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# Analysis of a Group of Weak Small-Scale Vortexes in the Planetary Boundary Layer in the Mei-yu Front

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**ABSTRACT**

A mei-yu front process in the lower reaches of the Yangtze River on 23 June 1999 was simulated by using the fifth-generation Pennsylvania State University-NCAR (PSU/NCAR) Mesoscale Model (MM5) with FDDA (Four Dimension Data Assimilation). The analysis shows that seven weak small mesoscale vortexes of tens of kilometers, correspondent to surface low trough or mesoscale centers, in the planetary boundary layer (PBL) in the mei-yu front were heavily responsible for the heavy rainfall. Sometimes, several weak small-scale vortexes in the PBL could form a vortex group, some of which would weaken locally, and some would develop to be a meso-$\alpha$-scale low vortex through combination. The initial dynamical triggering mechanism was related to two strong currents: one was the northeast flow in the PBL at the rear of the mei-yu front, the vortexes occurred exactly at the side of the northeast flow; and the other was the strong southwest low-level jet (LLJ) in front of the Mei-yu front, which moved to the upper of the vortexes. Consequently, there were notable horizontal and vertical wind shears to form positive vorticity in the center of the southwest LLJ. The development of mesoscale convergence in the PBL and divergence above, as well as the vertical positive vorticity column, were related to the small wind column above the nose-shaped velocity contours of the northeast flow embedding southwestward in the PBL, which intensified the horizontal wind shear and the positive vorticity column above the vortexes, baroclinicity and instability.

**Key words**: mei-yu front heavy rainfall, mesoscale numerical simulation, FDDA, meso-$\beta$-scale vortexes group, physical diagnosis and analysis

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## 1. Introduction

The mei-yu front heavy rainfall in the reaches of the Yangtze and Huaihe Rivers are often related to mesoscale convective systems (Zhang et al., 2004; Zhang et al., 2002; Ding, 1993; Lu et al., 1997; Gao et al., 2004). Recently, research on formation mechanisms and prediction theory of severe synoptic disastrous weather in China disclosed some important formation, development and evolution mechanisms of mesoscale heavy rainfall systems, such as the evolution mechanisms of isolated meso-$\alpha$-scale convective systems, or several closely related meso-$\beta$-scale convective systems in a meso-$\alpha$-scale convective system (Tao et al., 2001). Sun and Du (1996) pointed out that new small-scale vortexes could form locally in the middle and lower reaches of the Yangtze River with favorable terrain, moving slowly with complex evolution. However, the formation mechanism of such mesoscale heavy rainfall systems is still not clear because of complexity and variety. The weak small-scale cyclonic disturbances in the mei-yu front shear line, accompanied by heavy rainfall, have been too small and complex to be investigated or forecasted (Hu and Pan, 1996). Since, however, numerical simulation with improved initial fields and Four Dimension Data Assimilation (FDDA) of high spatial and temporal resolution has become an effective way to analyze the mechanisms of mesoscale heavy rainfall systems (Xu et al., 2001; Peng et al., 2002; Chen et al. (1998); Wang et al., 2003; Gao and Xu, 2001). Numerical simulation could help understand the processes responsible for the successful reproduction of an observed feature. Numerical simulation with high horizontal

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resolution could help disclose some formation, development and evolution mechanisms of mesoscale systems, offsetting spatial and temporal insufficiency of observations, which would further help in studying mesoscale systems. Heavy rainfall appeared in the middle and lower reaches of the Yangtze River from late June to early July in 1999, accompanied by several low vortexes along the mei-yu front (Gao and Xu, 2001). Chen et al. (1998) successfully simulated heavy rainfall processes of the low vortexes in the reaches of the Yangtze River (Cheng and Feng, 2003). However, most research in the past has mainly focused on the middle and low troposphere, and there has been little consideration of vortexes in the planetary boundary layer (PBL). The low vortex on 22 June 1999 was analyzed using a high resolution simulation output. It was discovered that the low vortex evolved from one of the small disturbances formed almost simultaneously in the PBL (Zhai et al., 2003), and the vortexes in the PBL on June 23–24 developed to become a meso–scale vortex through combination. This meant that some low vortexes might evolve from the reciprocity among several weak small-scale disturbances along the mei-yu front in the PBL through two processes. One is that these weak small-scale disturbances formed within a short period and developed upwardly to become low vortexes, such as those on 22 June 1999; and the other is that small-scale disturbances formed successively along the shear line in the PBL under a favorable circulation environment over a long period, developing into a larger scale low vortex through combination and upward development.

The low vortex moved eastward to the area of Sheyang (33.46°N, 120.15°E) in Jiangsu Province at 850 hPa, 0000 UTC 23 June 1999. The cyclonic shear behind the low vortex extended to Guilin (25.19°N, 110.18°E) along the middle and lower reaches of the Yangtze River. A significant mesoscale low vortex appeared in Jiujiang City (29.44°N, 116.00°E) in Jiangxi Province from 0000 UTC 24 June 1999, accompanied by a weak cyclonic surface disturbance and an intense rainfall process.

## 2. Simulation design

The model used for the simulation was the nonhydrostatic version, MM5, of the fifth-generation Pennsylvania State University-NCAR (PSU/NCAR) Mesoscale Model (MM5) (Grell et al., 1994). The model configuration included a coarse mesh of 90 km grid size, a fine mesh of 30 km grid size, and a finer mesh of 10 km grid size. Twenty three $\sigma$ levels were set up in the vertical direction, with five levels in the PBL. The model employed the Grell cumulus convection parameterization and the Blackadar High Resolution (BHR) PBL parameterization. The lateral boundary employed relaxation approximation. The MM5 model was initialized at 0000 UTC 22 June and ended at 0000 UTC 26 June 1999. Considering the difficulty of reproducing mesoscale vortex systems, especially weak small-scale vortexes, in simulation, Four Dimension Data Assimilation (FDDA) was used during the whole process of simulation to ensure accuracy. The data from the Huaihe River Basin Energy and Water Cycle Experiment (HUBEX) and dense surface observation data in East China was fully utilized. HUBEX included 21 aerological stations, with four observation times per day, and 98 surface stations with one-hourly observations, in East China. The weak small mesoscale vortex disturbance in this study was defined as a shallow system in the PBL with a horizontal scale of tens of kilometers. With emphasis on the formation and evolution processes of meso-$\beta$-scale vortexes and vortexes group, the heavy rainfall process in North Jiangxi Province on 23 June 1999 was investigated using output from the finer mesh of 10 km grid size.

## 3. Analysis of mesoscale vortexes in the planetary boundary layer

### 3.1 *Vortex disturbances group*

Figure 1 presents the 12-hourly stream field of observed data at 925 hPa and simulated data at the $\sigma$-level ($\alpha$=0.945) from 0000 UTC 23 June to 0000 UTC 24 June 1999. The shear line in the planetary boundary layer extended to the middle and lower reaches of the Yangtze River when the low vortex in the north of Nanjing moved eastward to the ocean at 0000 UTC 23 June 1999 (Fig. 1a). Possibly affected by the Huangshan Mountain, a weak mesoscale cyclonic divergence appeared in the shear line in Tongling City (30.58°N, 117.47°E) after 12 hours (Fig. 1b). A complete mesoscale low vortex moved to the Taihu Lake (31.20°N, 120.20°E) in Jiangsu Province (marked in Fig. 1b) with a strong cyclonic shear appearing from the Taihu Lake to Jiujiang City (29.44°N, 116.00°E) at 0000 UTC 24 June 1999 (Fig. 1c). Obviously, the observed vortex disturbance at 925 hPa appeared at about 1200 UTC 23 June. Although the vortex disturbance in northern Jiangxi Province was not significant, we could ascertain the existence of this weak disturbance due to the complete vortex in the stream field after 12 hours.

The simulation result was basically consistent with the observation. A disturbance appeared in Anqing (30.32°N, 117.03°E) at the $\sigma$-level ($\sigma$=0.945) at 0000

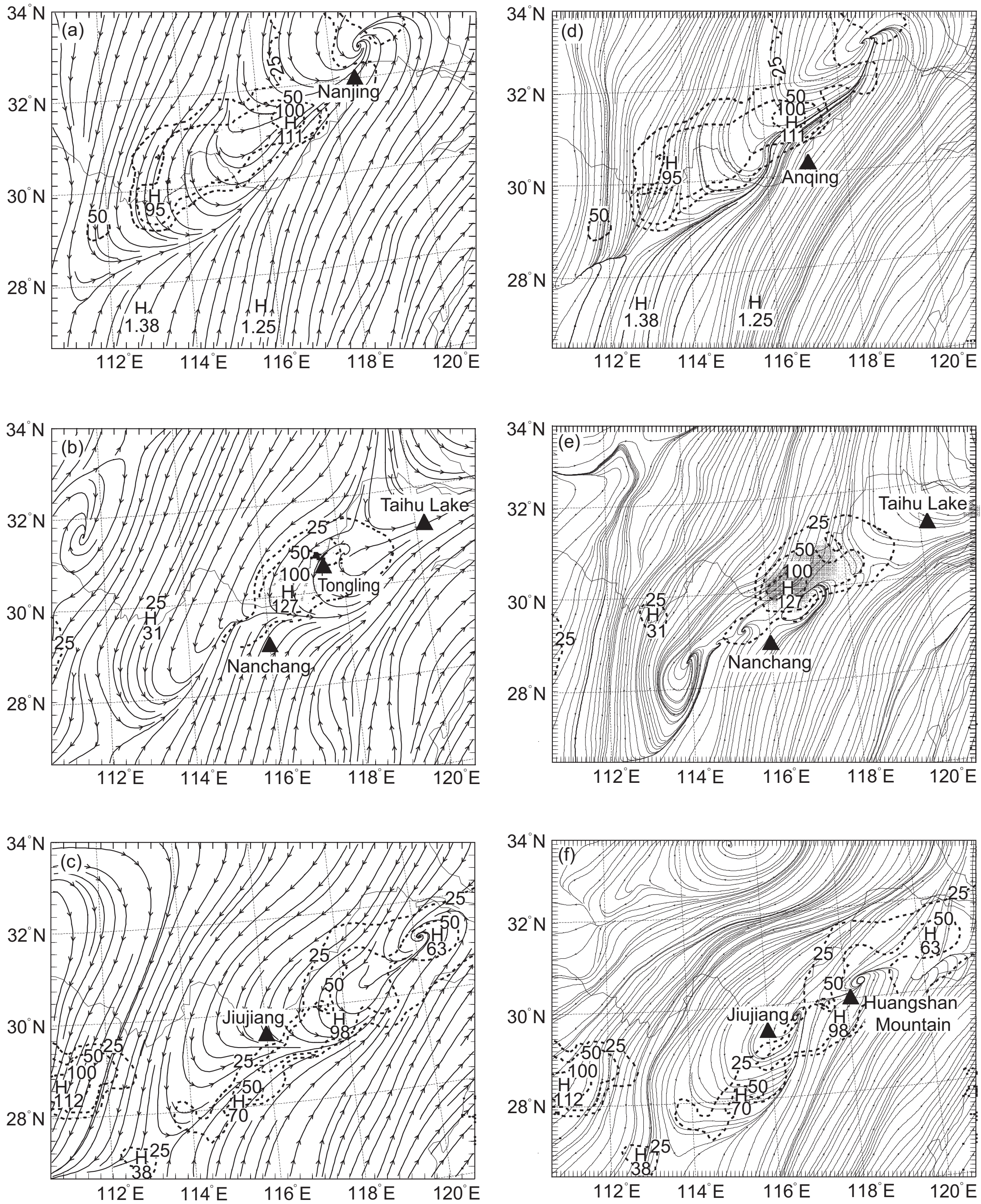


**Fig. 1.** Observed stream field at 925 hPa at (a) 0000 UTC 23, (b) 1200 UTC 23, and (c) 0000 UTC 24 June 1999; and the simulated stream field at the $\sigma$-level ($\sigma$=0.945) at (d) 0000 UTC 23, (e) 1200 UTC 23, and (f) 0000 UTC 24 June 1999. Dashed line indicates the six-hourly accumulative precipitation (mm).

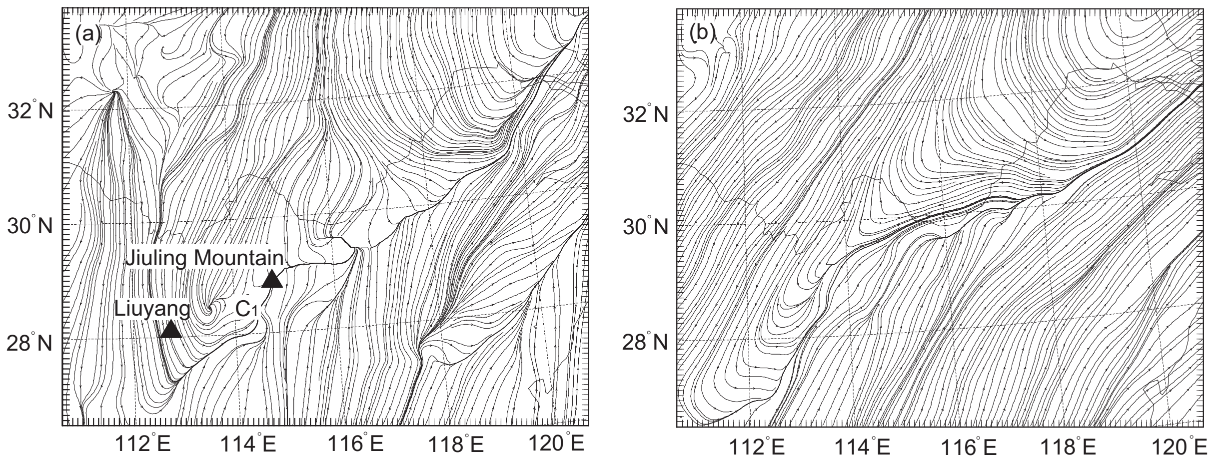


**Fig. 2.** Simulated stream field at the (a) ($\sigma$=0.97) and (b) 850 hPa at 0000 UTC 23 June 1999.

UTC 23 June 1999 (Fig. 1d), and several weak small mesoscale vortexes formed in the shear line in the PBL at 1200 UTC 23 June 1999, at basically an identical position to the observed cyclonic shear line (Fig. 1e). By 0000 UTC 24 June 1999, a complete low vortex circulation system formed in Huangshan Mountain (29.43°N, 118.18°E) and Jiujiang City (Fig. 1f). Despite the simulated vortex disturbance falling a little behind the observed vortex, both observed and simulated weak small mesoscale disturbances were distinct in the PBL, while there was no vortex feature at 850 hPa before 1200 UTC 23 June 1999 (Fig. 2). A simulated vortex ($C_1$) appeared in Liuyang Country (28.09°N, 113.38°E) of Hunan Province in the PBL at 0000 UTC 23 June 1999 (Fig. 2a), with only cyclonic shear at 850 hPa (Fig. 2b). Therefore, the vortex disturbances were more distinct and closer to the heavy rainfall center in the boundary layer than at 850 hPa. The shear line and the vortex disturbances in the meiyu front in the middle and lower reaches of the Yangtze River were two of the most important weather systems contributing to heavy rainfall.

Initially, the rainfall was located in the shear line in the mei-yu front. With the development of the vortex disturbances, the rainfall appeared in the center of the vortexes with a 12-hourly maximum precipitation center of 127 mm (Fig. 1b). When the vortex developed intensely in the Taihu Lake (Fig. 1c), a maximum observed precipitation center of 63 mm corresponded to its center with a precipitation center of 90 mm in northeastern Jiangxi (28°–30°N, 116°–118°E), which was exactly to the south of the simulated mesoscale vortex in northern Jiangxi (Fig. 1f).

The observed stream fields in the PBL showed that there were several vortex disturbances occurring successively from 1200 UTC 23 June to 0000 UTC 24 June 1999. Therefore, the simulated stream fields from the level ($\sigma$=0.97) to the level ($\sigma$=0.94), where the vortexes initiated, were analyzed to investigate the genesis and development of the vortexes in the PBL.

The first simulated mesoscale vortex disturbance ($C_1$, Fig. 2a) appeared at the end of the shear line, near Liuyang Country (28.09°N, 113.38°E) in Hunan Province, in the PBL at 0700 UTC 23 June 1999. This vortex was related to the north flow to the north of the shear line and the terrain of the Jiuling Mountain (28.75°N, 114.85°E). The vortex C1 moved northeastward slowly to the Lianyun Mountain (28.60°N, 113.87°E) in Hunan Province at about 0900 UTC 23 June 1999, and the second vortex $C_2$ formed in the shear line near Poyang Lake Country (29.00°N, 116.41°E) in Jiangxi Province at the same time, corresponding to the next one-hourly accumulative precipitation (dashed line in Fig. 3a). At 1200 UTC 23 June 1999, the vortex $C_1$ combined with another weak vortex to the south of it ($C_3$) to form a new vortex $C_4$. The intensity and horizontal circulation scale of the new vortex, $C_4$, were apparently strengthened. Two new vortexes, vortex $C_5$ at Xiushui Country (29.02°N, 114.35°E) and $C_6$ at Zhelin Reservoir (29.20°N, 115.25°E) in Jiangxi Province, also formed along the shear line at the same time. So, there were four vortex disturbances ($C_4$, $C_5$, $C_6$, $C_2$) from northwestern Jiangxi to southern Anhui Province, ranging from west to east (Fig. 3b). The horizontal scale of these vortexes was relatively small in their initial phase; the largest one of vortex $C_4$ was approximately 50 km. Several maximum one-hourly observation accumulative precipitation centers larger than 10 mm occurred near the simulated vortexes ($C_5$, $C_6$, and $C_2$), which demonstrates a good correspondence between the simulated weak small mesoscale vortexes and the observed rainfall. The vortex group composed of these vortexes moved eastward along the shear line. At 1500

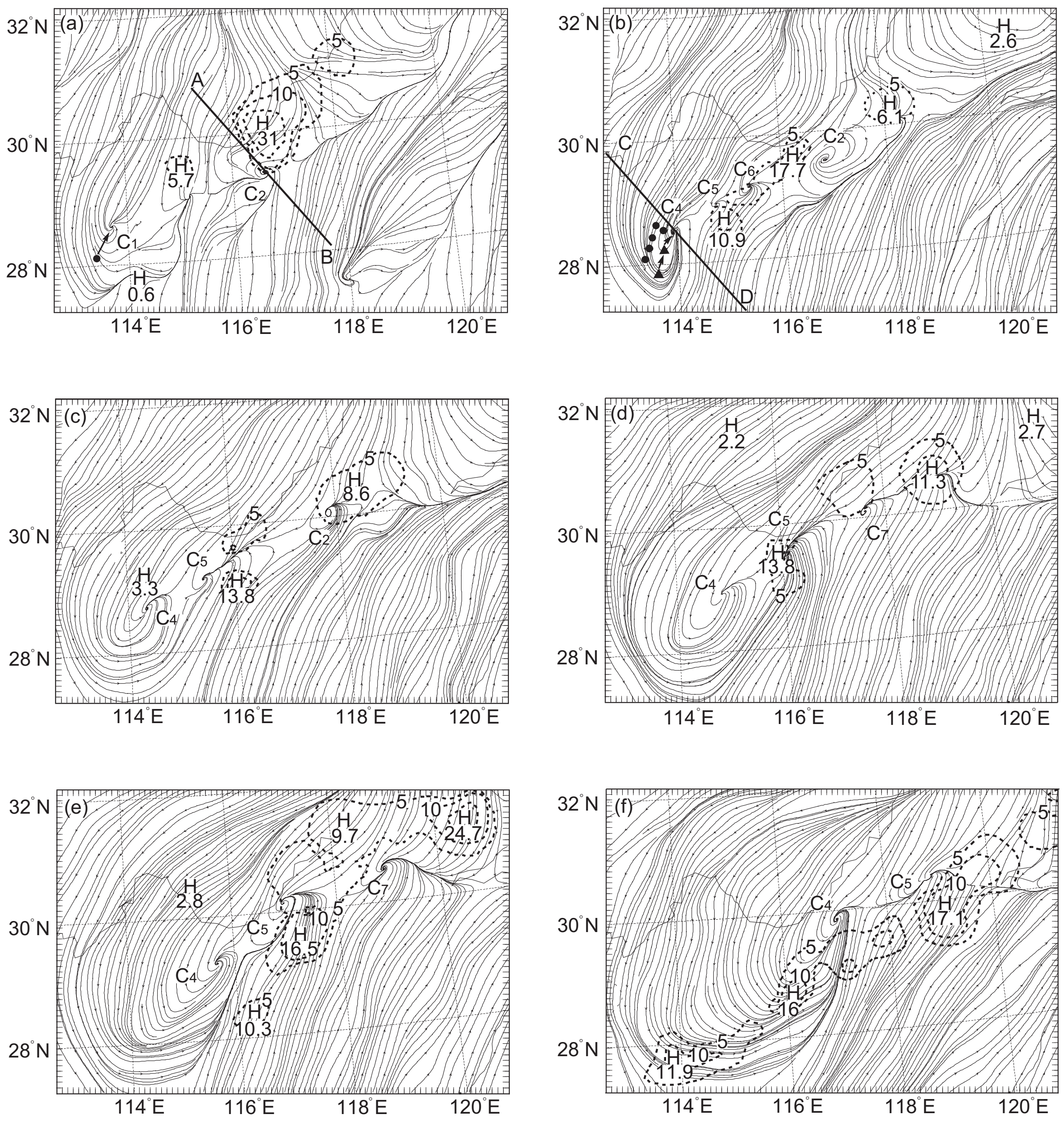


**Fig. 3.** Simulated stream fields and the observed acumulative precipitation (dashed line, mm) in the following one hour at (a) 0900 UTC, (b) 1200 UTC, (c) 1500 UTC, (d) 1800 UTC, (e) 2100 UTC, and (f) 0100 UTC 24 June 1999, where C denotes vortexes, the small circles and triangles in (a) and (b) denote vortex $C_1$ and $C_3$, respectively.

UTC 23 June 1999 (Fig. 3c), the vortex group composed of these vortexes moved eastward along the shear line, except for the vortex $C_6$, which became extinct. The vortex $C_4$ moved eastward to Tonggu Country (28.32°N, 114.23°E) in Jiangxi Province, accompanied by precipitation of several millimeters in the center, and the vortexes $C_5$ and $C_2$ moved eastward to De'an (29.20°N, 115.46°E) in Jiangxi Province and the Huangshan Mountain in Anhui Province, respectively, accompanied by persistent precipitation in the center.

At 1800 UTC 23 June 1999 (Fig. 3d), vortex $C_2$ moved into the topographic confluence line of the Huangshan Mountain and Tianmushan Mountain (30.21°N, 119.25°E), accompanied by an observed precipitation center, and a new vortex $C_7$, approximately 30 km in size, took the place of vortex $C_2$ to the west of the Huangshan Mountain. The circulations of vortex $C_4$ and $C_5$ gradually extended, with an observed

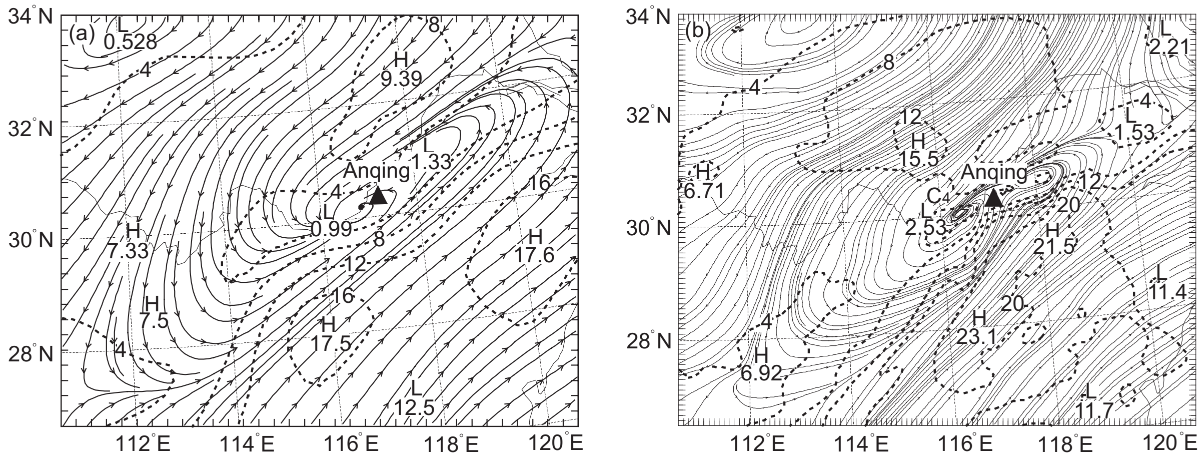


**Fig. 4.** Stream and wind speed (dashed line, m s$^{-1}$) fields of (a) observed and (b) simulated data at 850 hPa at 0000 UTC 24 June 1999.

intensive precipitation center of 38 mm in the center of vortex $C_5$, as they moved eastward. A new observed rainfall appeared to the southeast of the vortex $C_4$ because of strengthening of the southwest flow. The vortex $C_4$ developed to be a large meso-$\beta$-scale vortex when it moved to the west of the Lushan Mountain (29.35°N, 115.59°E) in Jiangxi Province at 2100 UTC 23 June 1999 (Fig. 3e), accompanied by a precipitation center to its southwest and a large rain belt around the shear line. A new intensified rainfall appeared to the south of the vortex $C_4$ near Jingde town (29.18°N, 117.12°E) in Jiangxi Province at 0100 UTC 24 June 1999 (Fig. 3f), and this phenomenon is distinctly reflected in Fig. 4. The simulated meso-$\beta$-scale low vortex center at 850 hPa ($C_4$, Fig. 4b) was consistent with the observed meso-$\beta$-scale low vortex center (Fig. 4a), both of which were located in the southwest of Anqing (30.32°N, 117.03°E).

With the eastward movement of the vortexes, the vortex disturbances in the convergence line to the east of the vortex $C_4$ weakened and merged into the topographic shear line. Furthermore, the vortex $C_4$ developed gradually to become a meso-$\alpha$-scale vortex. The observed precipitation was mainly concentrated in the south of the vortexes and the topographic shear line in western Zhejiang and southern Anhui. The rain belt was basically consistent with the shear line of vortexes. The whole evolution process of the vortex $C_4$ lasted for nearly 20 hours.

When a meso-$\alpha$-scale vortex moved to the ocean at 0000 UTC 23 June 1999, a shear line extended from its rear to the middle and lower reaches of the Yangtze River. The analysis shows that the intense rainfall was closely related to seven weak small-scale vortex disturbances in the shear line in the PBL in the mei-yu front. The shortest lifetime of these vortexes is approximately two hours, however one of the vortexes developed to become a meso-$\sigma$-scale low vortex through combination.

### 3.2 *Surface pressure and vortexes group analysis*

Because of the low level of the vortexes, dense surface observations were used to analyze the sea level pressure to investigate the vortexes in the PBL. A weak meiobar developed to become a low center near Nanchang (28.36°N, 115.55°E) at the bottom of the low trough extending southwestward from the center of the surface low, locating to the south of Nanjing (32.00°N, 118.48°E) at 1200 UTC 23 June 1999 (Fig. 5a). There was also a northeast-southwest long low center in the Jiuling Mountain (28.75°N, 114.85°E) and northern Jiangxi Province (27°–30°N, 114°–119°E). Compared with the simulation output (Fig. 1e), it was found that the observed surface low center was located to the southeast of the simulated boundary layer vortexes group. Twelve hours later (Fig. 5b), several mesoscale low centers appeared in the meiobar extending from northern Jiangxi Province (27°–30°N, 114°–119°E) to northern Zhejiang Province (29°–32°N, 118°–122°E). These mesoscale low centers were located to the south of the vortexes group for both observed and simulated results. From the above analysis, we can conclude that the formation and development of the vortexes in the PBL are related to the surface mesoscale low.

### 3.3 *Analysis of the vertical structure of the vortexes in the planetary boundary layer*

The vertical structures of the vortexes were investigated by analyzing vertical cross sections through the vortex centers. Figure 6 shows the vertical cross sec-

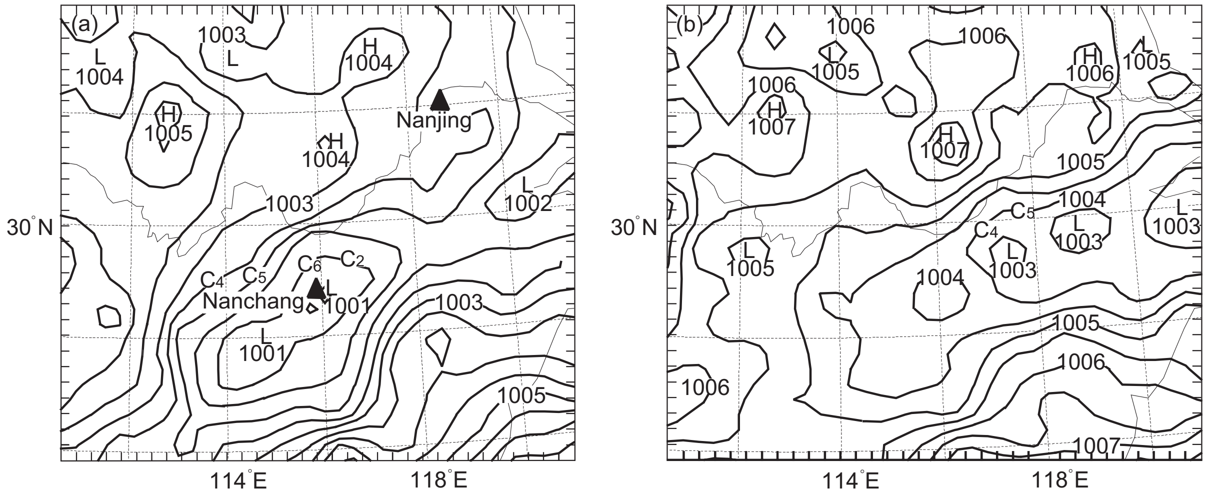


**Fig. 5.** Observed sea level pressure fields (hPa) at (a) 1200 UTC 23 and (b) 0000 UTC 24 June 1999, where C denotes the simulated vortex center at the $\sigma$=0.97 level.

tion through vortex $C_2$, which had not developed to the height of 850 hPa. The vortex disturbance appeared at 0900 UTC 23 June 1999 and disappeared at 1400 UTC 23 June 1999, lasting approximately six hours. During the initial phase of the vortex, there was heavy rainfall (30 mm $h^{-1}$) to the north of the vortex center. According to a horizontal wind component perpendicular to the cross section (Fig. 6a), there was strong northeast flow (dashed line) to the north of the vortex $C_2$ in the rear of the shear line in the PBL, and the velocity reached 8 m $s^{-1}$. This means that there was a strong cold air embedding southwestward into the rear of the mei-yu front in the PBL. The small-scale vortexes were located at one side of the northeast flow. The southwesterly wind predominated above the PBL. The axle velocity of the southwest low-level jet (LLJ) in the low troposphere above the vortexes reached more than 16 m $s^{-1}$.

Corresponding to the northwest side of the vortexes (triangles in Fig. 6) in the PBL, there was a vertical positive vorticity column (Fig. 6b). A positive vorticity center above the surface appeared to the south of the vortex in the PBL, corresponding to the mesoscale surface low; the axis of the positive vorticity tilts northwestward with height (Fig. 5). When it reached the boundary layer top, the positive vorticity showed a columnar structure with height. This characteristic was related to the cold flow in the rear of the boundary layer front. The analysis of the divergence field (not shown) indicated that convergence was located in the boundary layer near the vortex with divergence in the middle and lower troposphere, which formed a sub-circulation with weak downdrafts in both sides of the vorticity column. The gradient of potential equivalent temperature in the boundary layer strengthened significantly. The vortex occurred right in the largest gradient of the potential equivalent temperature, and a long narrow tongue of large $\theta_e$ (equivalent potential temperature) inclined upwardly to the middle level (Fig. 6c). So, the baroclinicity played an important role in the development of the vortex.

The analysis above indicates that the strong northeast cold flow embedding southwestward into the rear of the mei-yu front formed a nose-shaped structure of velocity contours above. It should be noted that the cold flow bulged upwardly due to the effect of the strong cold air at the lower level in the mei-yu front, leading to a relatively small velocity column ("SVC", Fig. 6a) above, and separated the southwest flow in the middle and lower troposphere. Thus, the horizontal gradient of wind shear in the vertical direction ($\partial u/\partial y$) strengthened, which was favorable for the formation and enhancement of the cyclonic vortexes. Corresponding to the positive vorticity column and largest horizontal wind gradient, there was a small velocity column in the vertical direction. A positive vorticity column appeared on the left side of the southwest LLJ center ($J_w$), with a negative vorticity column (dashed line, Fig. 6b) above the northeast jet ($J_{\rm E}$) in the PBL, to the north small velocity column, which indicates that the northeast wind in the PBL can lead to a variation in the wind field at the upper level. A nose-shaped structure formed at the front of the mei-yu front on the vertical cross section of velocity contours, with a large vertical wind shear ($\partial u/\partial z > 0$) appearing above it and below the southwest LLJ, which was favorable for triggering vortex disturbances. This might be one of the formation mechanisms of weak small-scale vortexes in the mei-yu front in the PBL.

Because the southwest jet center in the lower tro-

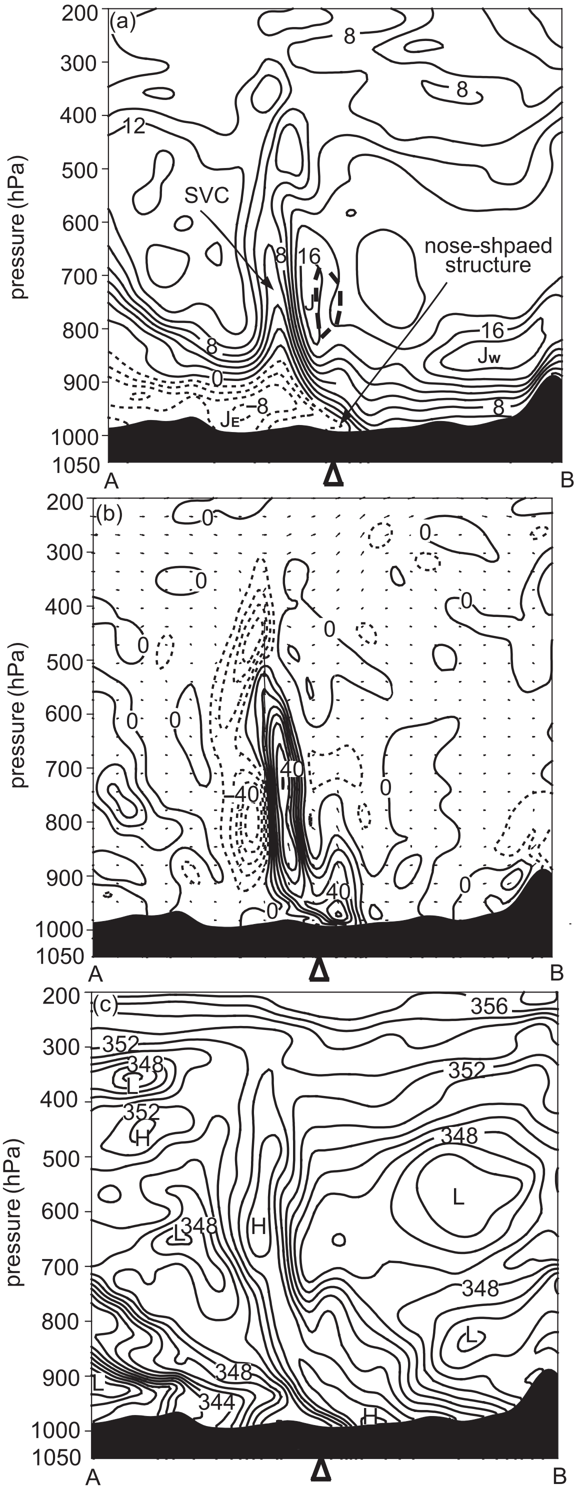


**Fig. 6.** Vertical cross section along A–B (Fig. 3a) at 0900 UTC 23 June 1999: (a) horizontal wind component (m s$^{-1}$) perpendicular to the cross section; (b) vorticity ($\times 10^{-5}$ s$^{-1}$); and wind vector (c) potential equivalent temperature (K), where the triangle represents position of the vortex, and the bold dashed line in (a) denotes the wind center one hour earlier, J denotes jet, and SVC denotes Small Velocity Column.

posphere (700–800 hPa) moved notably closer to the vortexes than one hour earlier (bold dashed line in Fig. 6a), a rapid strengthening of the horizontal wind shear and vorticity occurred. On the other hand, it could also cause intensification of the vertical wind shear above the vortex, which was advantageous to the development of the baroclinicity ($\partial v/\partial z$), and the decreasing of the Richardson number ($Ri$). Thus, mesoscale stability would decrease and the vorticity column would develop rapidly.

According Fig. 2, there was no obvious circulation of the vortex $C_1$ at 850 hPa at 0800 UTC 23 June 1999, so the vortex $C_1$ was just initiated in the PBL. At 1200 UTC 23 June 1999, distinct mesoscale vortex circulations could be found in both the observed and simulated stream fields at 850 hPa, which indicates that one of the vortexes had developed to the troposphere from the PBL. The moving tracks of the vortexes $C_1$ and $C_3$ to the south of it (Fig. 3a), illustrated the whole combination process to form vortex $C_4$, of the two vortexes which moved along the shear line more and more closely. It was only the vortex $C_4$ that developed rapidly to the troposphere through combination (Fig. 4).

Figure 7 shows the vertical cross section through the vortex $C_4$. The northeast wind in the rear of the mei-yu front strengthened evidently (dashed line in Fig. 7a), and ascended to 850 hPa. The southwest wind above was also divided by the small velocity column ("SVC" in Fig. 7a) above the vortex, and the southwest LLJ center was located to the south of the vortex with the wind shear similar to that in Fig. 6. The broadening of the horizontal range of wind shear in the lower level, because of the combination of the vortexes in the boundary layer, made the horizontal scale of the positive vorticity column of the vortex $C_4$ much larger than that of the vortex $C_2$. Additionally, because of the merging of the two vortexes, convergence was intensified above the vortex (dashed line in Fig. 7c) with strong mesoscale divergence in the upper troposphere. Thus, the updraft was apparently much stronger than that of vortex $C_2$ in Fig. 6, as well as the horizontal scale. As a result, the vortex developed upward to the middle and lower troposphere.

## 4. Conclusions

The distribution of precipitation along the mei-yu front is irregular. A mesoscale low vortex was one of mechanisms of mei-yu front heavy rainfall; weak small mesoscale vortex disturbances were also discovered in the mei-yu front in the reaches of the Yangtze and Huaihe Rivers. However, it is difficult to analyze these weak small mesoscale vortexes because of its small

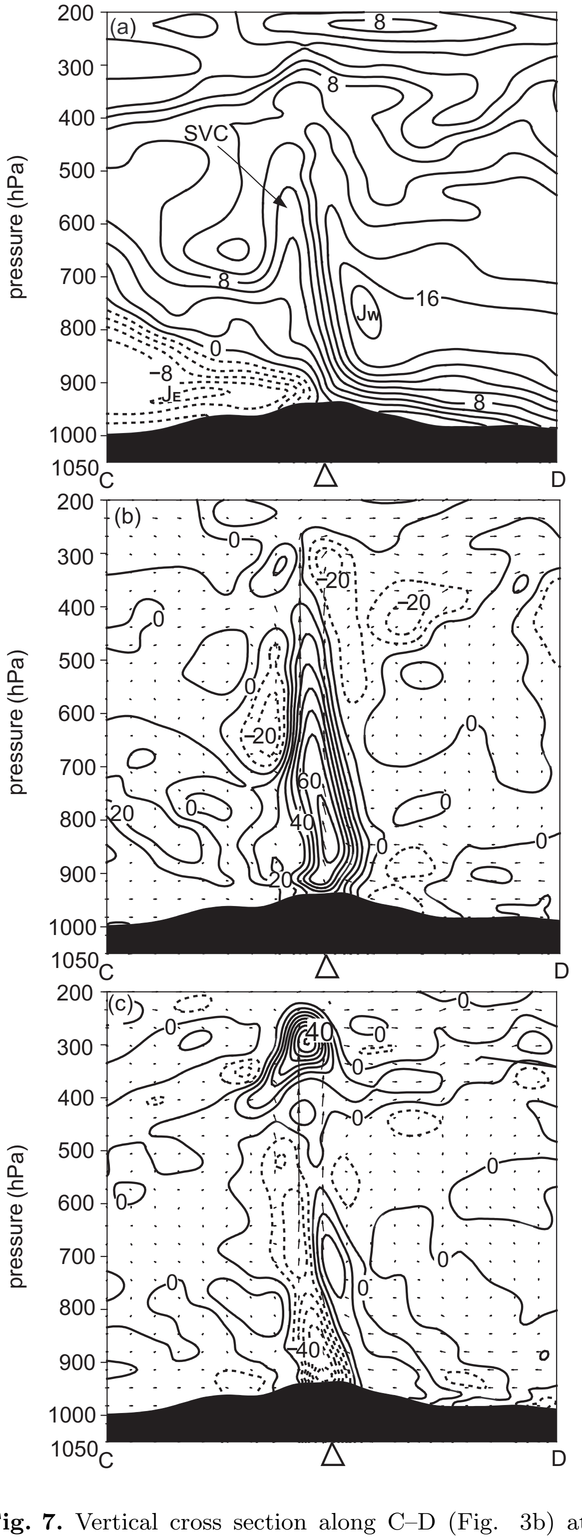


**Fig. 7.** Vertical cross section along C–D (Fig. 3b) at 1200 UTC 23 June 1999: (a) horizontal wind component (m $s^{-1}$) perpendicular to the cross section; (b) vorticity ($\times 10^{-5}$ $s^{-1}$); and wind vector (c) divergence ($\times 10^{-5}$ $s^{-1}$) and wind vector, where the triangle represents position of the vortex, SVC indicates the small velocity column, and $J_w$ denotes the jet center.

scale and weak intensity, especially in its initial phase. In order to disclose the phenomena and characteristics of these vortexes, assure the accuracy of simulation, and reproduce mesoscale physical processes and weak small mesoscale phenomena identical to observations, FDDA was used in the whole numerical simulation. The results show several weak small mesoscale vortexes of tens of kilometers formed in a group in the mei-yu front in the lower reaches of the Yangtze River. Some of the vortexes were accompanied by mesoscale rainfall in the initial phase, but some of them would not bring rainfall until several hours after their formation. The formation and evolution of these vortexes, especially at the initial stage, was located in the PBL where the stream field was distinct. Some of the vortexes weakened locally, and some developed through combination. Some vortexes corresponded to a surface low trough or several mesoscale low centers. The lifetime of the weak small mesoscale vortexes was usually several hours, but they could also develop to be meso-$\alpha$-scale low vortexes and lead to a new shear line in the lower troposphere in the reaches of the Yangtze and Huaihe Rivers, which could set up a favorable circulation environment for regenerating weak small mesoscale vortexes.

During the initial stage of the vortexes, a notable northeast flow embeded from the rear of the mei-yu front in the PBL. A nose-shaped structure of the northeast flow formed above the surface near the mei-yu front under the effect of surface friction; the vortexes appeared exactly on one side of the nose-shaped structure. This might be one of the reasons behind the formation of the weak small mesoscale vortexes in the PBL. Furthermore, the bulge of the northeast flow in its center led to a deep small-scale wind column above, which separated the southwest flow and brought it into the horizontal shear and positive vorticity above the mesoscale vortexes. The strong southwest LLJ from the front of the mei-yu front intensified the horizontal and vertical wind shear and the vertical positive vorticity column above the vortexes. The baroclinicity and Richardson number ($Ri$) were also strengthened because of the intensification of vertical wind shear and the horizontal gradient of $\theta_e$ in the lower level, which would help development of the vortexes.

In the initial stage of the vortexes, the positive vorticity column was located in the largest horizontal gradient of wind, but its vertical axis declined to the north with height in the PBL, which was related to the retroversion of the mei-yu front in the PBL. As a result, the surface positive vorticity center appeared to the south of the vortexes, which was advantageous to the transportation of positive vorticity to the mesoscale vortexes in the boundary layer by southerly winds. Convergence was located in the PBL, with divergence in the middle and lower troposphere in the initial stage. When vortexes developed upwardly to the middle and lower troposphere through combination, there was mainly horizontal wind shear in the middle and lower troposphere above the vortexes, and the positive vorticity column heightened and strengthened rapidly, and the horizontal scale extended. Furthermore, mesoscale convergence in the PBL developed upwardly to the middle troposphere, with divergence to the upper level. Subsequently, the vortexes developed steadily and moved northeastward, and the horizontal scale extended, to become a complete meso-$\alpha$-scale low vortex system.

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