consist of wind, geopotential height, temperature and moisture at standard and significant levels (but no moisture data above 300 hPa). Then the data are objectively analyzed on a 1°×1° grid mesh using a modified Barnes (1964) scheme.

The vertical p-velocity ω used in the heat and moisture budgets is obtained from the horizontal divergence by upward integration of the continuity equation in sphereical coordinates,

$$\frac{1}{a\cos\phi}\left[\frac{\partial u}{\partial\lambda}+\frac{\partial}{\partial\phi}(v\cos\phi)\right]+\frac{\partial\omega}{\partial p}=0 \qquad (1)$$

at each grid point with the surface boundary condition, $\omega=\omega_s$ at $p=p_s$.

The objectively analyzed surface winds and topographic height h are used to calculate the orographically forced vertical motion at the surface by (following Luo and Yanai, 1983)

$$\omega_s=-g\rho_s\left(\frac{u_s}{a\cos\phi}\frac{\partial h}{\partial\lambda}+\frac{v_s}{a}\frac{\partial h}{\partial\phi}\right) \qquad (2)$$

where g is gravity and $\rho_s=p_s/RT_s$, the density of surface air.

In computing ω, a linear adjustment of the divergence, increasing with height, is used to make the ω at 100 hPa small (following O'Brien, 1970)

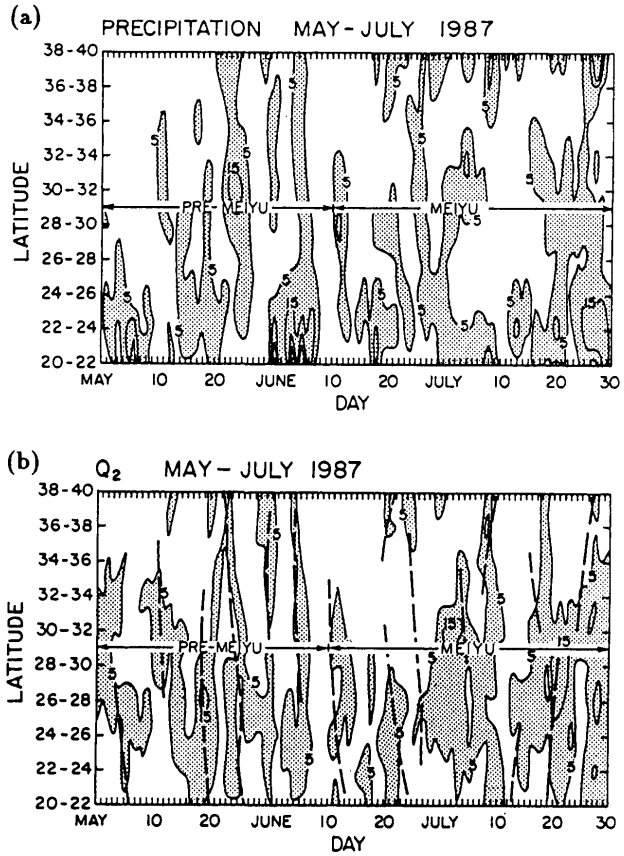

Fig. 2. Latitude-time sections of (a) precipitation and (b) vertically integrated drying rate [Q_2] for May–July 1987. Units are mm d^{-1}. Pre-Meiyu and Meiyu periods are indicated. Axes of precipitation maxima in (a) have been transferred to (b).

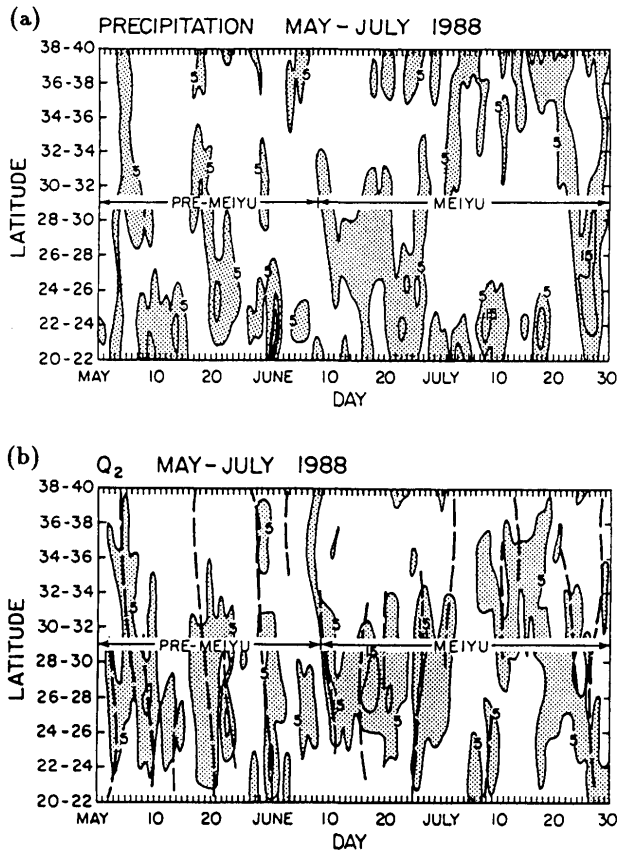

Fig. 3. As in Fig. 2, except for 1988.

$$\omega_{adj}(k) = \omega(k) - \frac{(1-\alpha)k^2}{N^2}\omega_{100} \tag{3}$$

where ω_{100} is the value of ω at 100 hPa before adjustment, k is the kth vertical layer (from surface to 100 hPa), N is the number of layers and $\alpha = 0.1$ Rather than forcing ω to be zero at 100 hPa, we make use of the empirical relation that the actual ω at 100 hPa is one-tenth of ω_{100}.

The apparent heat source Q_1, and the apparent moisture sink Q_2 are computed by

$$Q_1 = c_p\left[\frac{\partial\bar{T}}{\partial t} + \bar{\boldsymbol{V}}\cdot\nabla\bar{T} + \left(\frac{p}{p_0}\right)^{\kappa}\bar{\omega}\frac{\partial\bar{\theta}}{\partial p}\right]$$

$$Q_2 = -L\left[\frac{\partial\bar{q}}{\partial t} + \bar{\boldsymbol{V}}\cdot\nabla\bar{q} + \bar{\omega}\frac{\partial\bar{q}}{\partial p}\right],$$

where T is temperature, θ potential temperature, q mixing ratio of water vapor, $\kappa = R/c_p$, R and c_q gas constant and the specific heat at constant pressure of dry air, respectively, L latent heat of condensation, $p_0 = 1000$ hPa and overbar refers to a horizontal average.

Daily mean values of Q_1 and Q_2 for a given level are obtained by the procedure of Luo and Yanai (1984) that uses a 1-2-1 time filter (based on 12-h data) for the horizontal and vertical advective terms. Period-mean values of Q_1 and Q_2 are computed by summing daily mean values for the peiods and dividing by the number of days. The vertical integral of Q_2 will be compared to period total precipitation.

There are some inaccuracies in the derived budgets due to (1) irrecoverable errors in the data and (2) progressively fewer observations at higher levels. By far, the most frequent occurrence of errors is in the upper troposphere, above 300 hPa. In order to deal with this problem, excessively large values of the *time-filtered* Q_1 and Q_2 (positive values >25 K d^{-1} and negative values below -15 K d^{-1}) have been excluded from the monthly averages. This procedure led to the removal of 29.4 % of the values above 300 hPa, but only 5.9 % of the values below. Values exceeding these thresholds are considered not physically realistic above 300 hPa and only occasionally below on the scales examined here, especially considering the fact that filtered values are used.

Experiments with larger thresholds permitted fewer discarded values, but allowed for potentially greater errors in the monthly averages. It is felt that the impact of this procedure below 300 hPa is

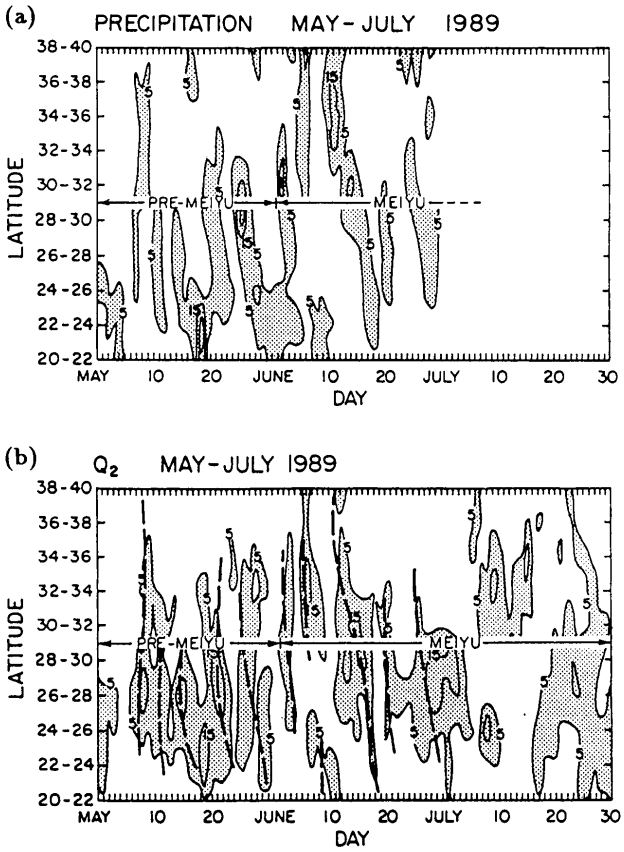

Fig. 4. As in Fig. 2, except for 1989.

minimal, but may reduce the reliability of the results above. Therefore, least emphasis will be given to results in the upper troposphere (above 300 hPa).

3. Selection of pre-Meiyu and Meiyu periods

As described by Tao and Chen (1987), the summer monsoon over eastern Asia advances northward in a stepwise fashion. The average onset in extreme southern China is in early May. Typically, the onset moves slowly northward in southern China through the middle of May, then stagnates in late May before moving rapidly northward in early June, arriving in the Yangtze Valley by mid-June (where it is then referred to as the Meiyu front). The Meiyu front remains in the Yangtze Valley through the first one-to-two weeks of July and then migrates quickly northward, arriving in northern China in late July.

The summer monsoon over China and Japan has been separated into periods of varying length by various authors. Murakami and Huang (1984) divided the 1979 summer monsoon into two periods based on precipitation records from three areas similar to those used in this study. The 1979 summer period was divided into four intervals—pre-, early, peak and post-Mieyu/Baiu—by Ninomiya and Muraki (1986) and Ninomiya (1989), again based on precipitation time series. A similar approach is

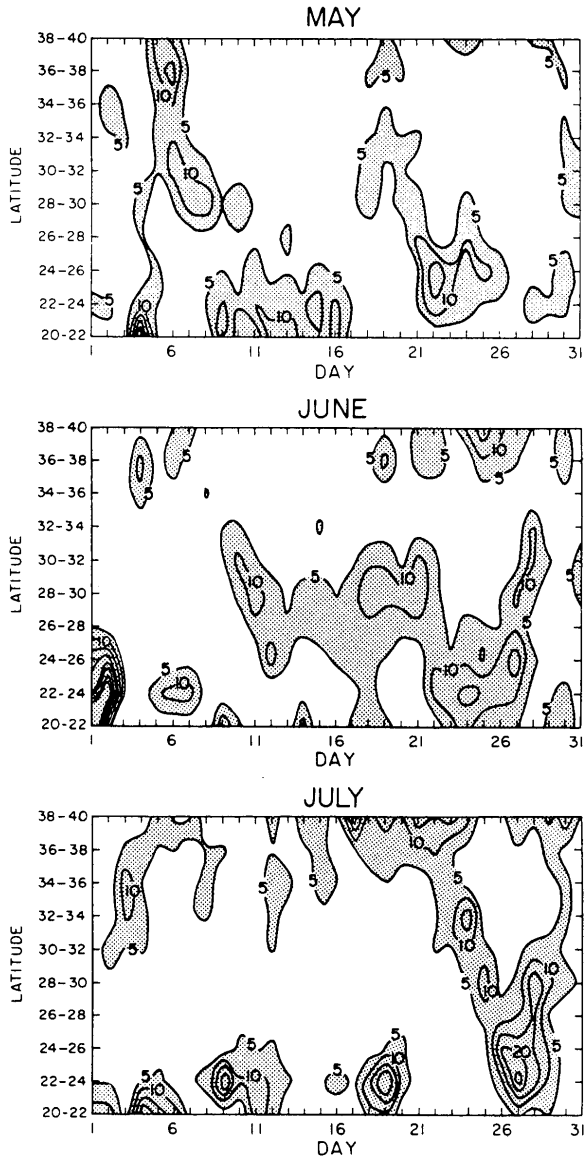

Fig. 5. Latitude-time section of precipitation for May–July 1988. Units are mm d^{-1}.

adopted in this study. For ease of comparison with previous works, two periods are selected from 1 May to 31 July: the pre-Meiyu and the Meiyu, where Meiyu is defined as the period when the rain arrives in the Yangtze Valley. Further subdivisions into four periods are not attempted due to limitations of the operational sounding data set.

To determine the pre-Meiyu and Meiyu periods, time series of daily precipitation and vertically integrated drying rate Q_2/c_p have been computed from

$$[P(t,lat)] = \frac{1}{13}\sum_{i=1}^{13} P(t,i,lat) \tag{4}$$

$$[Q_2(t,lat)] = \frac{1}{13}\sum_{i=1}^{13} \langle Q_2(t,i,lat)\rangle \tag{5}$$

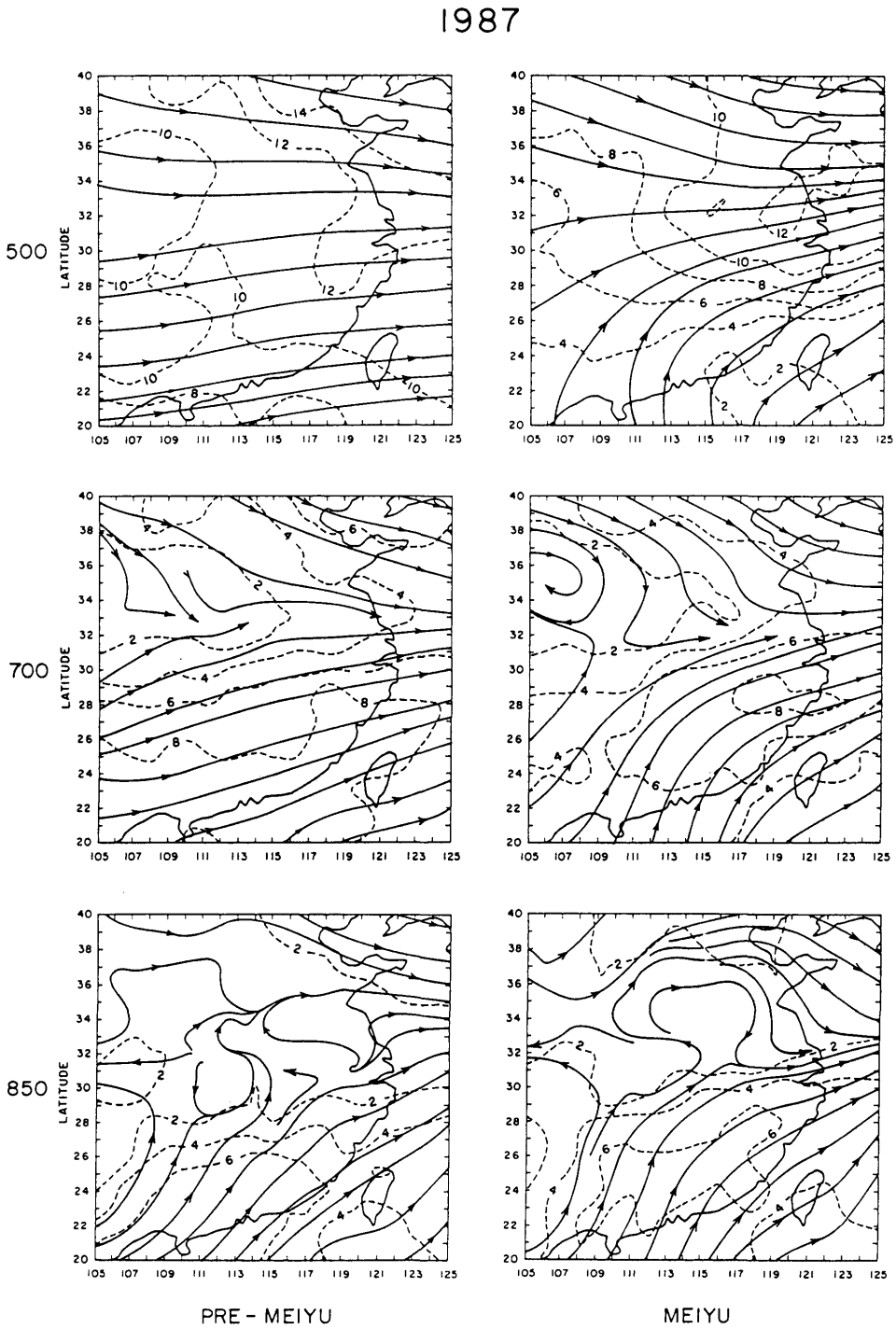

Fig. 6. Mean streamlines and isotachs (dashed, $\mathrm{m\,s^{-1}}$) at 850, 700, 500 hPa at 0000 UTC for pre-Meiyu and Meiyu periods of 1987.

where t represents date, $<Q_2(t,i,lat)>$ is the vertically integrated moisture sink, $P(t,i,lat)$ is the daily mean precipitation on a $1°\times1°$ grid and $\sum_{i=1}^{13}$ is the sum all of grid values between 110°E and 122°E (in the latitude-time plots, data are also averaged in 2°-latitude strips). Because the distribution of surface precipitation-reporting stations is not uniform in the analysis domain, the fields of $[Q_2]$ provide useful additional information for defining the pre-Meiyu and Meiyu periods.

Time series of $[P]$ and $[Q_2]$ are shown in Figs. 2, 3 and 4. Although there is some difficulty in the precise determination of the onset of the Meiyu, the following dates—June 12, 10 and 2—have been selected for 1987, 1988 and 1989, respectively. These dates are based on an apparent shift in the rainfall and $[Q_2]$ to the Yangtze Valley and northern

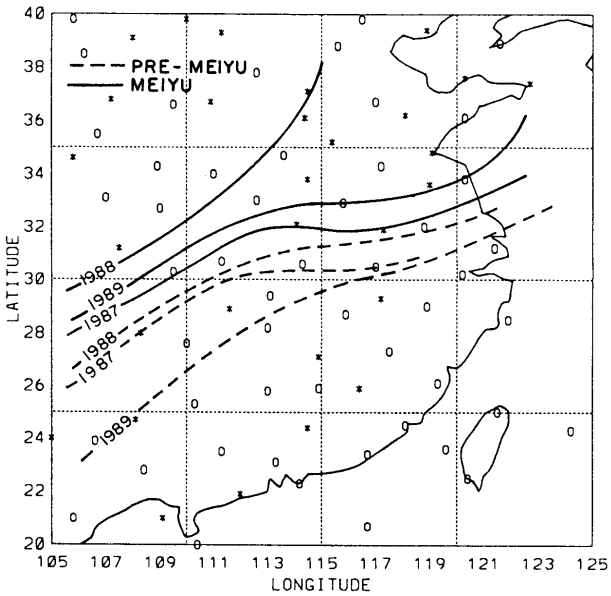

Fig. 7. Axes of 850-hPa shear line for pre-Meiyu and Meiyu periods 1987, 1988 and 1989.

China and have been selected so that they fall approximately within two weeks of the nominal start-date for the Meiyu, June 18 (Tao and Chen, 1987). These periods may be considered to correspond with Periods I and II of Murakami and Huang (1984) and approximately to the (pre- + early) and (peak + post-) periods of Ninomiya and Muraki (1986) and Ninomiya (1989).

Figures 2, 3 and 4 also provide information about the propagation characteristics of the rain systems during the summer monsoon period. The direction of propagation can be seen by referring to the slopes of the axes of the observed precipitation maxima, which have been superimposed on the $[Q_2]$ time-latitude sections in Figs. 2b, 3b and 4b (note that most tracks of $[Q_2]$ maxima have corresponding precipitation maxima associated with them). From May to mid-June, maxima in observed precipitation and $[Q_2]$ generally propagate from north to south; however, there are some periods, especially in southern China, where little to no propagation is apparent. Maximum values are normally located in southern China during this period. The direction of propagation of the rain systems is more easily seen in Fig. 5, for the year 1988, where the abscissa has been expanded. Since during the pre-Meiyu period (up to June 10) the propagation is almost exclusively north to south, we infer that the precipitation during this time period is related to disturbances in the midlatitude westerlies. Typical north-to-south propagation speeds are $\sim 10\,\mathrm{m\,s^{-1}}$.

From late June through July, the $[Q_2]$ and $[P]$ maxima propagate in both directions, to the north and the south (Figs. 2–5), suggesting that disturbances of both midlatitude and tropical origin are responsible for precipitation during this period. Monsoon disturbances and tropical depressions or cyclones presumably account for many of the northward-propagating features.

4. Seasonal mean flow features

The northward advance of the monsoon from the pre-Meiyu to the Meiyu of 1987, as manifested by the upper-level flow, is shown in Fig. 6. The most prominent change from the pre-Meiyu to the Meiyu is an increase in the southerly component of the flow in the southern part of the domain in association with a westward extension and northward advance of the western Pacific anticyclone, characteristic of the onset of the Meiyu (*e.g.*, Ninomiya and Muraki, 1986, Kato, 1989). During the Meiyu period, the 850-hPa Baiu trough and shear line can be seen over the Yellow Sea and into the Yantgze Valley (Ninomiya and Muraki, 1986). Throughout both periods, relatively strong southwesterly flow existed along the southern China coast. This feature is typical of the pretyphoon period and is associated with heavy rainfall over southern China (Huang *et al.*, 1986).

Rather than presenting mean flow conditions for 1988 and 1989 (which exhibit many of the mean flow features of 1987, Fig. 6), the mean positions of the 850-hPa shear line for the pre-Meiyu and Meiyu periods for the three years are presented in Fig. 7. A northward shift in the shear line associated with the Meiyu can be seen. The shear line shifted farthest north in 1988, consistent with a greater northward extension of the Meiyu rainfall during that year (Fig. 11, later).

5. Pre-Meiyu and Meiyu $<Q_2>$ and precipitation

In this section, the vertical intergral of Q_2 through the depth of the troposphere, defined as $<Q_2>$, is compared with observed precipitation. Patterns of $<Q_1>$ are similar and therefore not presented. As explained by Yanai *et al.* (1973), $<Q_2>$ plus the surface evaporation should, in principle, equal the observed precipitation. Direct measurements of evaporation are unavailable; however, Luo and Yanai (1984), for a 40-day, May-to-July period during 1979 over the Yangtze Valley, report a value of 1.3 mm d^{-1}, which will be used here for reference.

The horizontal distributions of $<Q_2>$ and mean rain rate for the pre-Meiyu 1987–1989 are shown in Fig. 8. Values over the ocean are considered unreliable and will be excluded from discussion. If we first ignore the effects of evaporation, we note that both $<Q_2>$ and the observed precipitation in the pre-Meiyu for the three years show the bulk of the rainfall to be confined to southern China south of 30°N. Details of the rainfall patterns do not every-

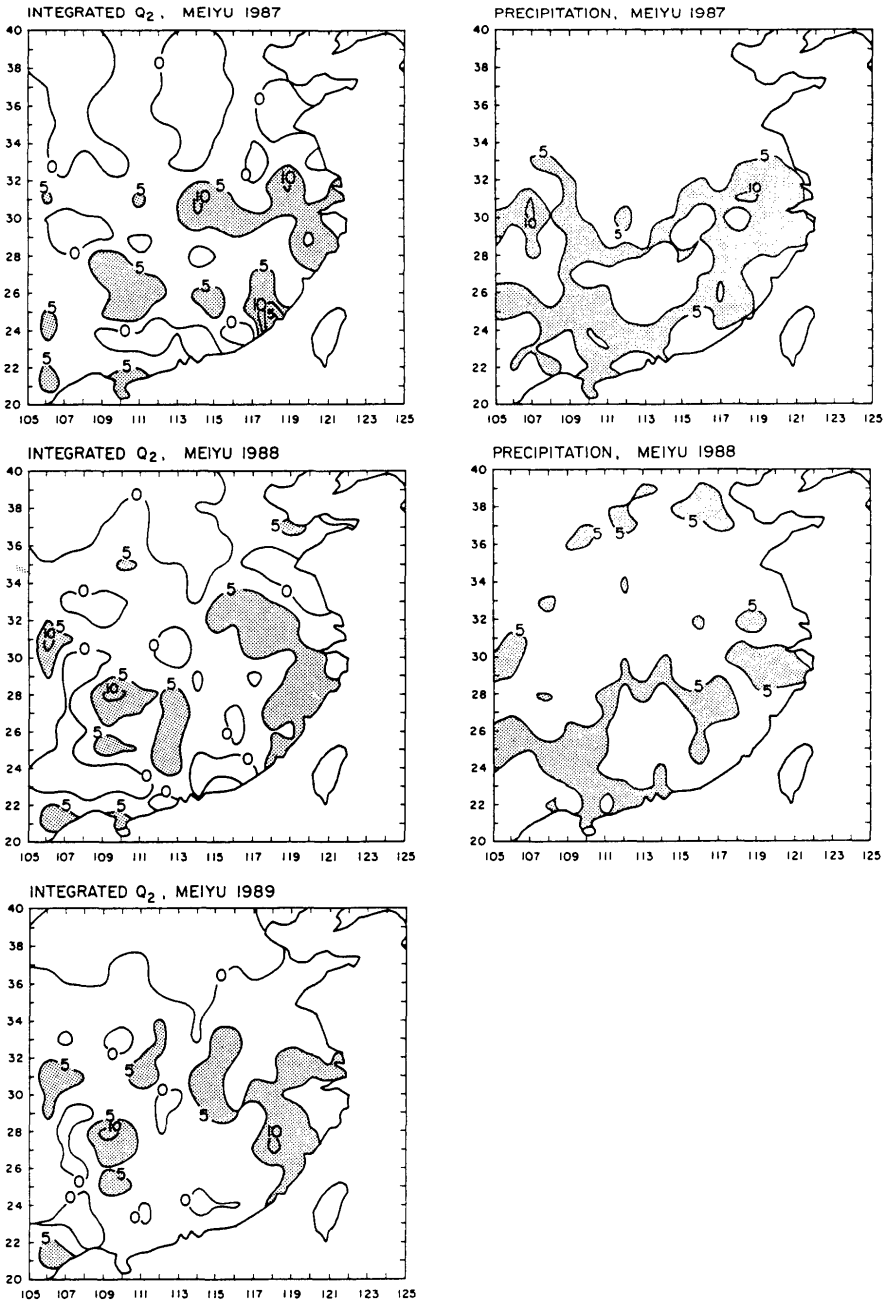

Fig. 8. Mean values of vertically integrated apparent moisture sink $<Q_2>$ and observed precipitation in mm d^{-1} for pre-Meiyu 1987, 1988 and 1989. Values >5 mm d^{-1} over land are shaded.

where agree. However, by adding an evaporation rate of 1.3 mm d^{-1} to $<Q_2>$ (recognizing that evaporation is not uniform over the region), the area of computed precipitation exceeding 5 mm d^{-1} is enlarged (not shown, but can be visualized from Fig. 8) and the agreement (including peak values) improves. [However, there still appears to be a general underestimate in the computed precipitation, which may be attributable to the procedure used to eliminate the effects of bad and missing data. Despite this deficiency, the differences are not great enough to alter qualitative conclusions regarding heating distributions and their comparison from one region to another.]

During the pre-Meiyu, the maximum band of precipitation is along and nearly parallel to the coastline. Convection is generated in this region in association with frequently-occurring synoptic-scale fronts over southern China (*e.g.*, Ninomiya, 1989). The presence of land-sea contrasts and mountains in southern China also suggest that diurnally varying local circulations may play an important role in May precipitation (Zhu *et al.*, 1983). The surface-wind differences between 0000 UTC and 1200 UTC (0800

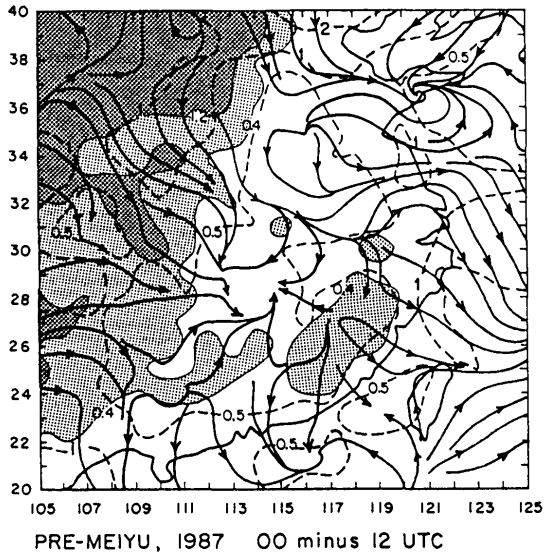

Fig. 9. Average 0800 to 1200 UTC (0800 minus 2000 L) differences of the surface wind (streamlines and isotachs, in m s^{-1}) for pre-Meiyu 1987. Elevations in km are indicated by shading.

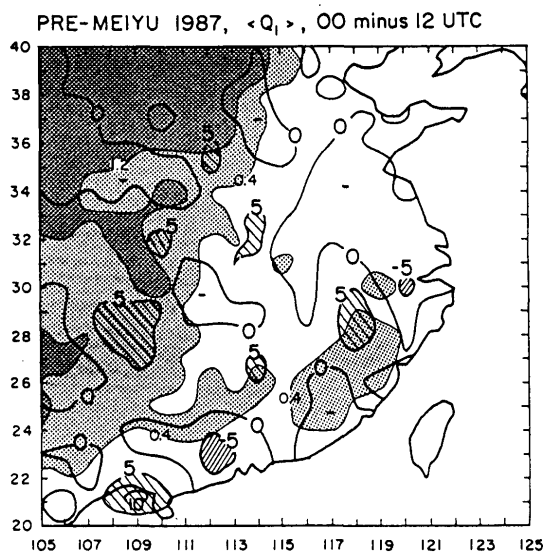

Fig. 10. Average 0000 to 1200 UTC (0800 minus 2000 L) differences of vertically integrated moisture sink $<Q_2>$ in mm d^{-1} for pre-Meiyu 1987. Values exceeding ±5 mm d^{-1} are hatched. Elevations in km are indicated by shading.

and 2000 L) during pre-Meiyu 1987 are shown in Fig. 9. This difference map accentuates the diurnal variations and because it contains 0800 minus 2000 L vector wind differences, it represents nightime circulation: land breezes along the China coast and valley breezes off the higher terrain in the interior.

In order to further examine the effects of topography and land-sea contrasts on the diurnal cycle of precipitation, the difference in $<Q_1>$ between 0000 and 1200 UTC (00800 and 2000 L) is shown in Fig. 10. Positive (negative) values indicate greater (less) rainfall in the early morning than the evening. Morning maxima (positive values) occur at lower elevations such as the Sichuan Basin (near 30°N 107°E), just north of the mountain ranges in southern China and in the Gulf of Tonkin. These regions correspond resonably well to convergent regions in Fig. 9 and are likely associated with downslope flows into the valleys and in the latter case, land-breeze convergence into the Gulf of Tonkin. Evening maxima (negative values) generally occur along the south China coast between the crest of the mountain ranges (Nan Ling and Wu Yi Shan ranges) and the coastline and in an area north of the Yangtze River east of 115°E. These maxima generally correspond to areas of convergence on a 1200 minus 0000 UTC surface wind difference map (which can be visualized from Fig. 9 by reversing the arrows). These results are consistent with those of Akiyama (1989) which show the important effects of topography on diurnal variations of rainfall, although there are some minor differences in the locations of the precipitation extrema due to the fact that she used satellite data in her study to infer the areas of rainfall.[2] There are additional extrema in the northwestern part of the domain that are suggestive of further topographic effects on the diurnal variation of rainfall.

In addition to land/sea and mountain/valley breezes, however, convergence of the southwest monsoon flow with the southern China coast may also be contributing to the precipitation along the coastline, as has been reported along the southwest coast of India (upstream of the western Ghats) during the summer monsoon (Grossman and Durran, 1984; Ogura and Yoshizaki, 1988). Ogura and Yoshizaki (1988) argue that strong latent and sensible heat fluxes from the occean and pronounced offshore flow aloft can contribute to the development of a precipitation maximum along the coast and immediately offshore rather than over the interior coastal range of India. In the case of China, offshore flow aloft does not exist and, therefore, rainfall by this mechanism would be favored over the coastal mountain range as well as along the coast itself.

Shown in Fig. 11 are the distributions of $<Q_2>$ and mean rain rate for the Meiyu during 1987–1989 (precipitation data for 1989 were missing). Some precipitation is still observed along the southern China coast during the Meiyu; however, there is an overall northward shift of precipitation toward the

[2]It should be noted that Akiyama's (1989) results are for the Meiyu period. However, the comparisons of Fig. 9 with Akiyama's results are still valid since the diurnal patterns are virtually the same in both the pre-Meiyu and Meiyu periods.

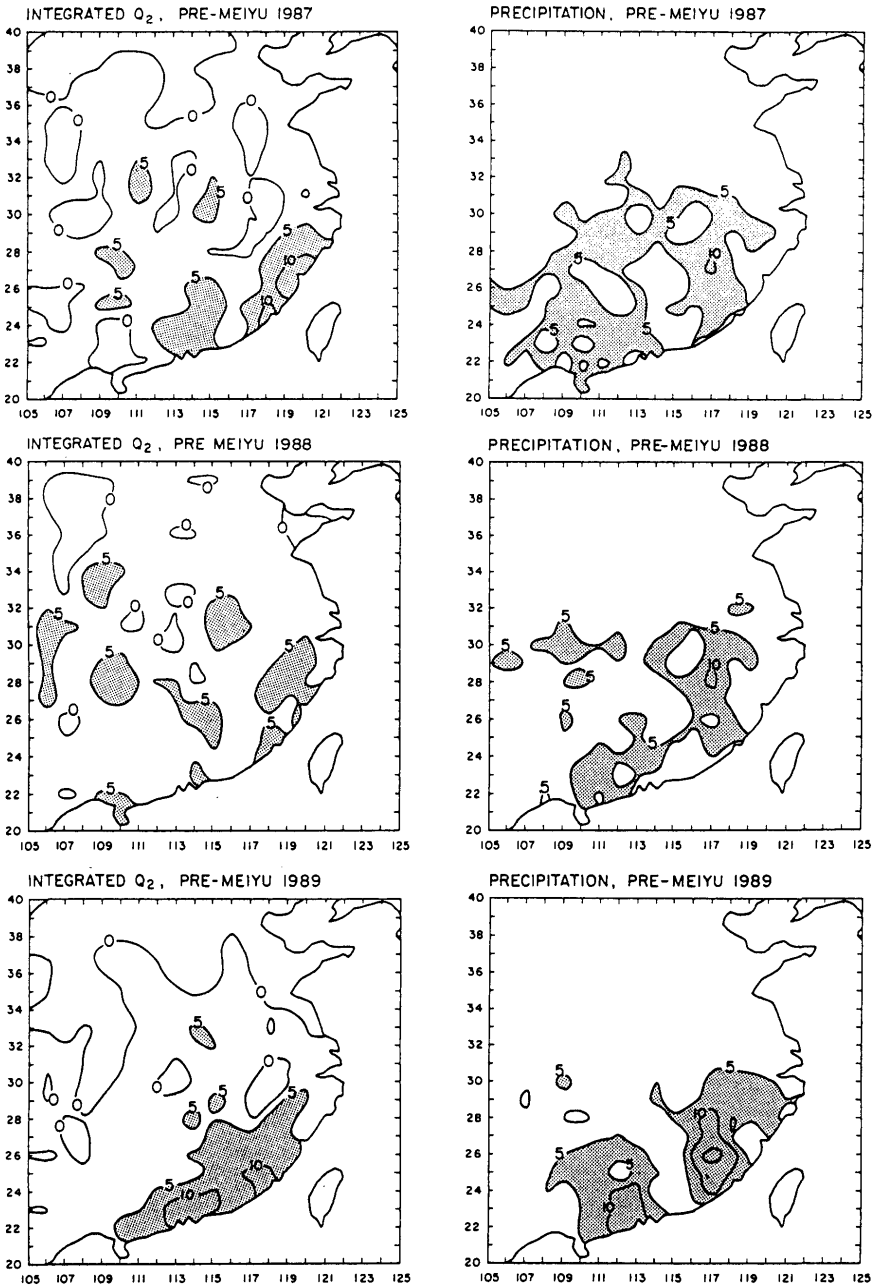

Fig. 11. As in Fig. 8, except for Meiyu.

Yangtze region. In 1988 there is an extension of precipitation to northern China, consistent with a far northward shift in the Meiyu front that year (Fig. 7).

The distributions of precipitation for the pre-Meiyu and Meiyu typify the northward shift of the summer monsoon over China. Overall, the computed precipitation patterns reflect this shift fairly well.

6. Regional characteristics of heat sources and moisture sinks

The entire analysis domain is divided into three subregions: SC (Southern China), Y (Yangtze River) and NC (Northern China) [Fig. 1]. Regional differences in vertical motion, heating and moistening are examined in this section.

In Fig. 12 the mean vertical profiles of vertical motion, heating rate and drying rate are shown for the pre-Meiyu from 1987 to 1989. In southern China (SC) the vertical motion is upward with a peak value of ω between 400 and 500 hPa. The heating rate is smaller than the drying rate in the lower troposphere, while the reverse is true in the upper troposphere, indicating a dominance of deep cumulus convection (Luo and Yanai, 1984). These results are

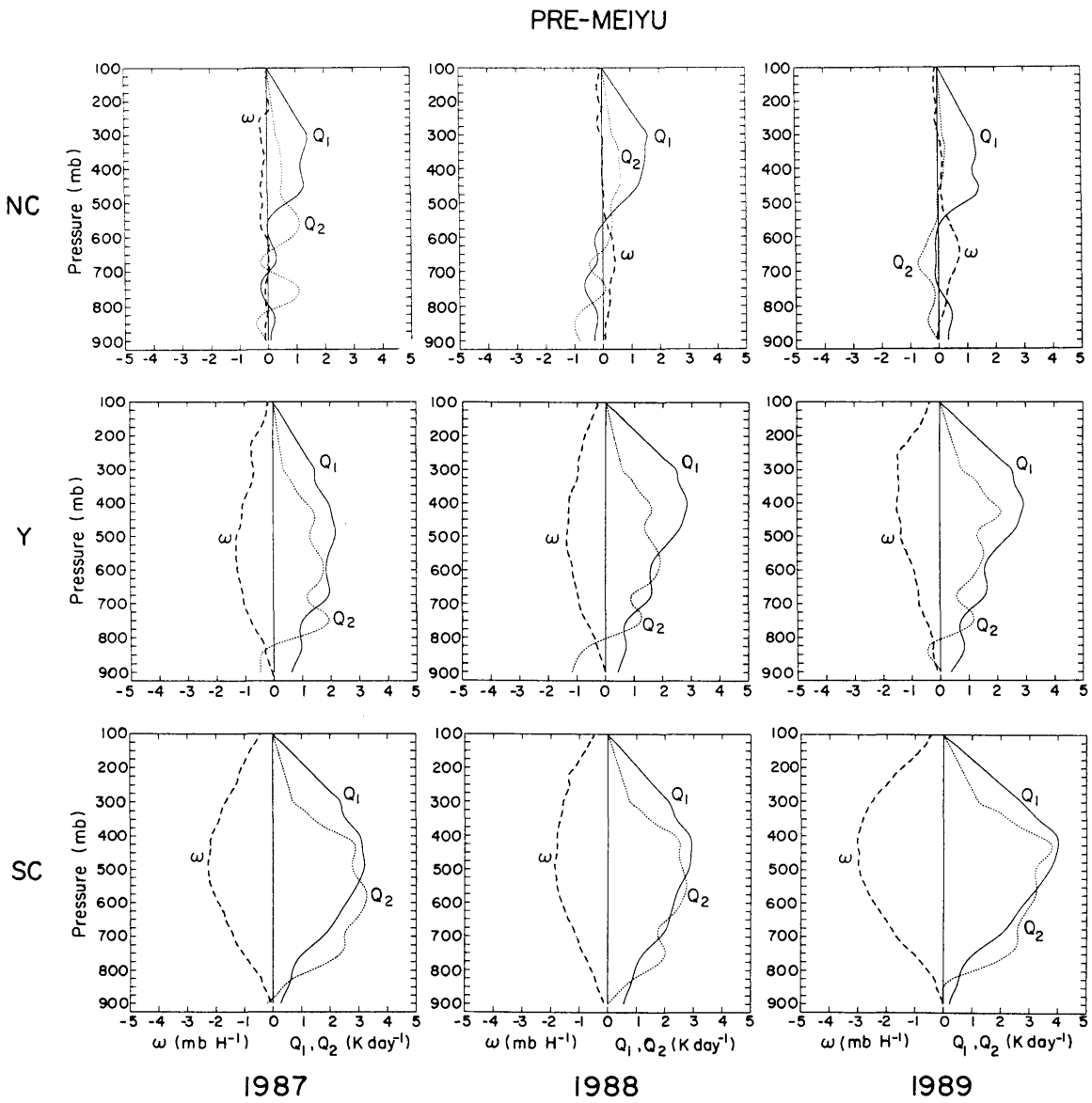

Fig. 12. Mean vertical distributions of ω (hPa h^{-1}) and Q_1/c_p and Q_2/c_p (K d^{-1}) for Southern China (SC), Yangtze River (Y) and Northern China (NC) for pre-Meiyu 1987, 1988 and 1989.

consistent with Ninomiya's (1989) inferences based on GMS satellite nephanalyses of a predominance of convective precipitation in southern China during the pre-Meiyu. In the Yangtze region (Y) the mean vertical motion during the pre-Meiyu is weaker than in SC, particularly in 1989, when the precipitation in Region Y was much less than that in SC (Fig. 8). Also in Y, the level of peak ω is variable (near 500–600 hPa in 1987 and 1988; from 200 to 400 hPa in 1989). In the lower troposphere in Y (below 500 hPa) the profiles of Q_1 and Q_2 are closer to each other, indicating the existence of less deep convection and a higher percentage of stratiform precipitation this region (Luo and Yanai, 1984, Ding and Wang, 1988). The small moistening occurring at low levels in Y indicates a higher cloud base and greater evaporation below cloud base in the Yangtze region than over southern China, similar to the findings in midlatitude mesoscale convective systems over the central United States (Gallus and Johnson, 1991). In northern China (NC) the only significant heating is in the upper troposphere, suggestive of upper-level stratiform clouds, presumably associated with baroclinic disturbances. Q_2 is small at upper levels due to small values of specific humidity.

The patterns of mean vertical profiles of heating and drying in southern China (SC) during the Meiyu (Fig. 13) are similar to those in the pre-Meiyu. In the Yangtze region (Y) there is pronounced increase in the amplitude of Q_1 and Q_2 during the Meiyu, consistent with the precipitation increases in Y from the pre-Meiyu to Meiyu shown in Figs. 8 and 11. In addition, there appears to be significant deep convection in Y during all three years. These findings

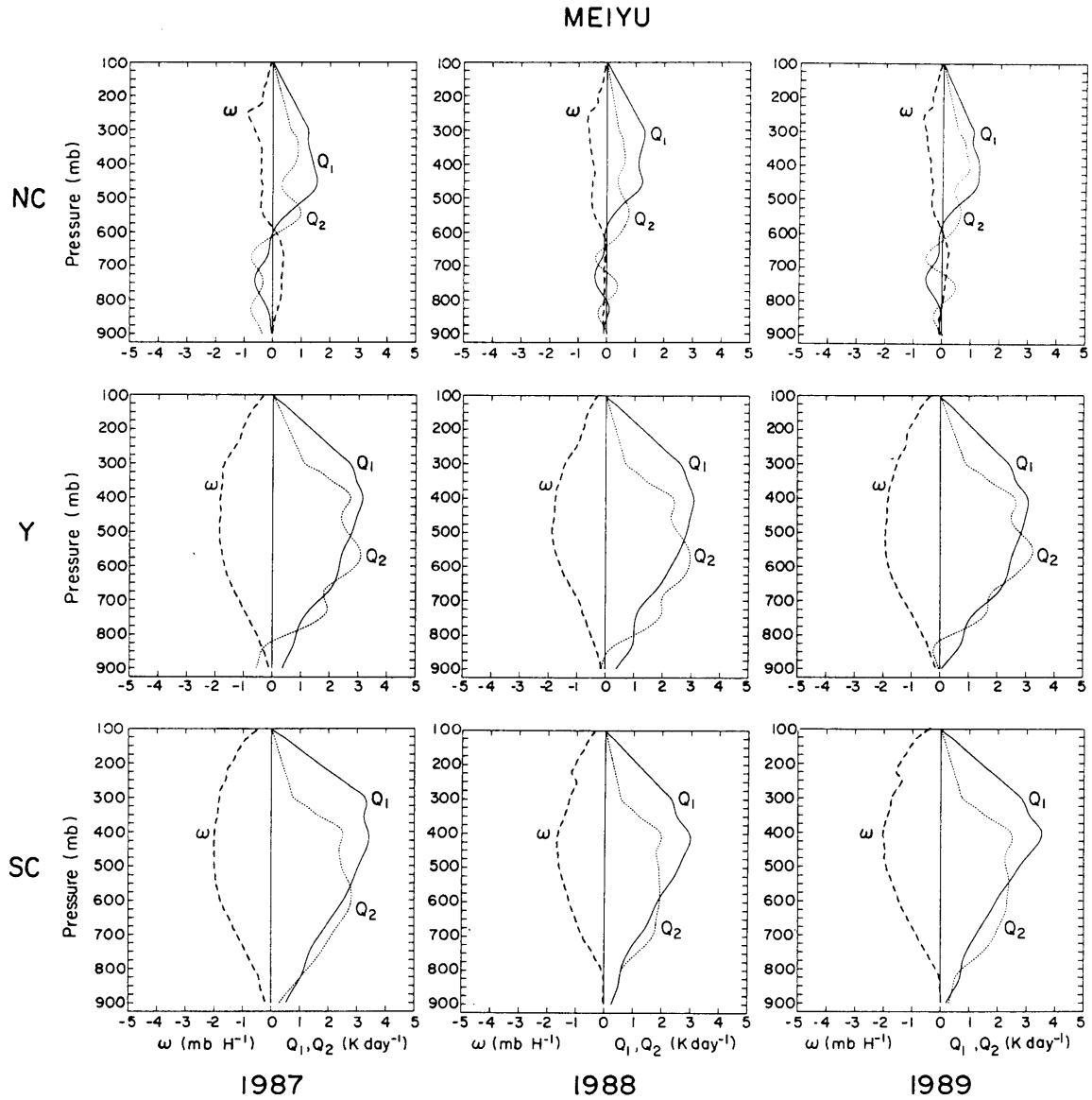

Fig. 13. As in Fig. 12, except for Meiyu.

are consistent with those of Ding and Hu (1988) for the 1984 Meiyu. In northern China (NC) the vertical structure of the heating and drying profiles does not change significantly between the pre-Meiyu and Meiyu, although the upward vertical motion in the upper troposphere increases during the Meiyu, indicative of increased precipitation. Moreover, although it does not show well in the average for the Meiyu, there is a strong indication of deep convection finally reaching northern China during the month of July 1988 (Fig. 14) when a rainfall maximum was observed there (Fig. 11).

Shown in Fig. 15 are the mean vertical distributions of the heating rate and drying rate averaged along 117 to 119°E (over the eastern part of China; see Fig. 1) for the pre-Meiyu 1988. From 21 to 24°N (over southern China) there is deep tropospheric heating and drying with a lower-tropospheric maximum in Q_2 , indicative of deep convection. Near 27°N there are weaker Q_1 and Q_2 maxima, both in the midtroposphere, suggestive of stratiform precipitation. These results are in agreement with Ninomiya's (1989) satellite-determined could types for the pre-Meiyu and also with the precipitation structure determined over southern China during the preflood period by Huang *et al.* (1986).

During the Meiyu 1988 there are again two distinct maxima in heating and drying along 117–119°E (Fig. 16); however, the southern peaks have remained near the southern China coast, while the peaks in the Yangtze region have shifted about 5° to the north. The $Q_1$and Q_2 profiles over SC are not coincident, indicating that during the Meiyu much of the precipitation over southern China is convective. Precipitation over Y appears to be a combination of convective and stratiform, as also noted by

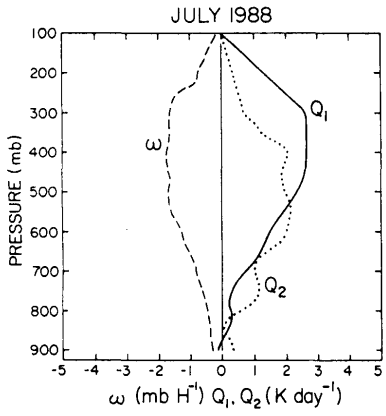

Fig. 14. As in Fig. 12, except for Northern China (NC) for July 1988.

Ninomiya (1989). Heating and drying are also seen in the midtroposphere over northern China, consistent with the rainfall observations in 1988 (Fig. 11).

7. Summary and future work

Spatial and temporal variations of the monthly mean heat sources and moisture sinks over China during the pre-Meiyu and Meiyu periods are investigated for three years: 1987, 1988 and 1989. The main findings of this paper can be summarized as follows:

(1) The horizontal distributions of vertically integrated heat sources and moisture sinks show that the maximum heating appears in a band parallel to the coastline of southern China during the pre-Meiyu with a secondary maximum over the Yangtze Valley. Analyses of the diurnal cycle of the flow suggest that land/sea and mountain/valley breezes play an important role in the timing and location of the precipitation. At night, rainfall maxima appear over the basins in the interior of China in response to mountain drainage flows. In the daytime, pronounced rainfall maxima occur between the China coast and the interior coastal mountain ranges. Dur-

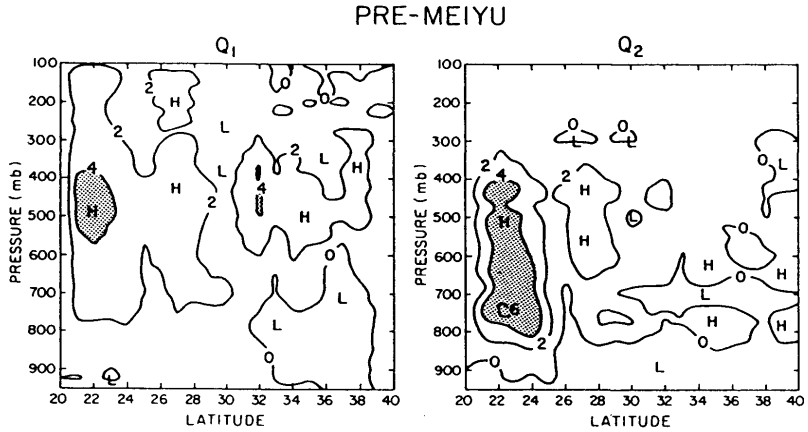

Fig. 15. Mean vertical distribution of (a) Q_1/c_p and (b) Q_2/c_p averaged along 117–119°E for pre-Meiyu 1988. Units are K d^{-1}.

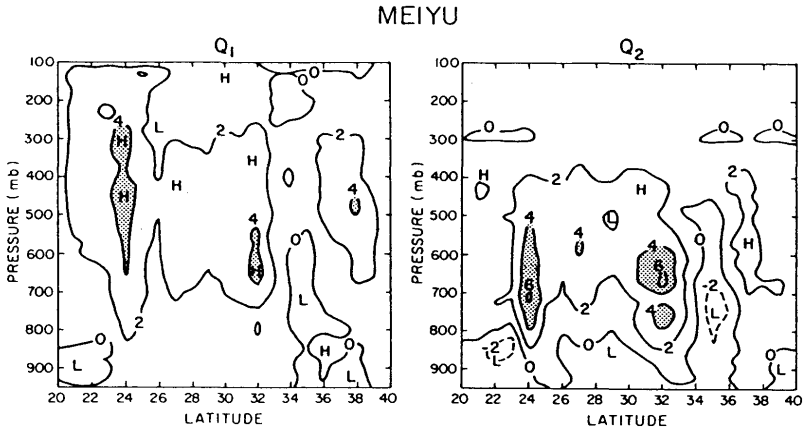

Fig. 16. As in Fig. 15, except for Meiyu, 1988.

ing the Meiyu, there are two zonal bands of maximum heating of comparable amplitude, one over southern China and the other over the Yangtze region. During, 1988, there was an additional maximum in heating and drying over northern China.

(2) The vertical profiles of areal mean heat source and moisture sink show regional differences from the pre-Meiyu to Meiyu. The precipitation in southern China is mainly convective throughout the period. The precipitation in the Yangtze region is a mixture of stratiform and convective types, consistent with the results of Luo and Yanai (1984), Ding and Wang (1988), Ding and Hu (1988) and Ninomiya (1989).

(3) The heating and drying in southern China occur throughout the whole troposphere, but low-level moistening occurs in the Yangtze region. The pattern in southern China resembles that observed in the deep tropics (*e.g.*, Yanai *et al.*, 1973), whereas that in Yangtze region is similar to that observed with midlatitude mosescale convective systems where low-level evaporation is important (*e.g.*, Ninomiya, 1971, Lewis, 1975; Gallus and Johnson, 1991).

(4) The vertically integrated heat source and moisture sink propagate from north to south during the pre-Meiyu. After that time, the heating and drying maxima propagate both from north to south and south to north. These results indicate that early monsoon precipitation is related to midlatitude baroclinic systems whereas late monsoon precipitation is controlled both by midlatitude and tropical disturbances.

Because of the limited resolution of the routine sounding data, especially in the vertical, the detailed structure of heating and drying in different regions could not be determined. It is important to be able to examine case studies of individual systems in order to better understand the contributions of both convective and stratiform precipitation to the total budgets in the different regions. The Mesoscale Experiment that was conducted over southern China and Yangtze region in 1989 and 1990 should provide useful data for more detailed heat and moisture budget studies.

Acknowledgments

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初夏のモンスーン季における中国大陸上の熱と水蒸気の収支について

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地上および上層のルーチン観測データを用いて、中国大陸における梅雨季前と梅雨季における熱収支と水蒸気収支を、1987、1988、1989年について算定した。

梅雨季前における、鉛直積分した熱源 $<Q_1>$ と水蒸気シンク $<Q_2>$ の水平分布によると、加熱の極大域は、華南地方で海岸線と平衡なバンド状に認められ、2次的極大域が、楊子江流域に見られる。梅雨季にはいると、楊子江流域での加熱が増大するが、華南でのバンド状の加熱もひきつづき起こる。1988年には、第3の加熱極大バンドが、華北地方でも認められる。梅雨季前、梅雨季ともに、海陸風・山谷風循環による降水の日変化が顕著である。夜間には降水は、内陸盆地などの低地を中心に起こり、日中には降水の極大域が、海岸と海岸に沿った山脈の間や、山風が吹きやすい地域へと移動することがわかった。

熱源 $<Q_1>$ と水蒸気シンク $<Q_2>$ の、中国大陸上の地域平均での鉛直プロファイルによれば、楊子江流域の降水は、梅雨季前、梅雨季ともに、対流性と層状性の混ざったタイプであるのに対し、華南では、厚い積雲対流が卓越していることが明らかになった。華南では、加熱と乾燥化が対流圏全層で見られたのに対し、楊子江流域では、下層での湿潤化が起こっている。華南での降水様式は、熱帯地域で観測されるものとよく類似しているのに対し、楊子江流域でのそれは、下層での蒸発が重要である、中緯度のメソスケール対流システムに類似している。