NUMERICAL SIMULATION OF A MESOSCALE CONVECTIVE SYSTEM (MCS) DURING THE FIRST RAINY SEASON OVER SOUTH CHINA*

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ABSTRACT

Based on the NCEP/NCAR reanalysis data and observations collected during the SCSMEX, a mesoscale convective system (MCS) occurring over South China during 23—24 May 1998 has been studied with a numerical simulation using the Fifth Generation Penn-State/NCAR Mesoscale Modeling System (MM5). The successful simulations present us some interesting findings. The simulated MCS was a kind of meso-β scale system with a life cycle of about 11 hours. It generated within a small vortex along a cold front shear line. The MCS was characterized by severe convection. The simulated maximum vertical velocity was greater than 90 cm s^{-1}, and the maximum divergence at about 400 hPa. The rainfall rate of MCS exceeded 20 mm h^{-1}. To the right of the simulated MCS, a mesoscale low-level jet (mLLJ) was found. A strong southwesterly current could also be seen to the right of MCS above the mLLJ. This strong southwesterly current might extend up to 400 hPa. A column of cyclonic vorticity extended through most part of the MCS in the vertical direction. Additionally, the simulated MCS was compared favorably with the observational data in terms of location, precipitation intensity and evolution.

Key words: mesoscale convective system (MCS), mesoscale low-level jet (mLLJ), heavy rainfall, South China first rainy season, numerical simulation

I. INTRODUCTION

Heavy rainfall and flooding occurring over South China during the first rainy season (the Apr. —Jun. flood season) have strong influences on the regional economy. In order to minimize the effect of heavy rainfall and severe flood damages, great efforts have been made to improve our understanding and skill in forecast and warning of these events, including the implement of the field experiments of "South China First Rainy Season Rainstorm Experiment" during the late 1970s and the "South China Rainstorm Experiment" (HUAMEX) project carried out in 1998. Based on the observations collected in these field experiments, scientists have made significant progresses in understanding the formation and development mechanisms of heavy rainfall events in these areas (Huang 1986; Wang et al. 2001).

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Studies evidence that most of the heavy rainfall happening during this period is associated with mesoscale convective systems (MCSs). Unfortunately, because the high spatial and temporal resolution observational data are not available, few research work has been done to the South China MCS (Zhang et al. 2000). The heavy rainfall event occurring during 23 — 24 May 1998 over South China is a typical rainstorm case of HUAMEX. It was associated with MCS. As for these two days just fall in the intensive observational period of SCSMEX, using the observational data collected during SCSMEX together with NCEP/NCAR reanalysis data, we have performed a numerical simulation study on one of the MCSs related to the heavy rainfall event mentioned above. The results of the numerical simulation, carried out by using the Fifth Generation Penn-State/NCAR Mesoscale Modeling System (MM5), show us some interesting findings. Though an insufficiency of the corresponding high-resolution observational data prevents us from directly verifying the mesoscale structure and evolution characteristics of the model simulated MCS, we consider that the numerical simulation is desirable and helpful in MCS research. Because the simulated MCS produced much the same precipitation as the observation, and compared favorably with the observed system in terms of location and evolution, the initiation and development of the simulated MCS may be supposed to be one kind of a typical pattern of MCS in South China.

II. OVERVIEW OF THE HEAVY RAINFALL EVENT AND NUMERICAL SIMULATION EXPERIMENTAL DESIGN

In 23 — 24 May 1998, during the HUAMEX period, influenced by the cold air, a heavy rainfall occurred over South China. Including Yangjiang City, 14 weather stations situated in the Xijiang River and Zhujiang River Basins recorded the rainfall over 80 mm in 24 h, among these, some stations to the west of Zhujiang River Mouth recorded the rainfall over 100 mm. The maximum of 24 h rainfall of 233. 7 mm was recorded at Sihui (Yi 1999). Macau also observed accumulated precipitation of 140. 8 mm between 0017 UTC 23 and 0010 UTC 24 May. A few studies have been devoted to this event, including the analysis of the environment and cloud clusters of the rainstorm (Wang et al. 2001), numerical studies on their mesoscale structures and cloud physical processes (Wu et al. 2001; Wang et al. 2002).

The numerical modeling system MM5 used in this numerical study is a non-hydrostatic, primitive equation model with terrain-following sigma (σ) vertical coordinate and sophisticated physical processes, which has been developed at Penn State and NCAR as a community mesoscale model. Many studies have proved that the modeling system has a good ability to simulate the mesoscale structure and evolution of mesoscale systems (Chen et al. 1998; Rogers and Fritsch 2001). In our study, the number of σ levels is 23, giving 22 layers of unequal thickness in which the temperature, moisture, and wind components are defined. The computational areas are composed of 2 stationary domains (Fig. 1), the 18-km domain (domain 02, 97×100) is nested within the 54-km domain (domain 01, 75×85). Two domains were run simultaneously using one-way interfaces. The MRF scheme is used for the parameterization of the surface and planetary boundary layer (PBL). Other physical parameterizations of the model used in the study include the

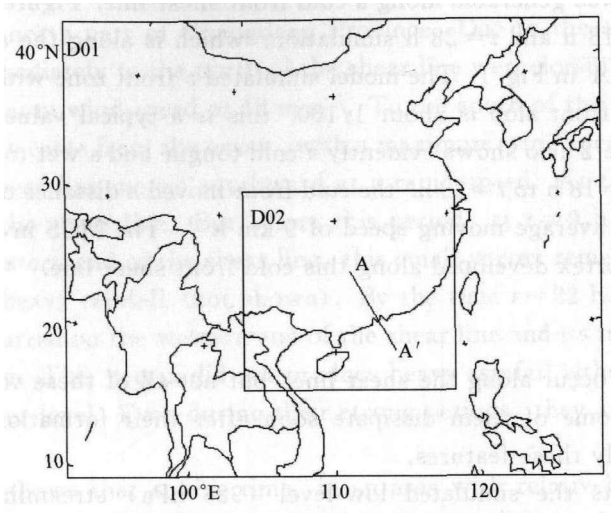

Fig. 1. The model domains. Coarse-mesh domain (D01, $\Delta x=54$ km) and fine-mesh domain (D02, $\Delta x=18$ km).

simple ice scheme for the explicit precipitation parameterization and KF scheme for the cumulus precipitation parameterization. Initialized at 0000 UTC 23 May 1998, the model was run for 42-h. Here we focus our discussions on the model output results of the 18-km domain.

III. SHEAR LINE AND SMALL VORTEX

1. *Cold Front Shear Line*

The numerical simulation shows that the MCS associated with the 23—24 May 1998

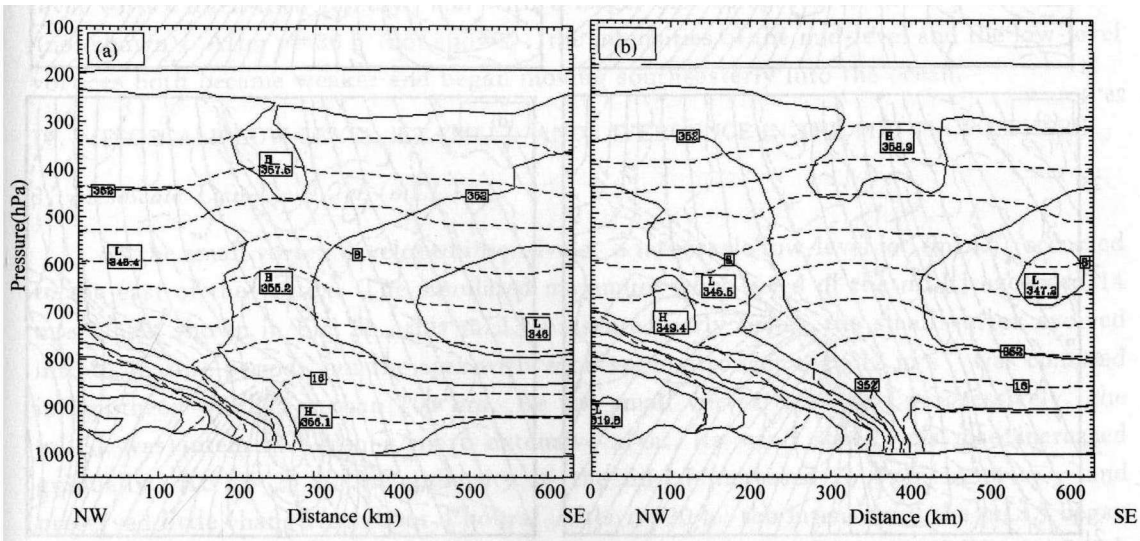

Fig. 2. Vertical cross-sections of equivalent potentials temperature (at intervals of 4 K, solid line) and water vapor mixing ratio (at intervals of 2 g kg^{-1}, dashed line) along the line $\overline{AA'}$ in Fig. 1 for $t=18$ h (a) and $t=28$ h (b).

heavy rainfall event was generated along a cold front shear line. Figure 2 presents vertical cross-section for $t=18$ h and $t=28$ h simulation, which is along the approximate north-south oriented line $\overline{AA'}$ in Fig. 1. The model simulated a front zone with strong θ_e gradient in the vicinity. The front slop is about 1/100, this is a typical value of cold front slop (Liang 1995). Figure 2 also shows evidently a cold tongue and a wet tongue in the vicinity of the front. From $t=18$ h to $t=28$ h, the cold front moved a distance of 90 km southward in 10 hours, with an average moving speed of 9 km h^{-1}. The MCS investigated here was generated within a vortex developed along this cold front shear line.

2. *Small Vortex*

Vortices usually occur along the shear line, but not all of these vortices cause heavy precipitation, even some of them dissipate soon after their formation. The simulation results show us clearly these features.

Figure 3 presents the simulated low-level (925 hPa) streamlines and speeds at different times in the vicinity of cold front shear line. The southward movements of the

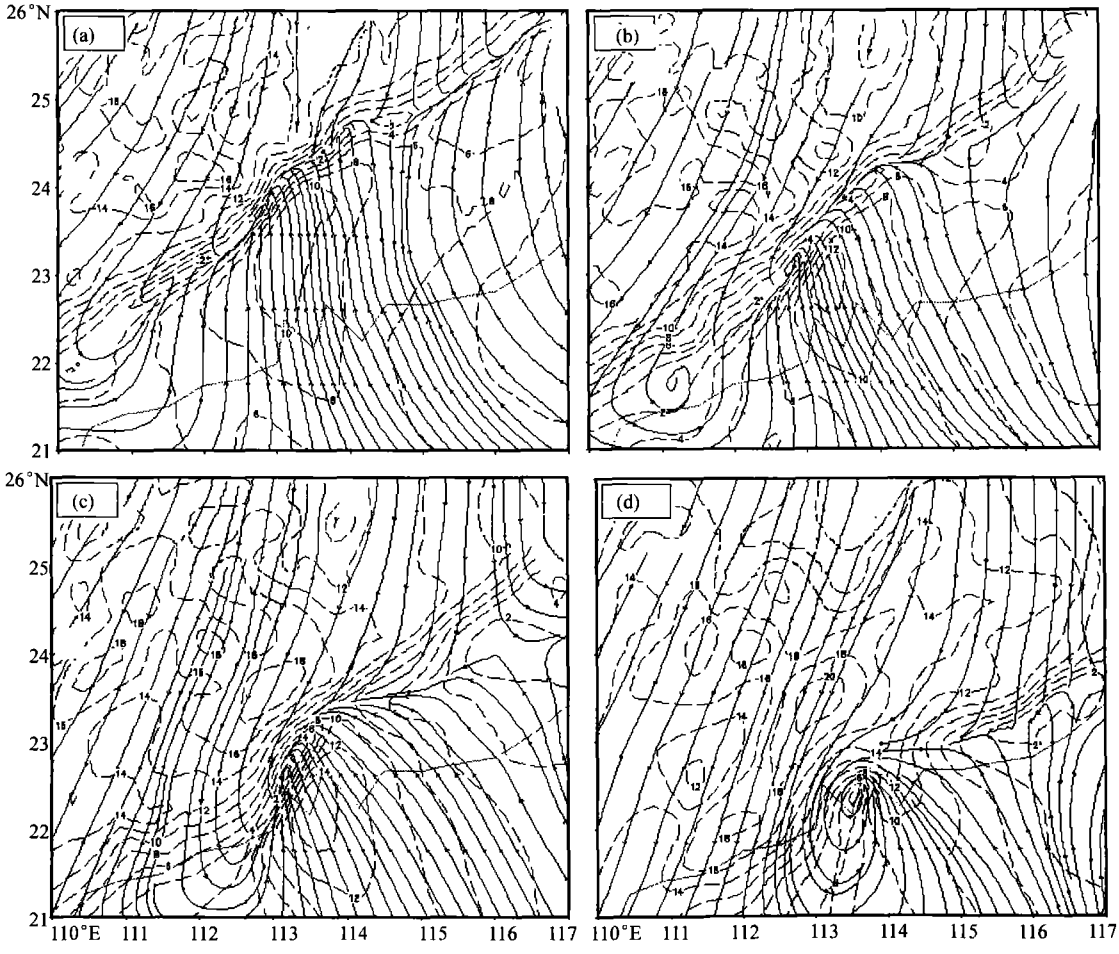

Fig. 3. Simulated 925 hPa streamlines (solid lines with arrow) and wind speeds (dashed lines at intervals of 2 m s^{-1}) for $t=18$ h (a), $t=22$ h (b), $t=28$ h (c) and $t=32$ h (d).

shear line can be clearly visualized. At $t = 18$ h (Fig. 3a) the cold front shear line approached middle-north part of Guangdong Province. Due to the effects of strong cold air, most parts immediately to the north of the shear line were dominated by the northeast wind, with a maximum wind speed of 18 m s^{-1}. To the south of the shear line, the warm and moist air mainly came from the ocean, with a maximum wind speed of about 10 m s^{-1}. As a result, the shear line moved southward at a rapid speed. At this time, no vortices were found along the shear line. But before this period, at $t = 9$ h, a small vortex had occurred on the western end of the shear line, this small vortex remained not a long time, and did not cause heavy rainfall (not shown). By the time $t = 22$ h, Fig. 3b reveals that another vortex occurred on the western end of the shear line and its intensity became weak as it moved easterly. This vortex did not produce heavy rainfall either. All these vortices are kept in the lower level. Even during their strong periods, they are confined below the 850 hPa.

Figure 3 also shows that at this time, in an area with relatively weak vertical wind shear (the vertical shear of meridional wind between 600 hPa and 925 hPa being 2 — 4 m s^{-1}, not shown), a small cyclonic vortex occurred. It was located over the model simulated heavy precipitation center, just in a strong convergence region of three different currents respectively from the northeast, southwest and southeast directions. In the next several hours, the small vortex developed rapidly and moved southeasterly. Figure 3c shows that the cyclonic circulation of the vortex developed firstly at low level when the vortex occurred. This feature was evident from the surface to 850 hPa, and above 700 hPa there existed a short-wave trough. As the small vortex developed progressively stronger, the short-wave trough was deepened in amplitude. By the time of about $t = 28$ h or late, when this low-level small vortex developed into its mature period, a closed cyclonic vortex occurred in the middle troposphere, 700—600 hPa above the low-level vortex. This mid-level vortex intensified rapidly, and with a larger size compared to the low-level vortex (not shown). After $t = 36$ h (not shown), the intensities of the mid-level and the low-level vortices both became weaker and began moving southeasterly into the ocean.

IV. MESOSCALE LOW-LEVEL JET (MLLJ) AND DIVERGENCE IN THE MID-TROPOSPHERE

1. *Mesoscale Low-Level Jet (mLLJ)*

As the small vortex developed intensively, a mesoscale low-level jet (mLLJ) occurred to the east of the vortex. The simulated maximum wind speed of the mLLJ exceeded 14 m s^{-1}. As shown in Fig. 3b, this mLLJ presented early before the small vortex evolved into its mature period, but the area with wind speed stronger than 12 m s^{-1} was confined in length or width less than 100 km. As the small vortex developed progressively, the mLLJ was intensified into a more extensive area. Its wind speed was also increased gradually. At $t = 26$ h, the intensity of the mLLJ increased to over 14 m s^{-1}, and preserved little change for about 4 hours. After $t = 30$ h, the intensity of the mLLJ began decreasing. The importance of the boundary layer mLLJ to the heavy rainfalls over South China has been noted in some research work (Li 1982; Liang 1996). In their numerical studies on a mesoscale convective system along South China Meiyu front, Zhang et al.

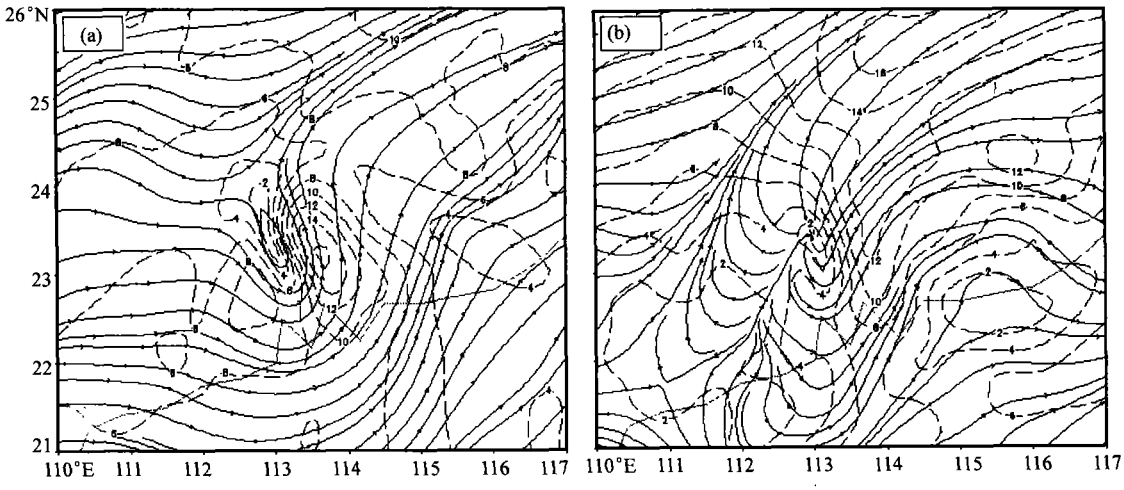

Fig. 4. Simulated streamlines (solid lines with arrow) and wind speeds (dashed lines at intervals of 2 m s^{-1}) at 600 hPa (a) and 400 hPa (b) for $t=32$ h.

(2000) also simulated an MCS-associated mLLJ. They emphasized that the mLLJ, which transported moistures into the MCS in the low-troposphere, plays an important role in moisture convergence within the heavy rainfall areas.

Since the thermal winds in the vicinity of the vortex were also in southwest direction, the upper southwesterly flows to the right of the vortex intensified with height, the maximum southwesterly wind areas can be observed upward to the 400 hPa. This also suggested that the vertical wind shear above the mLLJ is not evident, it is very difficult to separate the mLLJ from the strong southwesterly currents above it. During the mature period of the small vortex, the southwesterly wind speeds above the small vortex may be even stronger than that of the mLLJ. As shown in Fig. 4a ($t=32$ h), for instance, the maximum southwesterly wind speed was intensified up to 16 m s^{-1}.

As the small vortex developed intensively, going upward from 600 hPa, the cyclonic circulations of the vortex became weaker, and finally turned into anticyclonic diffluent outflows at 400 hPa. To the right of the 400 hPa divergent center above the small vortex, however, there still existed a strong southwesterly wind area. As shown in Fig. 4b, at $t=$ 32 h, we can still observe a strong southwesterly wind area with maximum wind speed of greater than 12 m s^{-1} situated to the right of the 400 hPa divergent center. Above 300 hPa, however, the strong southwesterly wind area has not been found.

2. *Divergence in the Mid-Troposphere*

As seen from Fig. 3, the flows in the vicinity of the small vortex are highly ageostrophic, the intensive convergent flows produced strong upward motion within the vortex. The divergent center corresponding to this strong vertical motion had its maximum located in the middle troposphere around 400 hPa. In its early period, the diffluent flows were not so strong, as shown at 400 hPa (see Fig 5a), the diffluent flows turned directing to eastward as they were controlled by the upper westerly flows. As the vertical motion and the corresponding divergence developed further strong, over the small vortex, the

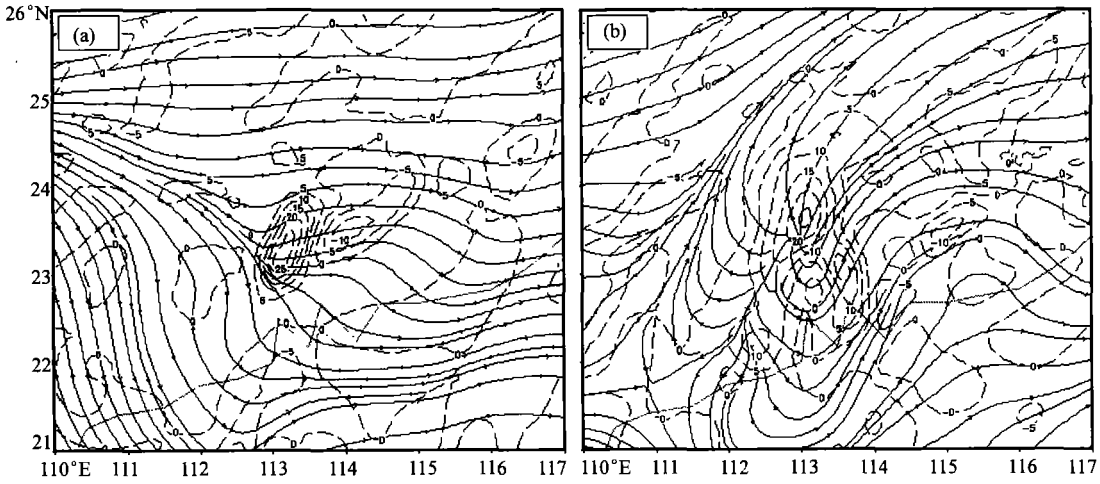

Fig. 5. Simulated 400 hPa streamlines (solid lines with arrow) and divergence fields (dashed lines at intervals of $5\times10^{-5}\ s^{-1}$) for $t=25$ h (a) and $t=32$ h (b).

apparently diffluent currents appeared, and flowed out from the center to the surrounding areas at 400 hPa (Fig 5b). This also means that there is a strong ageostrophic divergent center created in this layer. The related divergence can also be found at 300 hPa, but it does not look so strong as that of 400 hPa, and does not exhibit so evident ageostrophic characteristics either.

V. MESOSCALE CONVECTIVE SYSTEM (MCS)

An MCS is defined as a precipitation system with horizontal scales ranging from 10 to 500 km, a life cycle about 10 h or more and intense convective precipitation during its duration (Zhang 1999). It usually has been considered as a main of precipitation systems in some regions (Velasco and Fritsch 1987; Tao et al. 1998). According to Orlanski's subdivision of scales for atmospheric processes (Orlanski 1975), MCS belongs to a meso-β scale system.

As the aforementioned small vortex, there was an MCS developed within the vortex. Figure 6 presents vertical cross-sections along line $\overline{AA'}$ as shown in Fig. 2, indicating the MCS-associated vertical circulations and rainwater at different times. The shaded areas in Fig. 6 are the regions of rainwater mixing ratio greater than 0.4 g kg^{-1}. In addition, the corresponding 1 hour simulated precipitations at these different times are shown in Fig. 7. Comparison of Figs. 6 to 7 reveals that the simulated MCS is a typical meso-β scale system, with a scale of 40 km during its early development period, 100 km in mature period, and has a life cycle of about 11 h. Accounting for having abundant rainwater inside, the MCS produced precipitation of 20 mm or more every hour in its mature period. Specially, the MCS is characterized by severe convection, with the maximum vertical velocity located at about 600 hPa. Its maximum vertical velocity exceeded 90 cm s^{-1} when it developed strongest. More from Fig. 6, we are able to identify that, in its early period, before the development of the MCS, the nearly upright vertical motions of the MCS was concentrated within a very narrow region. Along with the evolution of the system, the

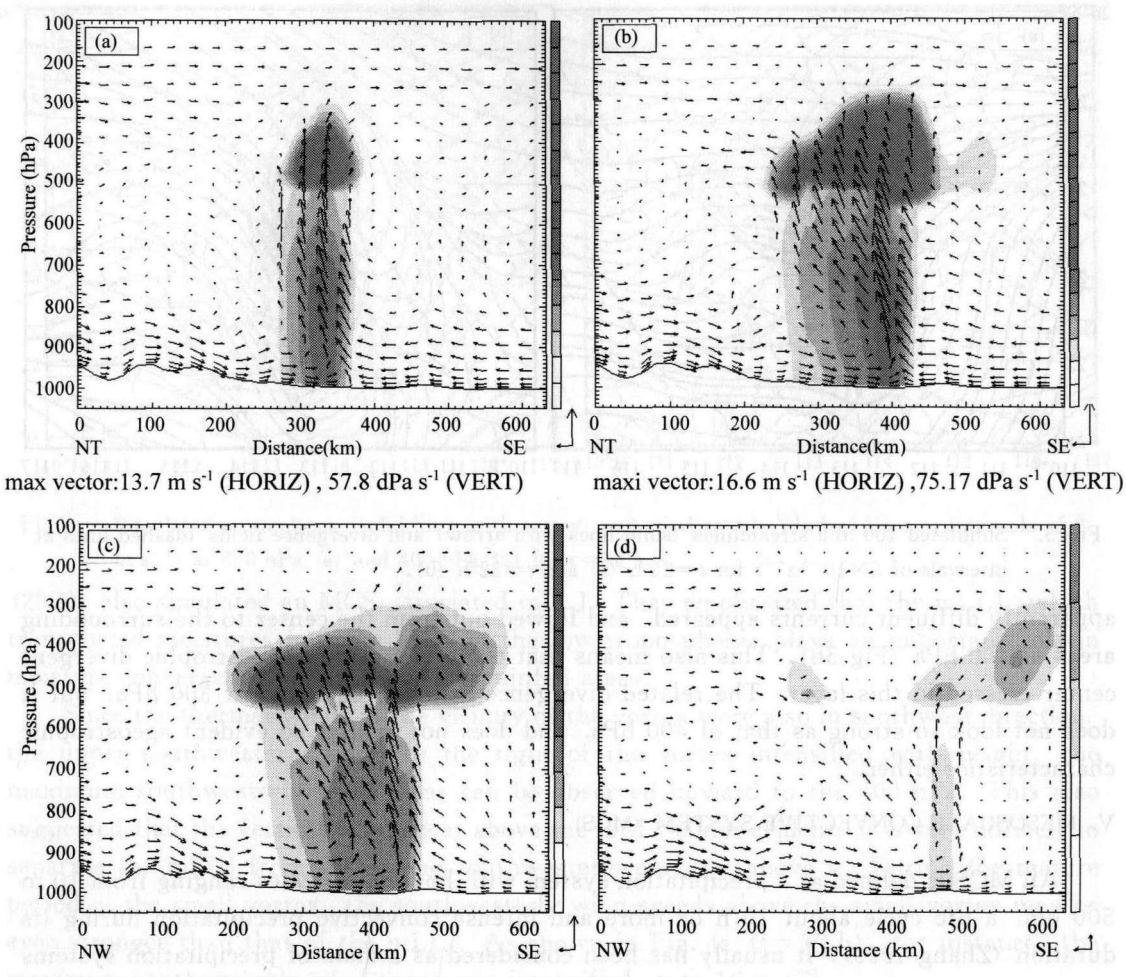

Fig. 6. Vertical cross-sections along line $\overline{AA'}$ in Fig. 1 for $t=25$ h (a), $t=29$ h (b), $t=32$ h (c), and $t=35$ h (d). Shaded areas are the regions of rainwater mixing ratio greater than 0.4 g kg^{-1}, wind vectors are vertical circulations.

vertical upward motion intensified gradually and dominated a wider range, with features of tilting northward.

It should be pointed out that in its strongest period, the rainwater of the simulated MCS may be extended up to 300 hPa, this compares well with the observed echo depth by Hongkong Doppler radar (not shown). In Fig. 8 we present the radar reflectivity of rainfall rate in the elevation of 0.5 km. As the observational data from $t=30$ h to $t=33$ h were not available, here in Fig. 8 only the echoes at $t=25$ h, 29 h, 35 h, 36 h are presented. Comparing with Fig. 7, it is found that the simulated precipitation is compared favorably with the intense radar reflectivity to the north of Hongkong, in the vicinity of Zhujiang River Mouth. And to a certain extent, the simulated MCS depicts the features of the observation, including the rainfall center position, the intensity, and the eastward movement and dissipation characteristics.

With such a strong vertical velocity, the intense convections within the MCS produced

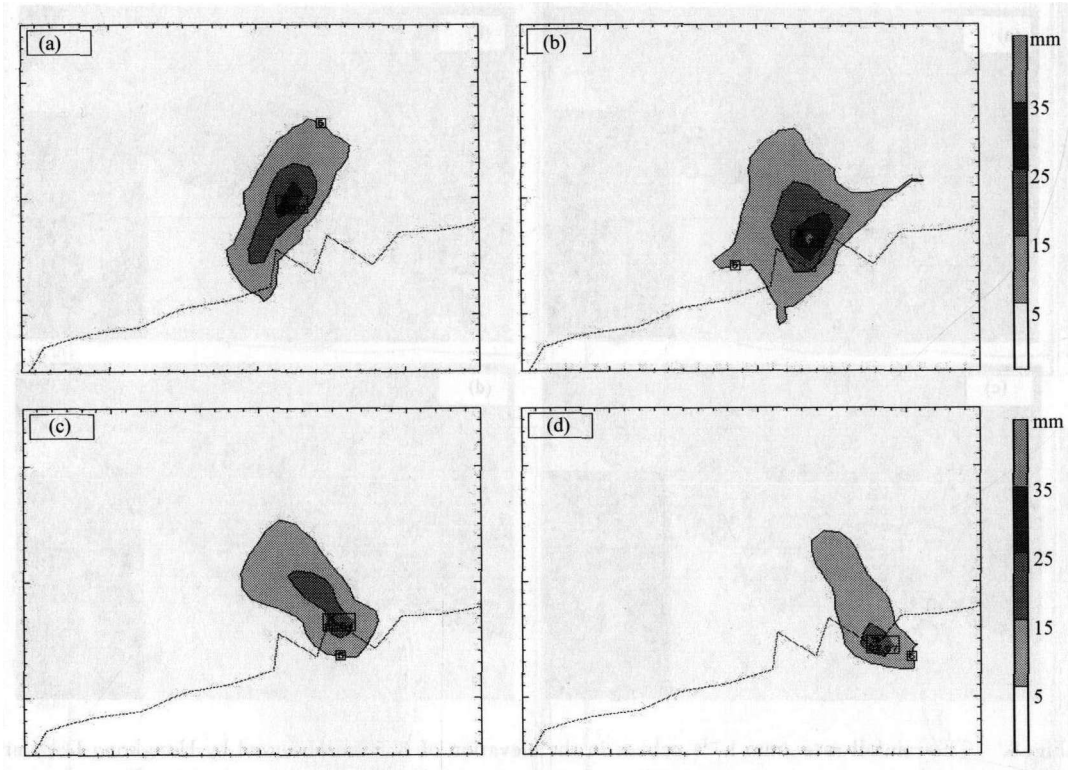

Fig. 7. Simulated 1 h precipitation of the MCS (mm) for $t=25$ h (a), $t=29$ h (b), $t=32$ h (c) and $t=35$ h (d).

a large amount of rainwater. As a consequence, a considerable latent heat was released. Figure 9 is as Fig. 6 and includes the corresponding latent heating fields. Compared with Fig. 6, it shows a close relationship between the vertical motion and the latent heat release. Within the MCS, the heating center located at a higher elevation (about 600 hPa) during its early period led to a rapid increase of vertical upward motion above the 600 hPa. As seen in Figs. 6a and 6b, in 4 hours, the top of the vertical motion extended up from 350 hPa to 250 hPa. But it is interesting to note that, as the MCS developed intensively, the heating center was dropped down to the lower layer, correspondingly the top of the vertical motion was also dropped down.

As aforementioned, the MCS was generated within a small vortex in the boundary layer, so it could be found that the maximum relative vorticity was located at a very low level. As shown in Fig. 10, when the MCS developed intensively, a column of cyclonic vorticity extended through most part of the MCS in the vertical direction. This suggests that because of the intense vertical motion, a pronounced vertical vorticity transport was exited. Figure 10 also reveals that the vorticity column was tilted northward, with the first maximum positive center found in the boundary layer, and a second maximum center presented in the middle troposphere.

In sum, the simulated MCS is very typical both in its structure and evolution characteristics. This also means that the MM5 can successfully simulate the generation

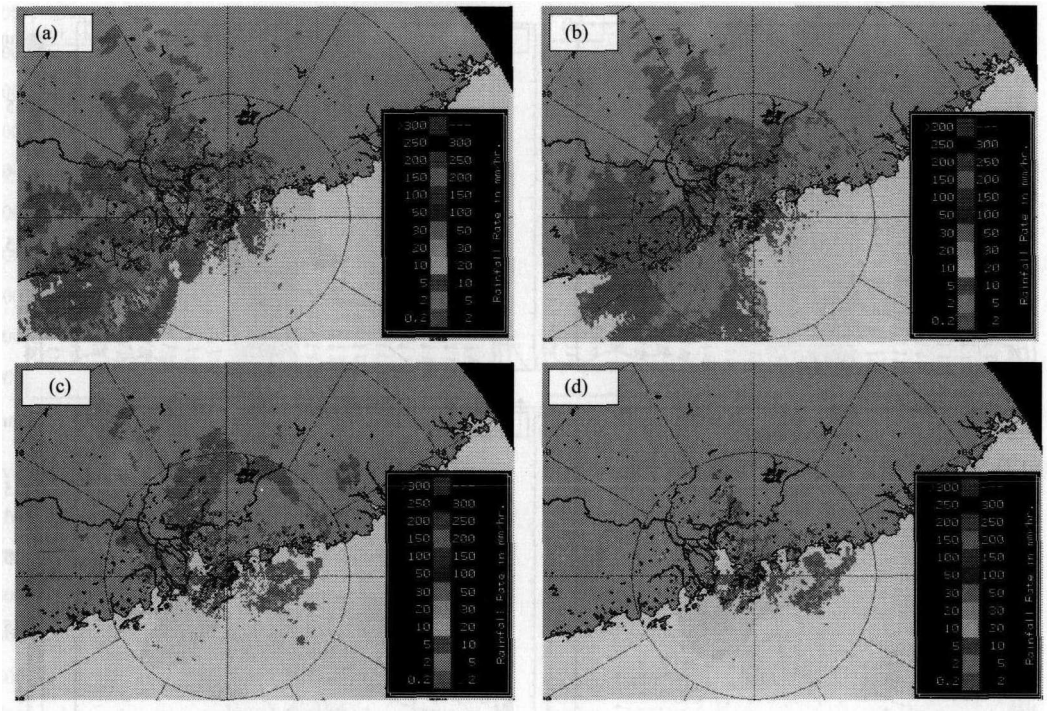

Fig. 8. The rainfall rate (mm h^{-1}) echoes in the elevation of 0.5 km observed by Hongkong Doppler Radar: (a) $t=25$ h, (b) $t=29$ h, (c) $t=35$ h, and (d) $t=36$ h.

and development of the MCS.

VI. COMPARISON BETWEEN THE SIMULATION AND THE CONVENTIONAL OBSERVATION DATA

From the results of comparing the simulated MCS with the conventional observation data, it can be found that the simulations are successful.

Firstly, the model predicted the substantial precipitation associated with this MCS. Figure 11 shows the 24-h (1200 UTC 23 May to 1200 UTC 24 May) accumulated rainfall for the observation and the simulation respectively. As shown in the figure, the model predicted that the maximum rainfall was 200 mm or more, approximately the same as the observation. However, the location of predicted heavy precipitation over South China was by east and by south, compared with the observation.

Secondly, the model gave a successful simulation of the evolution of the circulation systems. Figure 12 presents the distributions of streamlines and geopotential height fields at 850 hPa and 200 hPa respectively for the 24 h forecast of the numerical experiment and the corresponding verification fields constructed from the assimilation analysis of the SCSMEX observation data at 0000 UTC 24 May 1998. Comparison reveals that both the observations and the simulations at 850 hPa evidently show a cyclonic vortex over South China, they are almost located at the same place. Though the observational vortex shows more symmetric and more organized, the simulated geopotential height field shows that the simulated vortex is a little stronger than the observations. At 200 hPa, the model also

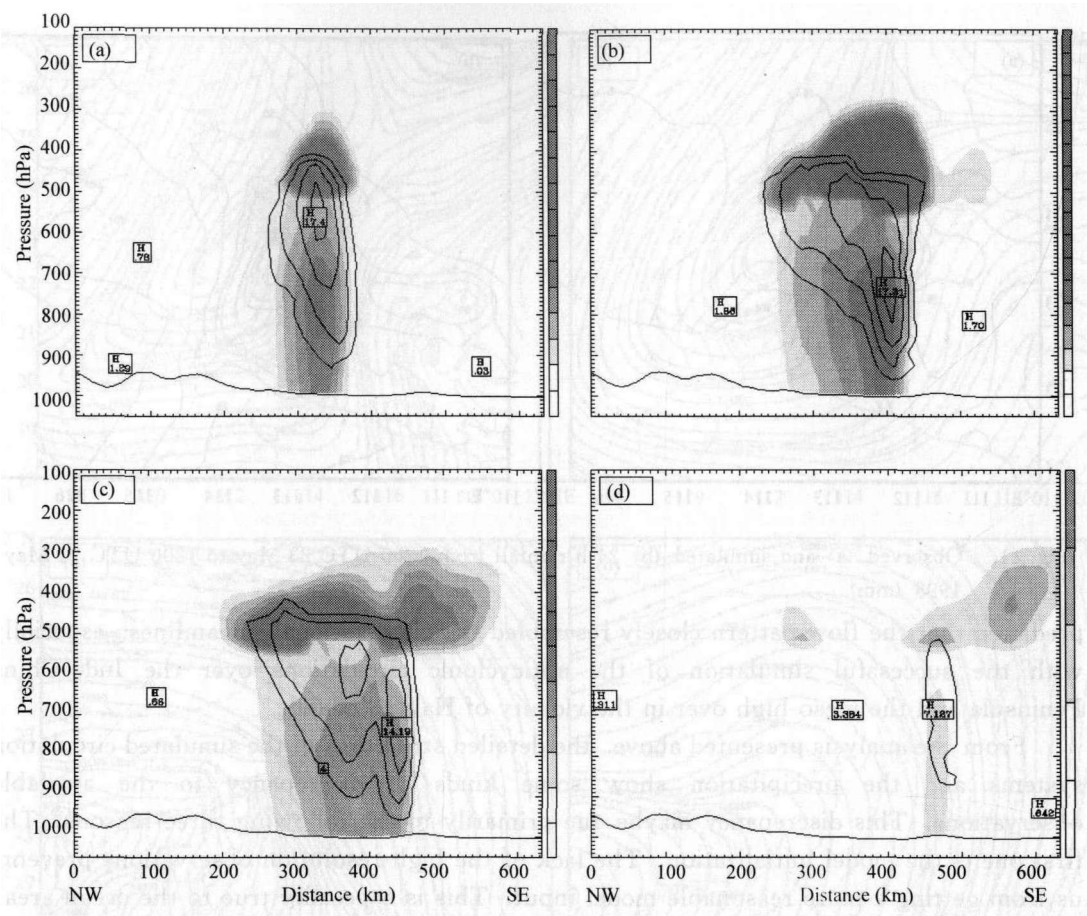

Fig. 9. Vertical cross-sections along line $\overline{AA'}$ in Fig. 1 for $t=25$ h (a), $t=29$ h (b), $t=32$ h (c), and $t=35$ h (d). Shaded areas are the regions of rainwater mixing ratio greater than 0.4 g kg^{-1}, solid lines are condensation heating (at intervals of 4 K h^{-1}).

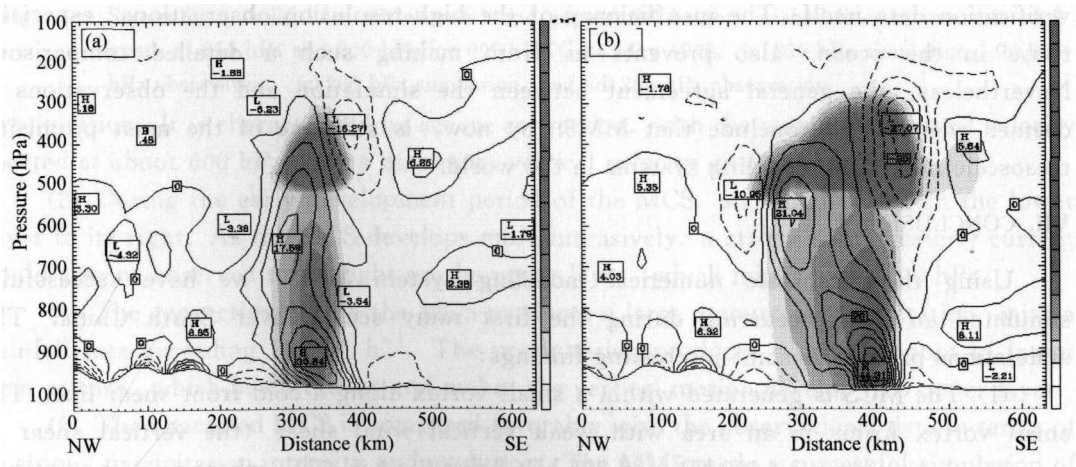

Fig. 10. Vertical cross-sections along line $\overline{AA'}$ in Fig. 1 for $t=25$ h (a), and $t=29$ h (b). Shaded areas are the regions of rainwater mixing ratio greater than 0.4 g kg^{-1}, solid lines (positive) and dashed lines (negative) are relative vorticity (at intervals of 5×10^{-5} s^{-1}).

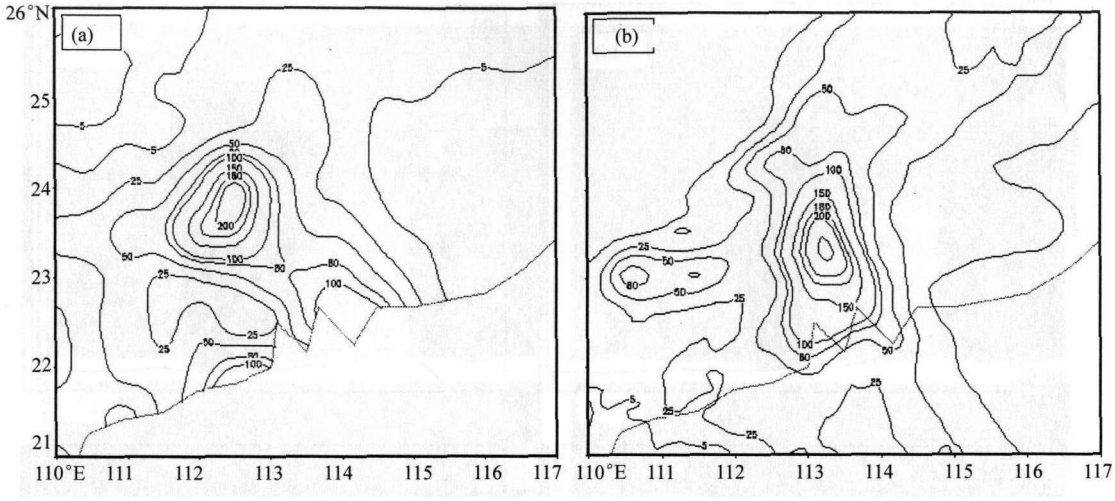

Fig. 11. Observed (a) and simulated (b) 24-h rainfall from 1200 UTC 23 May to 1200 UTC 24 May 1998 (mm).

predicted that the flow pattern closely resembled the observational streamlines, especially with the successful simulation of the anticyclonic circulations over the Indo-China Peninsula and the meso-high over in the vicinity of Hainan Island.

From the analysis presented above, the detailed structures of the simulated circulation systems and the precipitation show some kinds of discrepancy to the available observations. This discrepancy maybe due primarily to the following three reasons. The first one is the model initialization. The lack of the high-resolution observations prevents us from getting a more reasonable model input. This is especially true to the ocean area. The second one is that the model physical processes are not perfect, maybe they still need to be improved. For instance, a more reasonable cumulus precipitation parameterization scheme and the air-sea interaction processes should be concluded. The third one is the verification data itself. The insufficiency of the high-resolution observations, especially those in the ocean, also prevents us from making such a detailed comparison. Nevertheless, the general agreement between the simulation and the observations is deemed adequate to conclude that MM5, by now, is still one of the most promising mesoscale numerical modeling systems in the world.

VII. CONCLUSIONS

Using the mesoscale numerical modeling system MM5, we have successfully simulated an MCS occurring during the first rainy season over South China. The simulations present us some interesting findings:

(1) The MCS is generated within a small vortex along a cold front shear line. The small vortex forms in an area with weak vertical wind shear (the vertical shear of meridional wind between 600 hPa and 925 hPa being 2—4 m s^{-1}), where was also a strong convergence region of three different currents. These currents respectively came from the northeast, southwest and southeast directions.

(2) The MCS has a life cycle of about 11 hours, producing totally about 200 mm

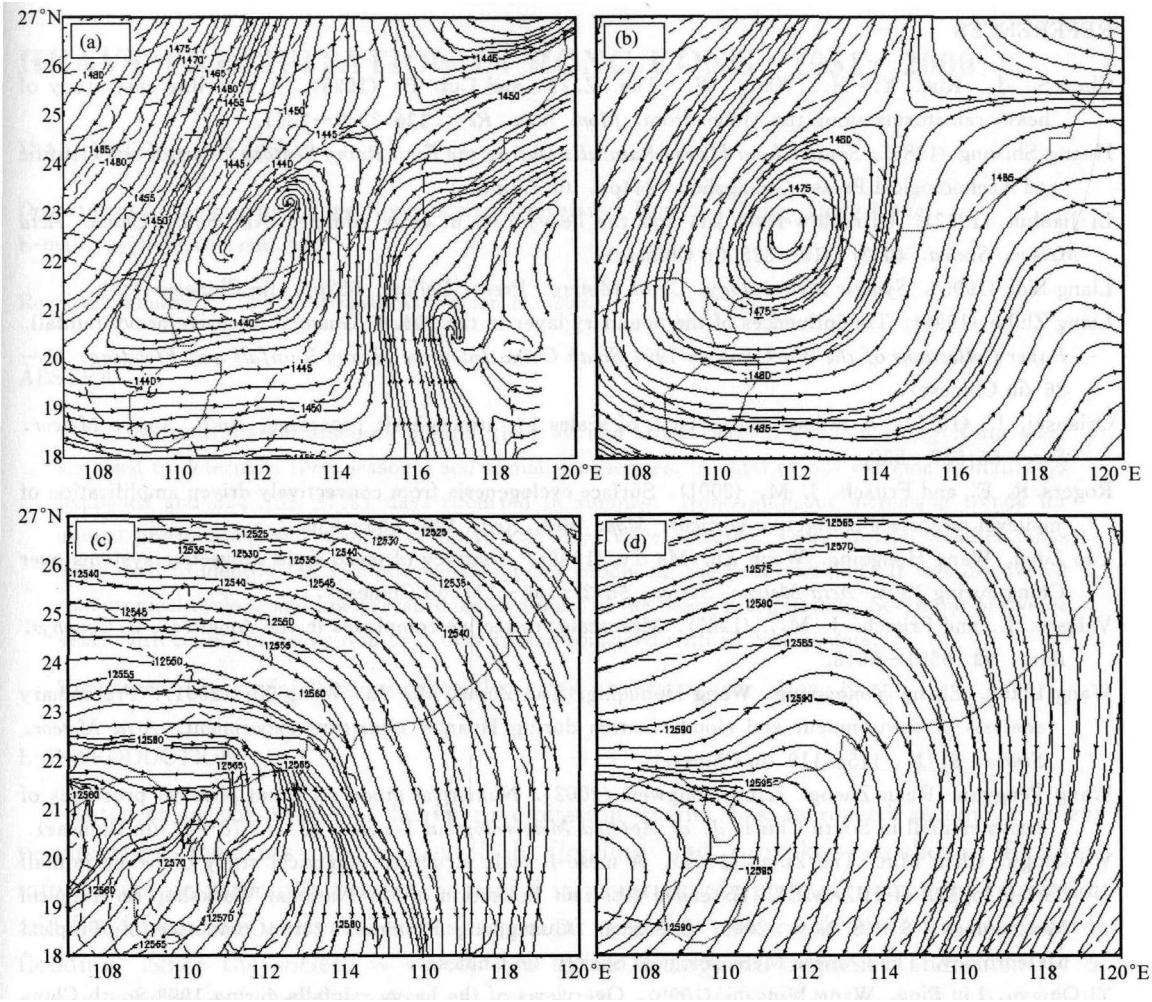

Fig. 12. Streamlines (solid lines with arrow) and gopotential height (dashed lines at intervals of 5 gpm) at 850 hPa and 200 hPa for 0000 UTC 24 May 1998. (a) 850 hPa simulation, (b) 850 hPa observation, (c) 200 hPa simulation, and (d) 200 hPa observation.

precipitation. It is characterized by severe convection, with the maximum vertical velocity located at about 600 hPa, and a maximum vertical velocity greater than 90 cm s^{-1}.

(3) During the early development period of the MCS, an mLLJ occurs in the lower layer to its right. As the MCS develops more intensively, a strong southwesterly current could also be observed to its right on the upper layer, which might up to 400 hPa.

(4) The convection within the MCS produces a large amount of precipitation, with a rainfall rate exceeding 20 mm h^{-1}. The precipitation produces a great amount of latent heat release, which heats the air and makes the vertical motion develop into upper layer.

(5) The simulated MCS is compared favorably with the observational data in terms of position, precipitation intensity and evolution. The MM5 made a successful simulation of the MCS.

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