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Mesoscale Analysis of a Heavy Rainfall Event over Hong Kong During a Pre-rainy Season in South China

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ABSTRACT

During the Heavy Rainfall Experiment in South China (HUAMEX) of 1998, a record heavy rainfall event occurred in the delta of the Pearl River during the 24 hours from 1200 UTC 8 June to 1200 UTC 9 June, 1998, and a 24-hour precipitation maximum of 574 mm was reported in Hong Kong. In this paper, some mesoscale characteristics of this heavy rainfall event are studied using data from satellites, Doppler radar, wind profilers, and automatic meteorological stations collected during HUAMEX. The following conclusions are drawn: (1) During this heavy rainfall event, there existed a favorable large-scale environment, that included a front with weak baroclinity in the heavy rain area and with an upward motion branch ahead of the front. (2) Unlike most extratropical or subtropical systems, the closed low in the geopotential height field does not exited. The obvious feature was that a southerly branch trough in the westerlies existed and Hong Kong was located ahead of the trough. (3) The rainfall areas were located in the warm sector ahead of the front, rather than in the frontal zone, which is one of the characteristics of heavy rainfalls during the pre-rainy season of South China. A southerly warm and moist current contributed to the heavy rainfall formation, including the transportation of rich water vapor and the creation of strong horizontal wind convergence. (4) The observations show that the heavy rainfall in Hong Kong was directly caused by a series of meso β systems rather than a mesoscale convective complex (MCC). These meso β systems moved with the steering current in the lower-mid troposphere, their life cycles were 3–6 hours, and their horizontal sizes were 10–100 km. (5) The disturbances in the lower and mid troposphere, especially that in the planetary boundary layer (PBL) were very shallow. However, they are a possible trigger mechanism for the occurrence and development of the mesoscale convective systems and related heavy rainfalls. Finally, a conceptual model of the heavy rainfall in the warm sector ahead of the front in South China is proposed.

Key words: warm sector heavy rainfall, mesoscale convective system, southerly branch trough in westerlies

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1. Introduction

Heavy rainfall and flooding represent very serious disasters around the world. In North America, Europe and Australia, many studies have been carried out on heavy rainfall and flooding (e.g., Danard, 1964; Palmen and Newton, 1969; Browning and Harrold, 1970; Zhao and Mills, 1991; Bell and Janowiak, 1995). Extratropical cyclones, tropical cyclones or local severe rainstorms are the main producers of heavy rainfall. China is located in the East Asia monsoon area. The characteristics of heavy rainfalls in East Asia, especially in China, are quite different from the aforementioned regions (Bell and Janowiak, 1995; Mo et al., 1995; Weaver et al., 2000). The summer monsoon transports rich moisture into China. There is a close relationship between the onset and advance of summer monsoon and the main seasonal rainbands into China. Chinese scientists have found that Asian monsoon is composed of two subsystems, namely, the Indian southwest monsoon and the East Asian monsoon, and the East Asian monsoon is an independent subsystem, at least, during the early summer season (Tao and Chen, 1988; Zeng et al., 1994). In fact, heavy rainfalls in South China, during the so-called pre-rainy season, start at the onset of the South China Sea monsoon (as a part of the East Asian monsoon) around the middle of May (Tao, 1980; Zeng et al., 1994; Sun and Zhao, 2000). Then, the mei-yu front occurs along the Yangtze River over China, in the middle of June when

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the East Asian monsoon shifts northward successively (Tao, 1980; Akiyama, 1984; Kato, 1985; Ninomiya and Muraki, 1986; Zhao et al., 2004). Finally, the rainbands maintain themselves in North China from mid July to mid August. The rainbands retreat southwards and disappear with the retreat of the summer monsoon in the fall.

South China is located at lower latitudes, and is influenced by various weather systems of both tropical and mid latitude origins. On average, there are two rainy periods in South China, namely, the pre-rainy season in May and June, and the second rainy season in July, August, or even September. The former is mainly associated with the interaction between the westerlies and the South China Sea monsoon, and the latter is mostly related to other tropical systems, including tropical cyclones. To understand the causes of heavy rainfall occurrence, a field experiment on heavy rainfall during the pre-rainy season in South China was conducted in the 1970s; the observational data revealed the influence of mid-latitude fronts and the contribution of the southerly branch trough in the westerlies. The southerly branch trough is a trough of southerly currents of two branches divided by the Tibetan Plateau during the early spring and winter seasons (Tao and Chen, 1988; Zhou et al., 2003). The aforementioned research led to a better understanding of the large-scale characteristics of heavy rainfall in South China. In addition, meteorologists in the Taiwan area conducted the Taiwan Area Mesoscale Experiment (TAMEX) in 1987 and the results emphasized the role of the southwest low level jet and the dynamical effect of the central mountains on the island of Taiwan (Kuo and Chen, 1990). To better understand the mechanisms and variability of monsoon, and the environment and structural characteristics of heavy rainfall during the pre-rainy season in South China, the Heavy Rainfall Experiment during the pre-rainy season in South China (HUAMEX) and the South China Sea Monsoon Experiment (SCSMEX) were conducted in 1998. During the two months from 1 May to 30 June during HUAMEX, data were collected for seven IOP (intensive observational period) cases. Using both conventional and non-conventional data, some research has been carried out (Zhou et al., 2003; Bei and Zhao, 2005). In addition, Chen and Zhao (2000, 2004) analyzed the large-scale systems during GARP (Global Atmospheric Research Program), and the circulation characteristics and weather systems during HUAMEX, respectively. In their work, the interactions between cold air and the South China Sea monsoon were investigated. However, none of these studies focused on mesoscale analysis of severe heavy rainfalls in South China, or in the Hong Kong region.

Hong Kong is a large city where international trade and culture exchange are very active, and is situated east of the Pearl River delta, within the heavy rainfall area in South China. However, Hong Kong is in a coastal area and surrounded by sea on the west, south and east sides. Precipitation characteristics different from those in other areas in South China may exist (Bei and Zhao, 2005; Dong et al., 2005a,b).

From 6–11 June 1998, a front was maintained along the coastal area in South China, a front that brought heavy rainfall to both Hong Kong and Taiwan. Bei and Zhao (2005) analyzed the mesoscale systems associated with the heavy rainfall in Taiwan for 7–8 June 1998. They pointed out that the heavy rainfall was caused by a series of meso-β scale systems moving along the central maintain range of Taiwan. However, the heavy rainfall in Hong Kong has not been investigated in detail. In fact, during the period from 1200 UTC 8 June to 1200 UTC 9 June 1998, severe heavy rainfall with a maximum of 574 mm per 24 hours occurred in Hong Kong. It was, indeed, one of the most severe heavy rainfall cases of the pre-rainy season in South China. Several questions can be asked, such as (1) Why did the strong heavy rainfalls appear particularly in Hong Kong? (2) What are the mesoscale characteristics during the heavy rainfall? (3) What weather systems were related to the heavy rainfall event? (4) What were the favorable environmental conditions for the occurrence of heavy rainfall? Fortunately, many observations were collected during HUAMEX and SCSMEX and the data are made available by the Hong Kong Observatory to facilitate current research. To understand the mesoscale characteristics of severe heavy rainfalls in Hong Kong and to clarify their structure and evolution, a diagnostic study of this heavy rainfall case is conducted, using Doppler radar, satellite imagery, wind profiler, radiosonde, and hourly surface observations.

The text of this paper is organized as follows. In section 2, weather patterns and precipitation distribution are presented, and the dynamic and thermodynamic conditions favorable for the occurrence of the heavy rainfall are diagnosed in section 3. The formation, development and evolution of meso-β scale systems are investigated in section 4, and the wind field disturbances and moisture distribution in the lower troposphere are discussed in section 5. A conceptual model of heavy rainfall in the warm sector ahead of the front during the pre-rainy season in South China is proposed in section 6. Finally, a discussion and conclusions are presented in section 7.

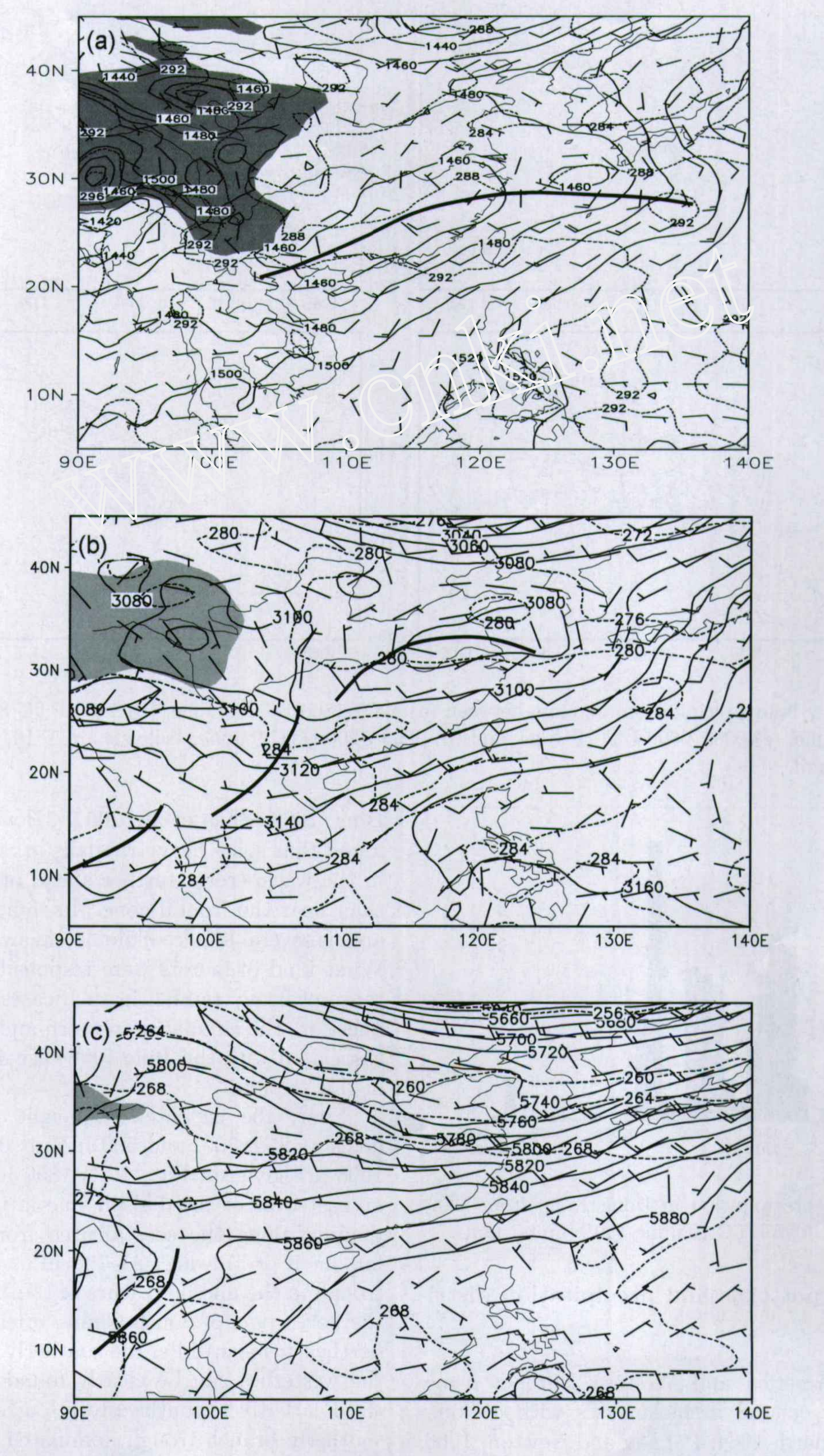


Fig. 1. Geopotential height (solid line) and temperature (dashed line) at 0000 UTC 9 June 1998 at (a) 850 hPa; (b) 700 hPa; (c) 500 hPa. Shaded areas represent the terrain height of more than (a) 1500 m; (b) 3500 m; (c) 5000 m. The bold line is the shear line in (a), and trough axes in (b) and (c).

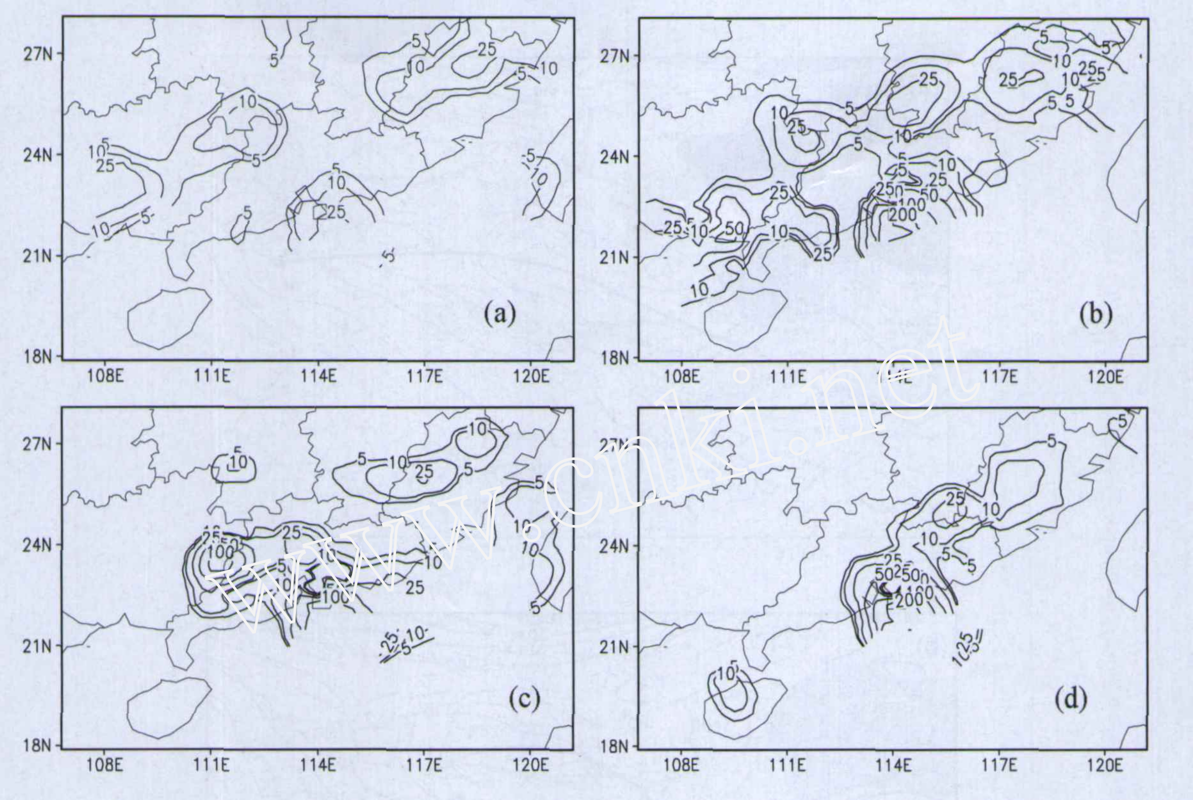


Fig. 2. Six-hour precipitation amounts between (a) 1200–1800 UTC 8 June, (b) 1800 UTC 8 June–0000 UTC 9 June, (c) 0000–0600 UTC 9 June, and (d) 0600–1200 UTC 9 June. Isohyets are 5, 10, 25, 50, 100, and 200 mm.

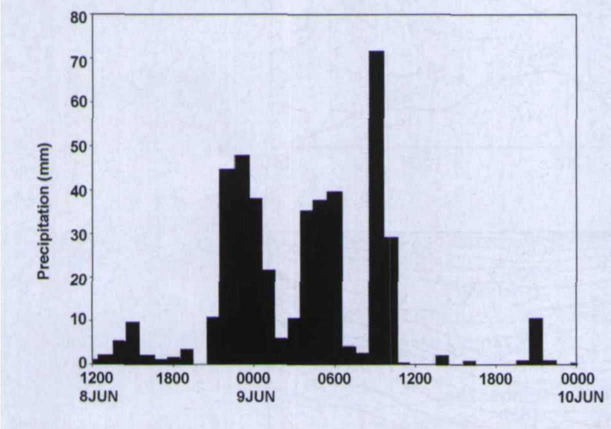


Fig. 3. Hourly precipitation in Hong Kong from 1200 UTC 8 June to 0000 UTC 10 June 1998 (units: mm).

2. Weather patterns and precipitation distribution

In North America and Western Europe, heavy rainfalls are associated in most cases with cyclones and fronts (Danard, 1964; Palmen and Newton, 1969; Browning and Harrold, 1970; Petterssen and Smebye, 1971). In East Asia, especially in the Yangtze River region, heavy rainfall is usually related to the quasi-stationary mei-yu (Baiu) front (Matsumoto et al., 1971; Tao, 1980; Ninomiya and Muraki, 1986; Ding, 1993; Zhao et al., 2004). However, it has been found that some heavy rainfalls in South China occur in the warm sector further ahead of the front, rather than near the frontal zone. In some cases, the rainy area is several hundred kilometers away from the front. What kind of factors were responsible for the occurrence of heavy rainfall in such cases? To answer this question, the circulation pattern and weather systems associated with the June 1998 case are examined first in this section.

First, the geopotential height and temperature fields at 850, 700, and 500 hPa at 0000 UTC 9 June 1998 are given in Fig. 1. At 850 hPa, there existed an east-west oriented shear line in the wind field extending along the coastal area from Guangdong to far north of Taiwan. At 700 hPa, there was a deep trough in the middle reaches of the Yangtze River and the north part of South China, oriented southwest to northeast; meanwhile, the southerly branch trough in the westerlies can be clearly found. In the delta of the Pearl River, southwesterly currents ahead of the southerly branch trough dominated, while the colder air behind the trough in the north part of South China moved southeastwards. In this situation, the geopotential height gradient between the upper level trough and the western Pacific subtropical high increased significantly, and at the same time, the southwesterly curr-

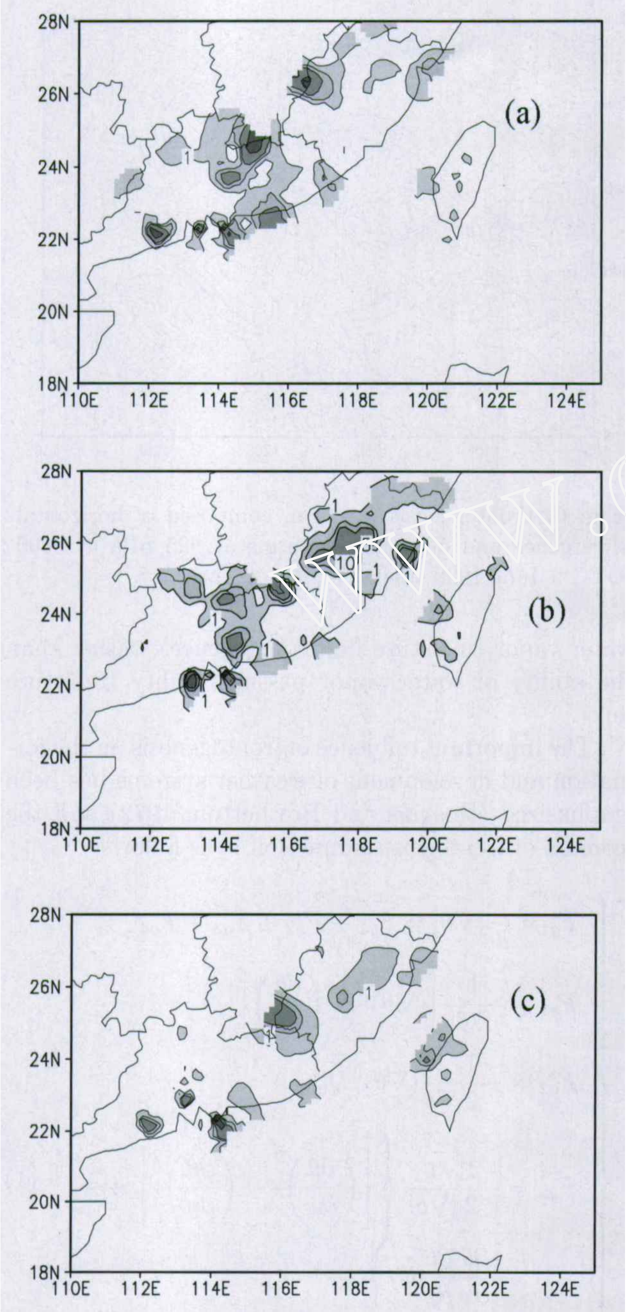


Fig. 4. Distributions of one-hour precipitation amounts at (a) 2300 UTC 8 June, (b) 0600 UTC 9 June, and (c) 0900 UTC 9 June. Isohyets are 1, 5, 10, 25, 50 mm.

ents in the lower troposphere became stronger. Therefore, the east part of the shear line along the coastal area induced stronger convergence. In this paper, the main purpose is to study the heavy rainfall in Hong Kong; therefore, the heavy rainfall related to the east part of the shear line will not be discussed further. At 500 hPa, a trough existed in the north part of the Bay of Bengal. South China and the Sino-Indian Peninsula were situated ahead of the trough. The isoline of 5880 geopotential meters (gpm), which defines the north edge of the subtropical high, was located in the north part of the South China Sea, which was still controlled by the south edge of the westerlies. During this period, only the southerly branch trough, shear line, lower level jet, and cold air with the weaker front existed; no well-developed cyclones were found in South China. It, therefore, belongs to the type of heavy rainfall that occurs in the warm sector ahead of the front during the pre-rainy season in South China.

The accumulated precipitation amount from 0000 UTC 8 June to 0000 UTC 12 June 1998 (not shown) indicates that the main rainbands were mostly concentrated in the coastal area of South China. There were two maxima, which were more than 200 mm, respectively; one of them was located in the Pearl River delta and to its south, and the other near the island of Taiwan. Generally speaking, the precipitation from 8–9 June was strong. In the six hourly precipitation maps (Fig. 2), there was a strong heavy rainfall of more than 200 mm on the east side of the Pearl River delta from 1800 UTC 8 June to 0000 UTC 9 June (Fig. 2b), and again from 0600 UTC to 1200 UTC 9 June (Fig. 2d). Overall, there were strong heavy rainfalls in the Pearl River delta, with a maximum of 222.7 mm per 24 hours in Zhuhai (22°17′N, 113°35′E). A maximum of 574 mm per 24 hours, as mentioned earlier, was reported over Hong Kong. To better describe the time evolution of heavy rainfall, two stations in Hong Kong are examined. Their station numbers are 45004 (22°19′N, 114°10′E) and 45005 (22°18′N, 114°10′E), respectively. It can be found that heavy rainfall peaks appeared mainly between 1800 UTC 8 June and 1200 UTC 9 June. At station No. 45004, the peak of 6-hour precipitation amounts in 1800 UTC 8 June to 0000 UTC 9 June, 0000 UTC to 0600 UTC 9 June, and 0600 UTC to 1200 UTC 9 June were 185 mm, 120 mm and 242 mm, respectively (not shown). These precipitation peaks were clearly related to mesoscale systems causing strong convection, which are the focus of this study.

For checking the mesoscale characteristics of heavy rainfall, the hourly precipitation amount in Hong Kong is given in Fig. 3. A maximum of 71.7 mm appeared around 0900 UTC 9 June. During the period from 1800 UTC 8 June to 1200 UTC 9 June, the average gap between the neighboring peaks was about 3–6 hours, which was comparable to the life cycle of the convective cloud clusters producing the heavy rainfall. It should be emphasized that the results in Fig. 3 are only the temporal variation of precipitation amount in Hong Kong. To check the special distribution and the horizontal scale of rainy clusters, the charts of one hour precipitation amount centered around the time of three rainfall peaks, that is, at 2300 UTC June 8, 0600

UTC 9 June, and 0900 UTC 9 June are plotted. The hourly precipitation data in South China are analyzed and given in Fig. 4. It can be seen that the horizontal scales of the strong precipitation cloud clusters were, indeed, smaller, at about 20–50 km. They concentrated mainly on the Hong Kong and Pearl River delta. During the same periods, however, the precipitation along the east part of the shear line, in Fujian Province and East Guangdong Province, was not so heavy.

3. Diagnostic analysis of dynamic and thermodynamic conditions

For clarifying the mechanism and dynamical factors of heavy rainfall formation, a diagnostic analysis has been done. In this section, the dynamic and thermodynamic factors related to the Hong Kong heavy rainfall are studied, including the lower level jet, frontogenesis function, and the vertical structure of the wind field. First, the characteristics of low level jet (LLJ) are discussed. Figure 5 shows the wind vector and wind speed at 850 hPa, 0600 UTC 9 June 1998, at which time there was the LLJ streak with a maximum speed of 15 m s^{-1} located to the southeast of Hong Kong. A strong convergence zone of wind speed related with the LLJ extended from southwest to northeast along the coastal area in South China, and provided very rich water vapor supply which was favorable for the occurrence of the heavy rainfall. In the field of moisture flux divergence in the entire air column (not shown), the negative values (convergence) were located in the coastal area of Southeast China. That indicated the concentration of water vapor was very predominant. It has been found (Zhao and Zhou, 1984:; Zhao et al., 2004) that the occurrence of heavy rainfall depends mainly on the concentrating ability of water vapor (moisture flux convergence), rather than the ability of water vapor passage ability (moisture flux).

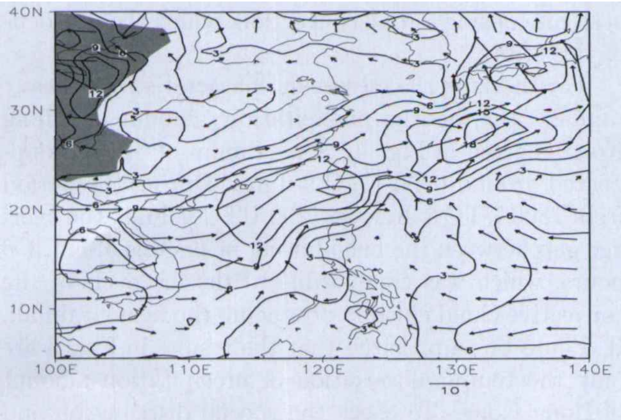


Fig. 5. Wind vector and wind speed at 850 hPa at 0600 UTC 9 June 1998 (units: m s^{-1}). Shaded area represents the region where terrain is higher than 1500 m.

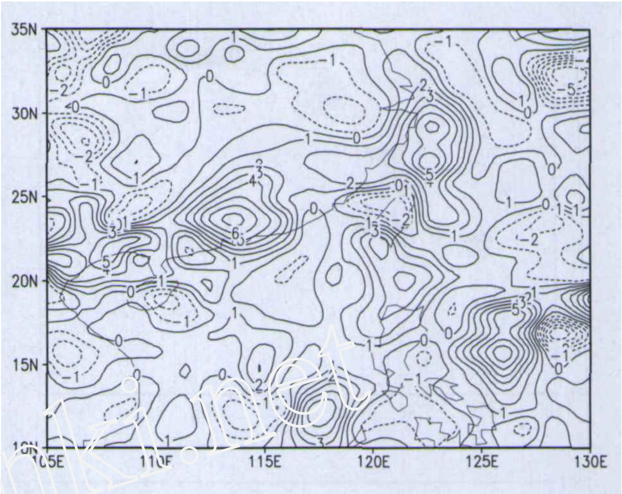


Fig. 6. Frontogenesis function, composed of horizontal divergence and deformation terms at 925 hPa at 0600 UTC 9 June 1998 (units: K m^{-1} s^{-1}).

The important influence of frontogenesis on the formation and development of weather systems has been emphasized (Hoskins and Bretherton, 1972) and the formula of frontogenesis function is as follows:

$$
\left\{
\begin{aligned}
&F_g = \frac{d}{dt}|\nabla\theta| = F_{g1} + F_{g2} + F_{g3} + F_{g4} \, , \\
&F_{g1} = \frac{1}{|\nabla\theta|}\left[(\nabla\theta)\cdot\nabla\left(\frac{d\theta}{dt}\right)\right] , \\
&F_{g2} = -\frac{1}{2}\frac{1}{\nabla\theta}(\nabla\theta)^2 D_{\mathrm{h}} \, , \\
&F_{g3} = -\frac{1}{2}\frac{1}{|\nabla\theta|}\left\{\left[\left(\frac{\partial\theta}{\partial x}\right)^2 - \left(\frac{\partial\theta}{\partial y}\right)^2\right] A_f + \right. \\
&\qquad \left. 2\frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial y}B_f\right\} , \\
&F_{g4} = -\frac{1}{|\nabla\theta|}\frac{\partial\theta}{\partial p}\left(\frac{\partial\theta}{\partial x}\frac{\partial w}{\partial x} + \frac{\partial\theta}{\partial y}\frac{\partial\omega}{\partial y}\right) , \\
&A_f = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}, \ B_f = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \, .
\end{aligned}
\right.
\tag{1}
$$

Here, θ is potential temperature and D_{h} the horizontal divergence. F_g is the frontogenesis function. $F_{g1}, F_{g2}, F_{g3}, F_{g4}$ are diabatic heating, horizontal divergence, horizontal deformation, and the tilting term, respectively (Ogura and Portis, 1982; Li and Zhao, 1996).

Figure 6 shows the frontogenesis function composed of the horizontal divergence term and deformation term at 925 hPa, 0600 UTC 9 June 1998. It can be clearly seen that the frontogenesis area was also in

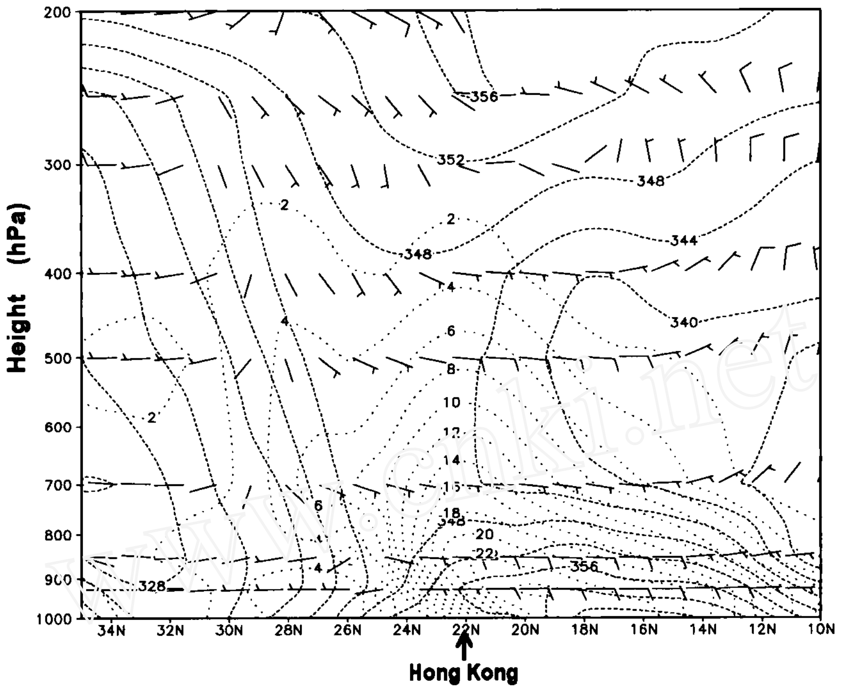


Fig. 7. Meridional vertical cross section across Hong Kong, of wind, specific humidity (dotted line, g kg^{-1}), pseudo-equivalent potential temperature (dashed line, K), at 0600 UTC 9 June 1998.

the southwest-northeast oriented zone. In the frontogenesis zone, a maximum was near Hong Kong and the Pearl River delta. It indicates that the weak cold air activities which are related with the frontogenesis, especially the upward motion branch ahead of the front, could play a very important role in initiating the heavy rainfall in Hong Kong.

To reveal the vertical structure of the frontal zone, the vertical cross section has been analyzed. Figure 7 shows the meridian vertical cross section across Hong Kong, of wind, special humidity, and pseudo-equivalent potential temperature at 0600 UTC June 9 1998. It can be seen clearly that a frontal zone existed between the surface and 500 hPa, and between 25°N and 28°N, which is consistent with Fig. 6. A strong convergence zone between southerly and northerly winds appeared below 800 hPa between 23°N and 25°N and an upward motion was to the north of Hong Kong. A moisture tongue to the south of Hong Kong below 800 hPa with a maximum of 24 g kg^{-1} could also be found. The isohume of 4 g kg^{-1} extended upward to above 500 hPa and that of 2 g kg^{-1} even up to 350 hPa. The area of moisture tongue and the region of upward motion closely matched. The warm and moist air ascended slantly along the front. It should be emphasized that Hong Kong (22°18′N) is in the warm sector ahead of the front. In this region, the convection could be very active because there was a region of convective instability south of 26°N and below 800 hPa. It should also be noted that the potential instability extended up to 700 hPa at 1800 UTC 8 June before the occurrence of heavy rainfall. After that, the region of potential instability decreased.

To understand the evolution characteristics of heavy rainfall, high resolution upper air sounding data at the various stages of the heavy rainfall event collected by the Hong Kong Observatory were analyzed in Fig. 8. It can be seen that the environmental conditions were very favorable to the occurrence of convection. Especially, the detailed structure in the lower troposphere could be detected by using high resolution upper air sounding data (Figs. 8a–f).

At the time of heavy rainfall (Figs. 8b, d, e and also Fig. 3) the LFC was lower, below 990 hPa. In the entire air column, CAPE was concentrated mainly in the middle troposphere. It was also noticed that the higher value of CAPE reappeared (Fig. 8f) after the heavy rainfall. It indicated that a feedback of the precipitation to the environment may exist. Probably, the favorable large-scale environment was still maintained and the CAPE can be soon rebuilt.

4. Formation, development and evolution of meso-β systems

In the previous sections, large-scale circulations and weather systems associated with the heavy rainfall in Hong Kong have been analyzed. It should be empha-

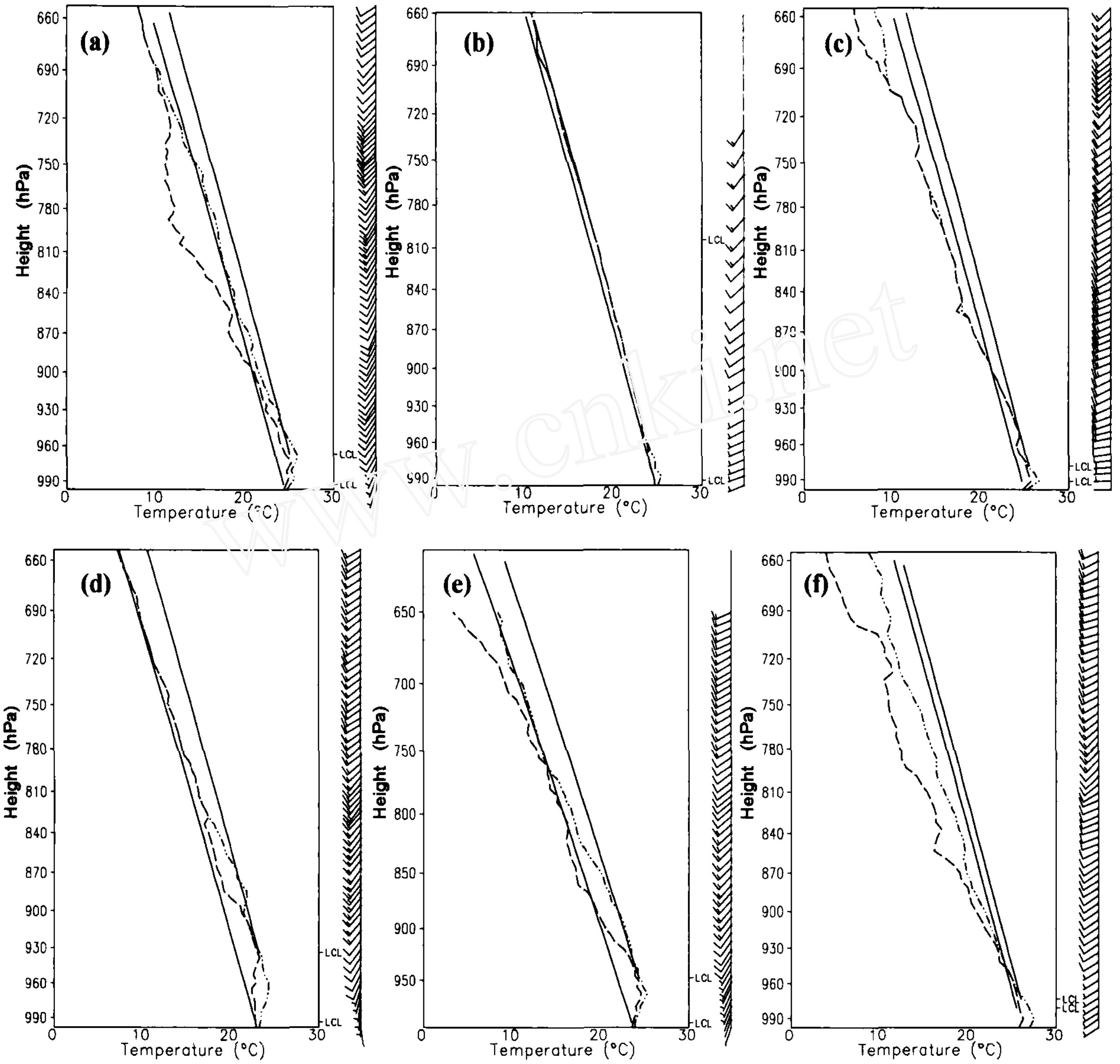


Fig. 8. High resolution upper air soundings of Hong Kong at (a)1800 UTC 8 June, (b) 2200 UTC 8 June, (c) 0300 UTC 9 June, (d) 0600 UTC 9 June, (e) 0900 UTC 9 June, and (f) 1200 UTC 9 June, 1998. State curve (–), dew point temperature (- - -), stratification curve (— · · — ··).

sized that mesoscale systems, especially meso-β scale systems, produced the localized heavy rainfall directly and, therefore, should be studied in detail. Moreover, it has been noticed that these meso-β scale systems seemed to be quite different from the mesoscale convective complex, MCC, in North America (Maddox, 1980, 1983). For this reason, the meso-β systems here should be paid more attention, and special, denser observational data, including satellite, Doppler radar, and automatic surface station data should be utilized extensively for gaining a better understanding of the detailed structure of the systems and their environment.

During the heavy rainfall in Hong Kong, strong convective systems can be detected on TBB (Black Body Temperature) images (Fig. 9). A cloud band extended from Guangdong to north of Taiwan and strong convective cloud clusters formed, developed and dissipated one after another. There were three main cloud clusters, Nos. 1, 2, and 3 (Fig. 9), which influenced the Pearl River delta and Hong Kong. From the TBB image at 1800 UTC 8 June, it can be seen that two meso-α scale cloud clusters with horizontal widths of 400–500 km were located in the east and west parts of Guangdong Province, respectively. The western cloud cluster may have caused the heavy rainfall in Hong Kong. Here, the cloud cluster with a TBB value of -40°C to the west of Hong Kong was named as cloud cluster No. 1. It can be found that cloud cluster No. 1 moved eastwards and developed, producing the strong

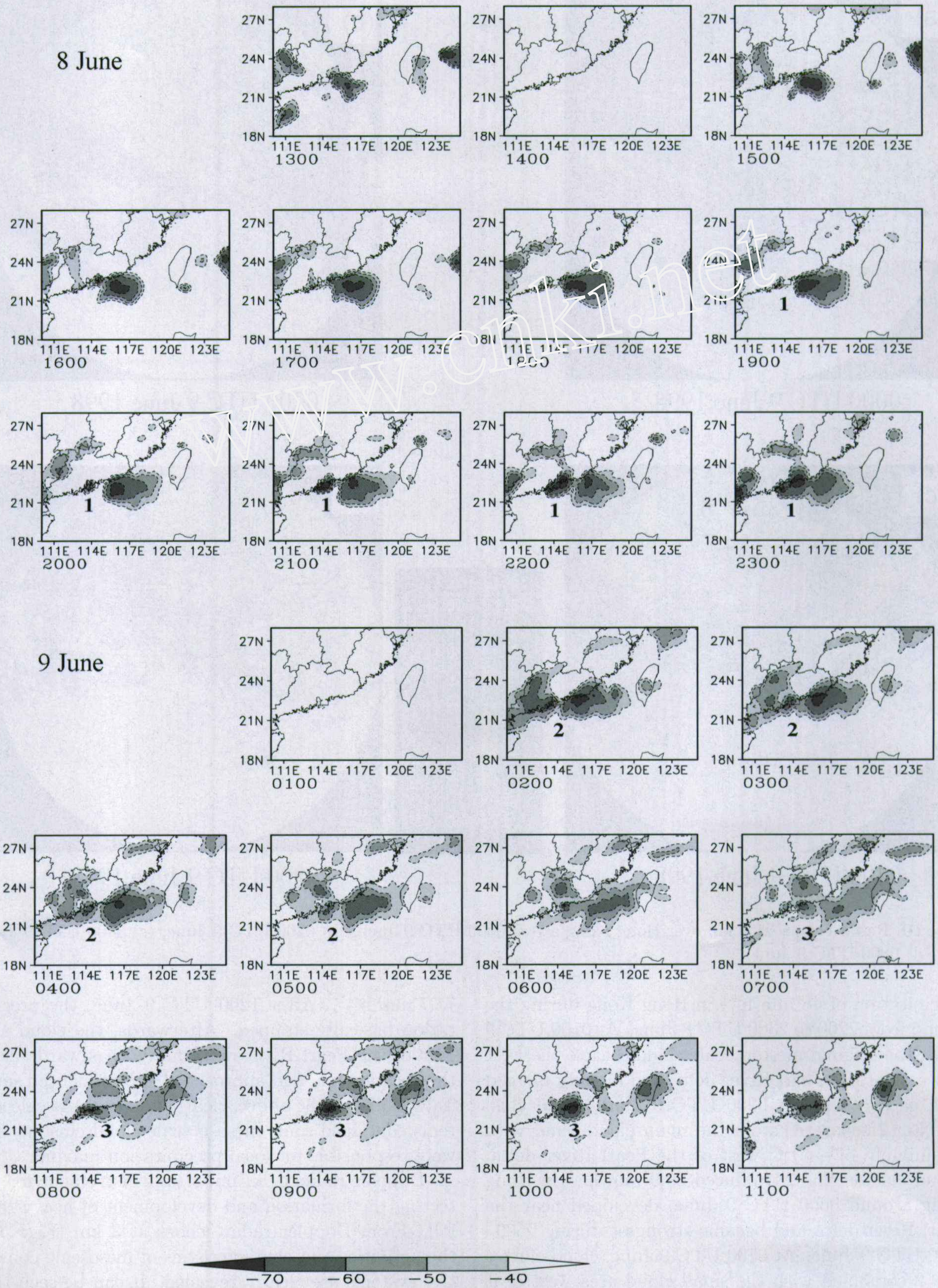
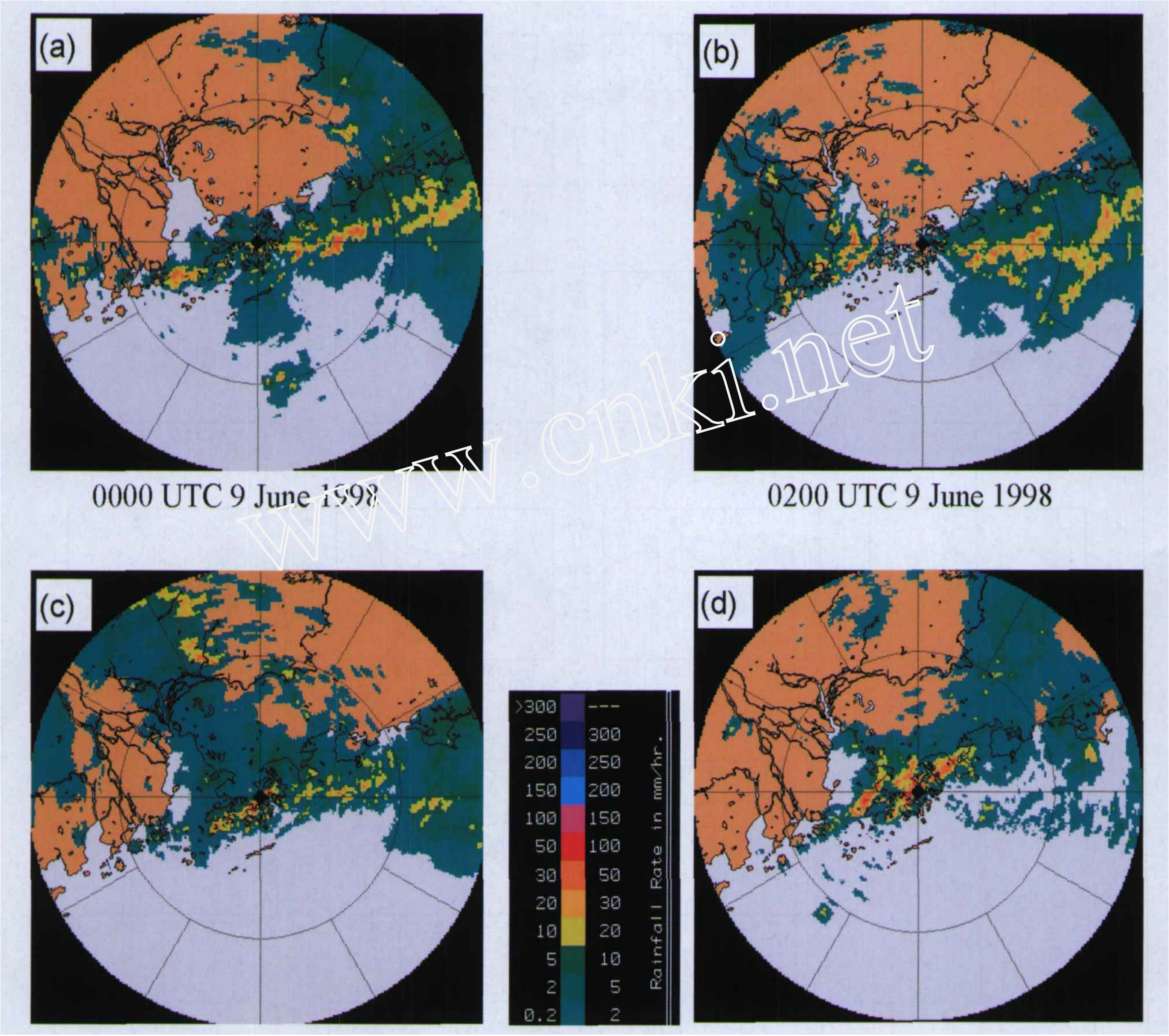


Fig. 9. Isolines of Black Body Temperature, 1300 UTC 8 June–1100 UTC 9 June 1998. Isolines are −40, −50, −60, and −70 (units: °C), respectively.



0000 UTC 9 June 1998

0200 UTC 9 June 1998

0400 UTC 9 June 1998

0800 UTC 9 June 1998

Fig. 10. Radar echoes at 3 km over Hong Kong at (a) 0000 UTC 9 June, (b) 0200 UTC 9 June, (c) 0400 UTC 9 June, and (d) 0800 UTC 9 June.

precipitation of 48 mm h^{-1} in Hong Kong during the period from 2200 to 2300 UTC 8 June. At 0100 UTC 9 June, the original meso-α scale cloud area to the west and east of the Pearl River delta had already merged with each other. At 0200 UTC 9 June, cloud cluster No. 2 separated from the main cloud band with a minimum of −60°C west of the Pearl River delta. Cloud cluster No. 2 produced 39.9 mm h^{-1} in Hong Kong around 0600 UTC 9 June, developed near the Pearl River delta and became strongest during 0500–0600 UTC 9 June. At 0700 UTC 9 June, cloud cluster No. 2 combined with the small cloud area west of it to intensify and become cloud cluster No. 3. At 0900 UTC 9 June, cloud cluster No. 3 became strongest and then produced the maximum precipitation amount of 71.7 mm h^{-1}. After 1200 UTC 9 June, the precipitation basically stopped. Afterwards, the cloud area east of the Pearl River delta moved eastwards along the coastal area, and approached and influenced south Taiwan. From the above, clearly, the meso-α scale systems contained some meso-β scale cloud clusters that were responsible for local precipitation maxima.

Doppler radar is an important instrument for detecting the formation and development of heavy rainfall. From Doppler radar echoes at 3 km (Fig. 10), the activities and characteristics of mesoscale convective systems are clearly revealed. It can be seen that some convective systems formed, one after another, in a warm and moist southwesterly current, and moved along the current from southwest to northeast. At

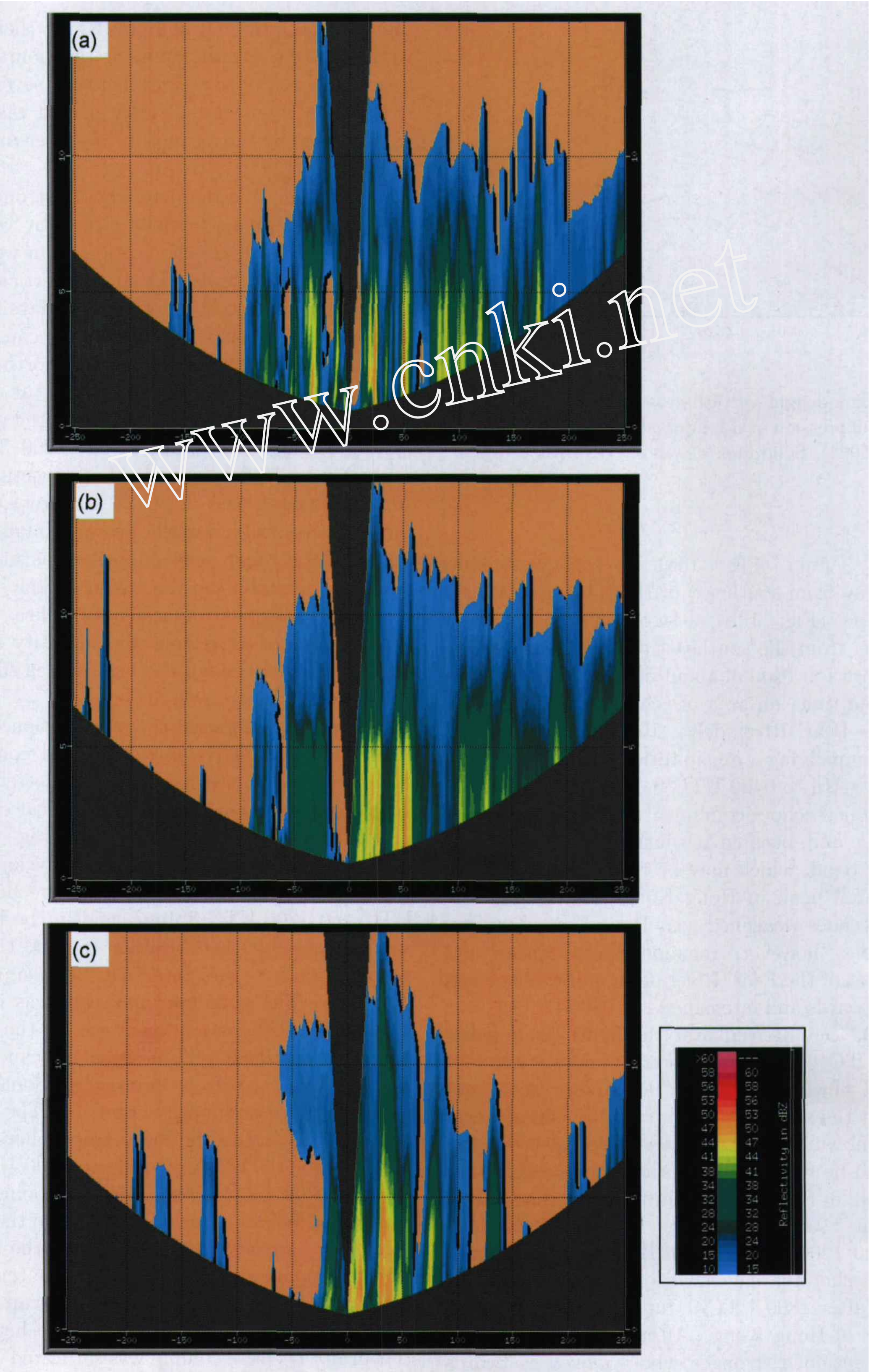


Fig. 11. East-west oriented vertical cross section of radar echoes in Hong Kong: (a) 2300 UTC 8 June, (b) 0600 UTC 9 June, and (c) 0900 UTC 9 June 1998 (units: dBZ).

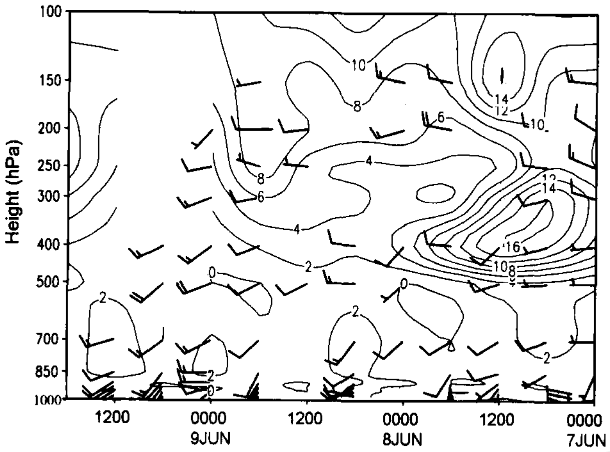


Fig. 12. Time-height vertical cross section of wind and dew-point depression at 6-h intervals in Hong Kong (station No. 45004). Solid line: dew-point depression (units: K).

0000 UTC 9 June (Fig. 10a), no echo was found 100 km away from southeast of Hong Kong. At 0200 UTC 9 June, (Fig. 10b), a stronger echo appeared 50 km away from the southeast of Hong Kong which produced precipitation of about 50 mm over one hour. At the same time, an area of echoes appeared in the west of the Pearl River delta, 100 km west of Hong Kong, accompanying a precipitation rate of more than 20 mm h^{-1}. Up to 0400 UTC 9 June (Fig. 10c), the aforementioned echoes combined with each other near Hong Kong and became a southwest-northeast oriented echo band, which may be related to the strong heavy rainfall peak in Hong Kong. After that, the combined echoes weakened near Hong Kong; stronger radar echoes, however, remained near Macao and Zhuhai, west of the Pearl River delta and these echoes moved eastwards and intensified. At 0800 UTC 9 June (Fig. 10d), they arrived over the Pearl River delta. At 1000 UTC 9 June, they were almost stationary and moved slowly towards the Pearl River delta (not shown). At the same time, three smaller and stronger maxima embedded in band-shaped echoes developed, which could be responsible for the other strong heavy rainfall peak in Hong Kong. These echoes then moved eastward at 1100 UTC 9 June, to east of Kowloon Peninsula at 1200 UTC 9 June. By 1600 UTC 9 June, the strong echo area had moved eastwards and weakened, and after 1800 UTC 9 June, arrived 58–80 km to the east of Hong Kong. After 2200 UTC 9 June, the aforementioned stronger echoes moved eastwards continuously and weakened. Similar characteristics can be seen in the radar echoes in Guangzhou (not shown). From the abovementioned facts, it can be confirmed that active mesoscale systems existed during the heavy rainfall in Hong Kong, their life cycles were between several hours to ten hours, and their spatial horizontal sizes were between several and several tens of kilometers. They moved eastwards and were steered by the current in the lower-middle troposphere.

In addition, the characteristics of strong convective systems can also be revealed clearly by vertical cross sections of the radar echoes oriented in west-east and south-north directions. From the vertical cross sections of the radar echoes, or RHI displays at the times of peak rainfalls shown in Fig. 10, it can be revealed that the horizontal size in the south-north direction of the convective systems was narrower, at only tens of kilometers, and the horizontal size in the west-east direction was larger (Fig. 11), at up to 200–300 km. The convective cells, developed in the convective rainband, with horizontal sizes of 20–30 km, were the systems directly responsible for the heavy rainfall. The maximum of the radar echo intensity was more than 50 dBZ and the echo top was up to 12 km. In comparison with the typical radar echoes of heavy rainfall in the Yangtze River region, the intensity in this case is similar, even though the echo top is slightly taller (Zhao et al., 2004).

To better understand the evolution of the vertical structures of the environmental conditions, radiosonde data at 6-h intervals are plotted in a time-height cross section. From the vertical cross section of wind and dew-point depression (Fig. 12), it can be found that there existed obvious cyclonic shears in the wind field in the mid troposphere between 0000 UTC and 1200 UTC 8 June, and in the lower troposphere from 1800 UTC 8 June to 0000 UTC 9 June, where there were also interfaces between the dry and moist air. The maximum moisture was in the lower troposphere, whereas dry air was in the mid troposphere before 0000 UTC 8 June. It can be deduced that the weak cold front approached South China before the occurrence of heavy rainfalls. The water vapor increased greatly in the lower troposphere during the period from 1800 UTC 8 June to 1200 UTC 9 June. Around 0000 UTC 9 June, the dew-point depression was zero at 500 hPa, meaning the air in the mid troposphere was already saturated. From the high resolution radiosonde data (not shown), the temporal variation of the wind and moisture fields can be detected clearly. Before the occurrence of the heavy rainfall, the air in the entire column was saturated around 2200 UTC 8 June, and the cyclonic shear in the wind field was in the lower troposphere at 0600 UTC 9 June. However, a temporal resolution of six hours seems too coarse to detect more detailed structures.

5. Wind field disturbances and moisture in the lower troposphere

Previous research has shown that the wind field, especially its disturbances, plays a very important role in the formation and development of heavy rainfalls (Zhao and Zhou, 1984:; Zhao et al., 2004). This is particularly true in South China. Generally speaking, the frontal system became shallower when it moved to lower latitudes. Therefore, wind data in the planetary boundary layer (PBL) should be analyzed carefully. However, only conventional data were used in previous studies. In this study, wind profiler data during the period of HUAMEX are available. At 1800 UTC 8 June, the southwest winds dominated below 3600 m, but were confined to several hundred meters above the ground. By 2200 UTC 8 June, the southerly winds can be found in the entire PBL. This means that the strong northward transportation of the warm and moist air in the PBL existed. From the hourly wind profiler data in Hong Kong (Sham Shui Po, Sha Lo Wan), it can be noticed that the layer of strong southwesterly wind became thicker after 0100 UTC 9 June. This implies again that a warm and moist southerly current contributed very significantly to the occurrence of heavy rainfall in South China (Fig. 13). In addition, high temporal resolution (10-minute intervals) wind profiler data in Sham Shui Po (22°18′N, 114°12′E) are analyzed (Figs. 14–15). In Fig. 14, the detailed structure of the wind field can be seen from the 200-m vertical resolution wind profiler data. In particular, the disturbances in the lower troposphere and in the PBL propagated from west to east, the lower level disturbances, moved eastwards around 0100, 0600, 0900 UTC (see dotted solid line in Fig. 14) and the wind intensified up to 18 m s^{-1}. The intensification of wind can also be found in the lower layer from 60-m vertical resolution wind profiler data at Sham Shui Po in Fig. 15. For example, the maximum of 15 m s^{-1} appeared in the 400–500 m layer between 0500–0600 UTC 9 June. The same characteristics were also seen in the data at Sha Lo Wan at 113°54′E and 22°18′N (not shown).

The moisture field is related closely with the occurrence of heavy rainfalls. Therefore, the vertical distribution of water vapor should also be investigated. From relative humidity data with the 100-m vertical resolution below 3600 m shown in Fig. 16, relative humidity in the lower troposphere was not so large at 1800 UTC 8 June; it was only 70% around the height of 2100 m at 0300 UTC 9 June before the heavy rainfalls. However, relative humidity approached 100% from 400–3600 m at 2200 UTC 8 June and then the moist layer thickened at 0300 UTC 9 June. This implies that the air column was saturated at least below 700 hPa. Only the air in the upper-middle troposphere at 0300 UTC 9 June was not saturated, but still larger than 80%. Generally speaking, the convergence of

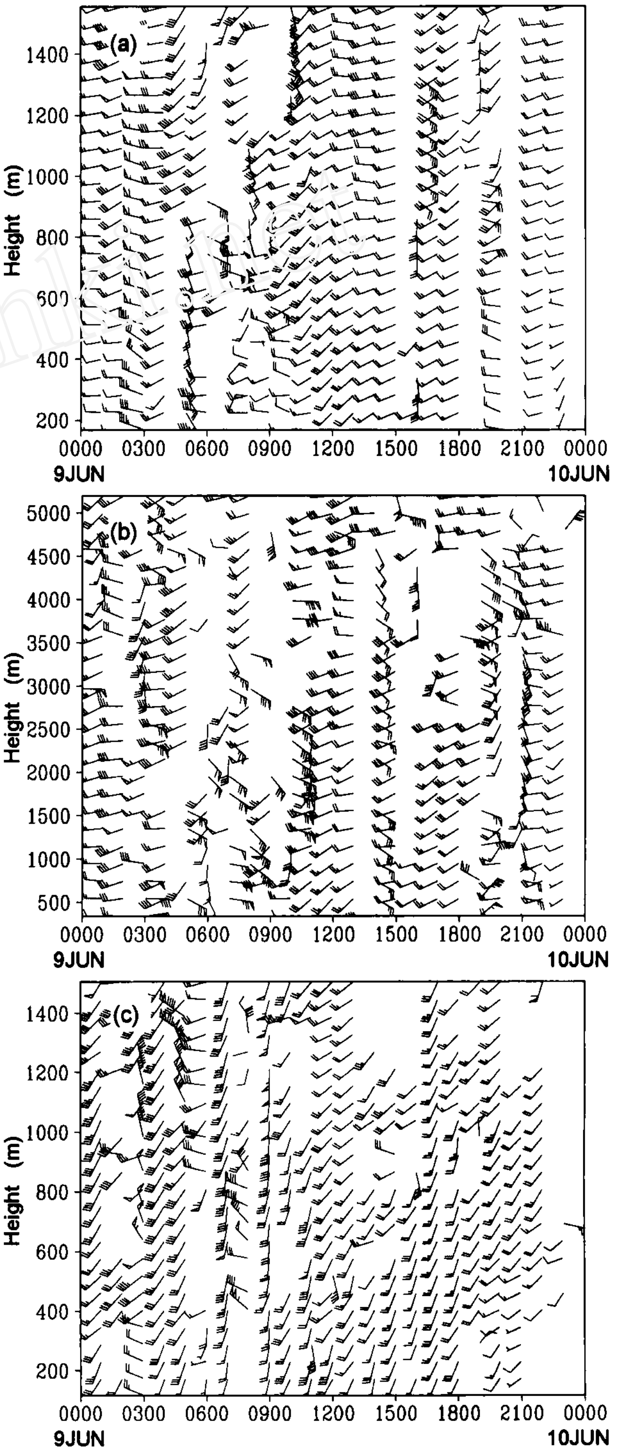


Fig. 13. Time-height vertical cross section of wind profiler data in Hong Kong at one-hour intervals, 9 June 1998 for different depths and stations. (a) Sham Shui Po, 2000 m; (b) Sham Shui Po, 6000 m; and (c) Sha Lo Wan, 2000 m.

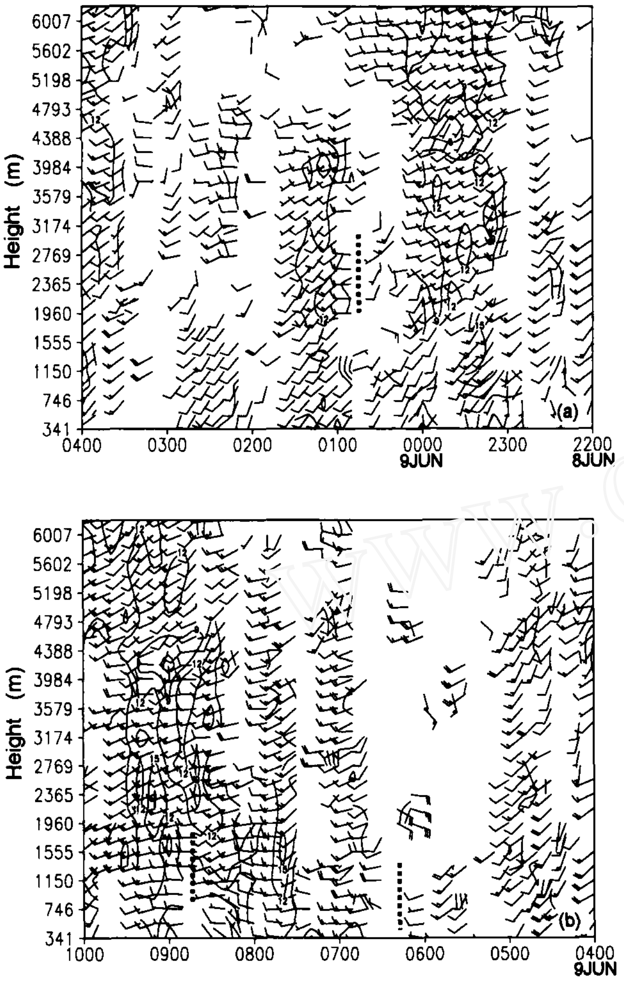


Fig. 14. Time-height vertical cross section of wind profiler data in Hong Kong [Sham Shui Po (22°8′N, 114°14′E)] at ten-minute intervals, 9 June 1998. Solid line: isotach more than 9 m s^{-1}. Vertical resolution: 200 m.

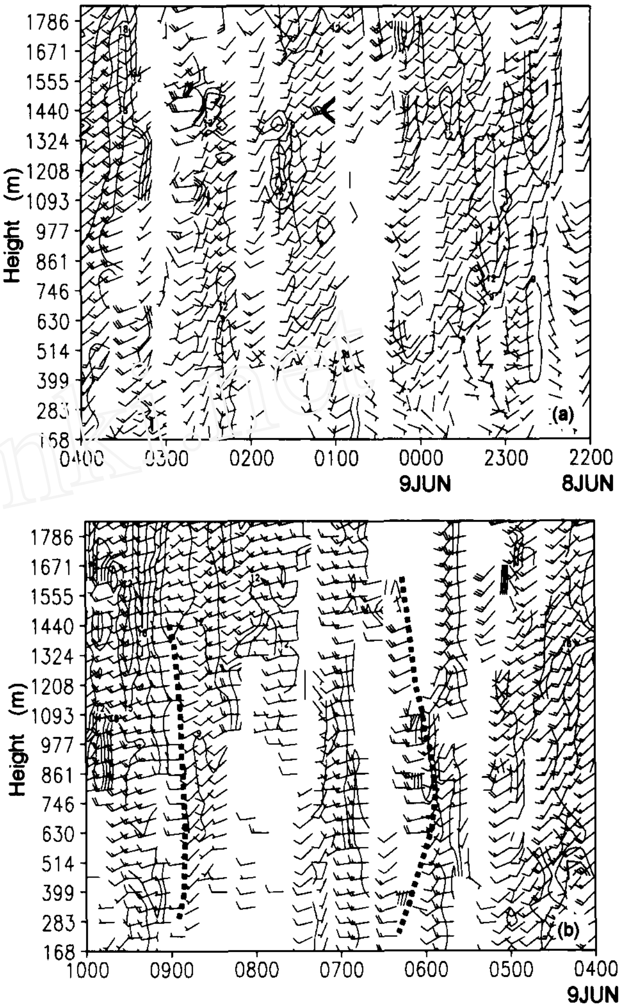


Fig. 15. Time-height vertical cross section of wind profiler data in Hong Kong (Sham Shui Po) at ten-minute intervals, 9 June 1998. Solid line: isotach more than 9 m s^{-1}. Vertical resolution: 60 m.

water vapor was stronger, and enough moisture supply existed.

The influence in the South China Sea monsoon on the heavy rainfall is very obvious. In particular, the southern current contributes significantly to the occurrence of the heavy rainfalls. However, the South China Sea is an area with sparse data and it is very difficult to do a detailed analysis. Fortunately, the data were collected in Dongsha Island (20°40′N, 116°43′E), which is situated in the northeast of the South China Sea. The virtual temperature is chosen to examine the variation in temperature and moisture. It can be seen that the virtual temperature (T_V) in the lower troposphere in Dongsha Island increased gradually (Fig. 17), from 28°C at 0300 UTC 8 June, up to 30°C at 0600 UTC 8 June, and to 31°C at 1200 UTC 8 June. This temperature was then maintained. This implies that the northward advancement of warm and moist air after 0000 UTC 8 June, and this result was consistent with the intensification of southerly winds and the associated moisture transportation.

The time series of various parameters at the surface of 1-h intervals in Hong Kong can describe well the mesoscale characteristics of heavy rainfall processes. In this section, the variation of meteorological parameters at the surface before and after the strong heavy rainfall in Hong Kong is discussed, including the time series of surface dew-point depression, sea level pressure, surface pressure, and wind fields (Fig. 18). Before the heavy rainfall occurrence, dew-point depression decreased significantly and the moisture at the surface clearly increased. In the hourly dew-point depression chart at the surface, the average value of 1°C can be seen from 0000 UTC to 1200 UTC 9 June. It demonstrates that the large-scale environment in the

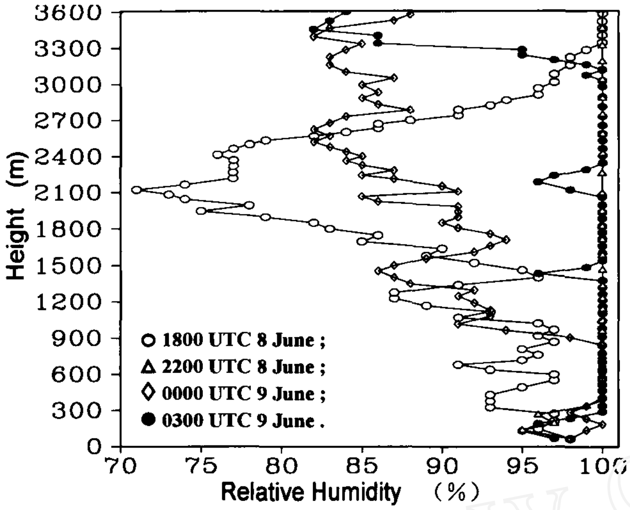


Fig. 16. Distribution of relative humidity in Hong Kong.

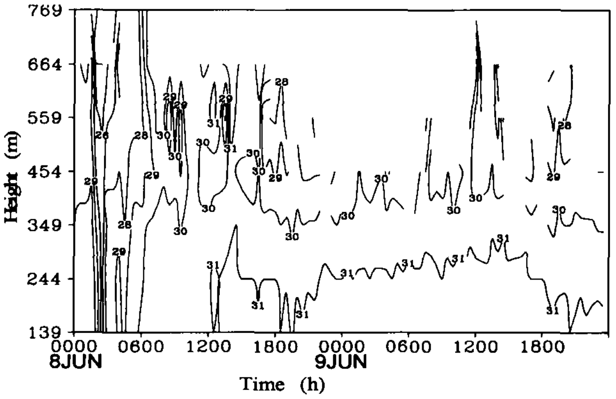


Fig. 17. Time series of virtual temperature (T_v, °C), in the lower troposphere in Dongsha Island.

heavy rainfall region was very moist. In addition, the surface pressure changed greatly and Hong Kong was controlled by low pressure systems (Fig. 18b) during the heavy rainfall.

In the wind data, the southern component of wind intensified obviously, with maximum wind speed approaching 8 m s^{-1}. In addition, there was an easterly wind before 1200 UTC 8 June, which shifted to a westerly and then to a southwesterly wind. The surface pressure increased and relative humidity decreased after 1500 UTC 9 June . Therefore, no strong precipitation existed in Hong Kong after 1600 UTC 9 June, even though radar echoes were still detected. The analysis of time series of several parameters at the surface is in agreement with the results from the other special observation data. The results indicate again that the strong heavy rainfall was, indeed, caused by mesoscale systems that occurred within the favoring large-scale conditions.

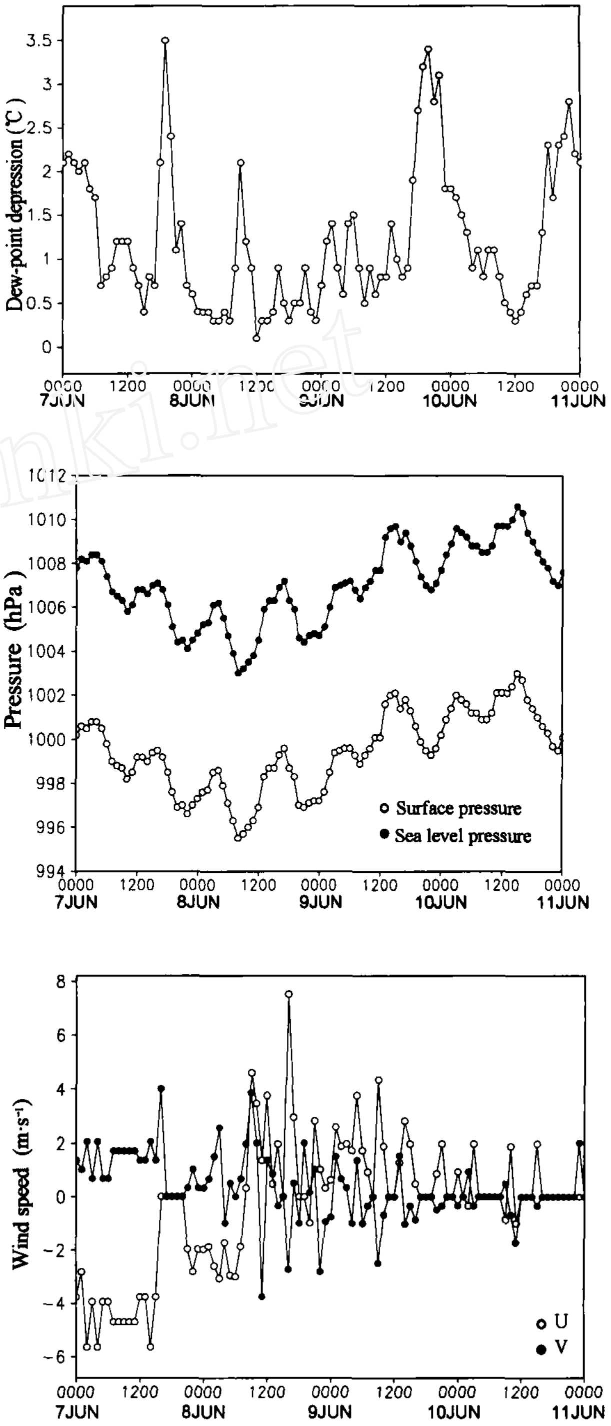


Fig. 18. Time series of meteorological parameters at the surface in Hong Kong during the period from 0000 UTC 7 June to 0000 UTC 11 June 1998.

6. Conceptual model of heavy rainfall in Hong Kong

To better understand the mechanism and structure of heavy rainfall that occurs in the warm sector ahead

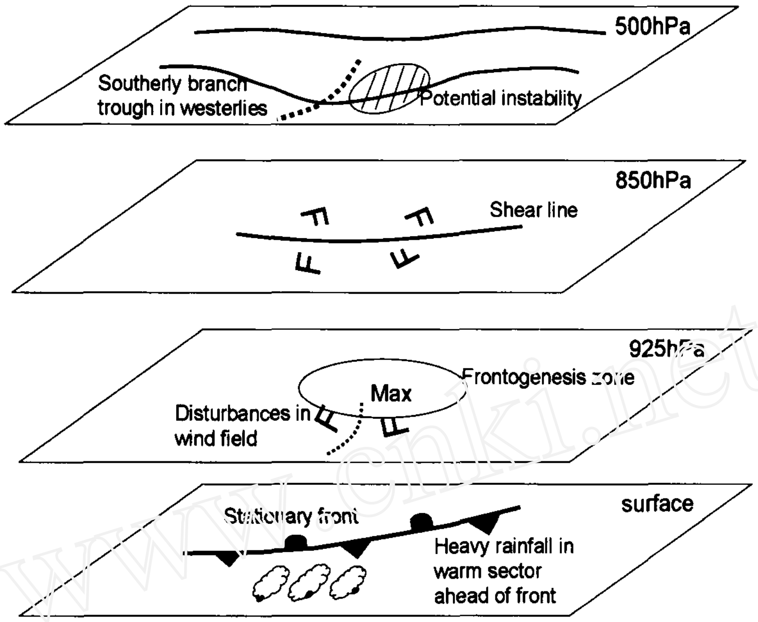


Fig. 19. A conceptual model of one kind of heavy rainfall in the warm section ahead of the front during the pre-rainy season in South China.

of a front during the pre-rainy season of South China, including Hong Kong, a conceptual model is proposed here.

As illustrated in Fig. 19, at 500 hPa, the southerly branch trough in the westerlies existed to the west of the Sino-Indian peninsula, and Hong Kong is located ahead of the trough; and at 700 hPa, South China is located ahead of the trough situated over the middle reaches of the Yangtze River and also ahead of the southerly branch trough in the westerlies (see Fig. 1a). At 850 hPa a shear line is oriented west-east and Hong Kong is situated south of the shear line. A frontogenesis zone exists north of Hong Kong. The impact of the cold air still exists, even though the cold air from higher latitudes has become shallow by the time it reaches Hong Kong. Meanwhile, disturbance in the middle-lower troposphere, especially in the PBL, propagates from west to east and arrives over Hong Kong and adjacent areas. These disturbances initiate the development of convective clouds and precipitation systems. This model conceptualizes a type of heavy rainfall that occurs in South China, where heavy rainfall appears in the warm sector ahead of the front during the pre-rainy season of South China. A comparison with other types of heavy rainfall will be given in the following section.

7. Discussion and conclusions

Hong Kong is located on the east side of the Pearl River delta where heavy rainfall occurs very often after the onset of the South China Sea monsoon and the beginning of the pre-rainy season of South China. On 8–9 June 1998, strong heavy rainfall with a maximum of 574 mm over one day occurred in Hong Kong. In this paper, mesoscale systems and their relationships with the heavy rainfall have been studied by using denser observational data collected during HUAMEX and SCSMEX experiments, including data from satellites, Doppler radar, wind profilers, and automatic meteorological stations. Detailed structure of the heavy rainfall and its evolution were investigated. The main conclusions are given as follows:

(1) The record heavy rainfall in Hong Kong in June 1998 occurred in the warm sector ahead of a weak surface cold front during the pre-rainy season of South China. During this period, favorable large-scale environmental conditions existed. The southerly branch trough in the westerlies was one of the important weather systems that affected South China. Particularly, the existence of a cold front and a shear line, a frontogenesis zone and a convergence zone between the southerly and northerly winds provided a favorable environment, which produced the deep moist unstable layer and the upward motion branch of vertical circulation (see Fig. 7).

(2) After the onset of the South China Sea monsoon, the southerly or southwesterly current in the form of a low level jet transported rich water vapor to the Hong Kong area and provided ample moisture supply. In addition, cold air originating from the middle and higher latitudes invading into South China could enhance the potential instability in the mid troposphere.

(3) In this case, unlike the Norwegian school's extratropical model (Palmen and Newton, 1969), no obvious synoptic scale cyclone or warm front presented. In addition, the situation may be quite different from that during the mei-yu season, as no medium-scale cyclone whose horizontal size is 500–1000 km existed (Matsumoto et al., 1971; Akiyama, 1984; Ninomiya and Muraki, 1986). Unlike the two kinds of lows in the mei-yu front (Zhao, 1988; Zhao et al., 2004), the systems were shallow and no obvious vortex system existed in some cases. However, other important information can still be found from Fig. 1a: a stronger ageostrophic current existed, in South China specifically, before the occurrence of the heavy rainfalls. This can cause heavy rainfalls because the strong convergence is closely related with the ageostrophic current. What is responsible for the appearance of the ageostrophic current? Is it forced by large-scale systems or by the systems in the PBL? Further investigation relating to this aspect is needed in the future.

(4) Revealed by the Doppler radar echoes and hourly data of surface automatic stations, a series of meso-β scale systems were found to have formed and developed over Hong Kong from 0000 UTC 8 June to 0000 UTC 9 June 1998. They were systems directly responsible for the formation of heavy rainfalls. Their echo top approached 12 km, even though the related large-scale system, such as the stationary front, was shallow. In addition, the meso-β scale systems in this case were quite different from the MCC found in North America, as defined by Maddox (1980, 1983). The life cycle of the meso-β scale systems here was 3–6 hours and the horizontal size was from several tens to one hundred kilometers. From TBB data, it was detected that some meso-β systems were embedded with meso-α cloud clusters in the warm sector ahead of the surface cold front. The active meso-β scale systems moved along with the steering current in the lower-middle troposphere. Therefore, they are called mesoscale convective systems (MCS) in East Asia. These can be an important feature of heavy rainfalls in the East Asia monsoon region, especially in South China, including Hong Kong.

(5) In this case, special observational data were utilized. It is revealed from the wind profiler data that, in the lower troposphere, obvious cyclonic disturbances in the wind field moved one after another along the horizontal shear line from west to east; a close relationship between the disturbances and the strong heavy rainfall in Hong Kong appears to exist. The upward motion caused by the convergence associated with the disturbances in the wind field may be a possible trigger for the formation of heavy rainfall. It should be noted that there exists a sparse data region over the South China Sea, where data on small islands, such as Xisha and Dongsha Islands have been very valuable. The collection and utilization of these data are important.

(6) Finally, a conceptual model was proposed for the type of heavy rainfall that occurs in the warm sector ahead of a surface cold front in South China during the pre-rainy season. It should be emphasized that, in this paper, only one case was investigated; the conceptual model should, therefore, be further validated with more cases.

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