

A Study of Influencing Systems and Moisture Budget in a Heavy Rainfall in Low Latitude Plateau in China during Early Summer

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(Received 19 April 2006; revised 8 August 2006)

ABSTRACT

Analysis of a heavy rainfall in a lower latitude plateau and characteristics of water vapor transportation have been conducted by using conventional data and denser surface data. The results show: (1) the heavy rainfall was caused by a series of mesoscale systems under favorable large-scale conditions when the warm moister air and cold air interacted with each other. At the same time, the coupling between the upper- and lower-level jets was revealed. It is also found that there exists some different characteristics among the main influencing systems of heavy rainfalls in Yunnan, such as the Indian-Myanmar trough and the path of the cold air, compared with those in East and South China. (2) The interaction between mesoscale convergence lines near the ground may be a possible triggering mechanism for the occurrence of mesoscale systems, and the dynamical and thermal dynamical structure of the mesoscale systems was very obvious. The convergence lines may relate closely to the terrain of Yunnan, China. (3) The computation of the water vapor budget reveals that the primary source of water vapor supply for heavy rainfall was in the Bay of Bengal. In this case, the water vapor could be transported into Yunnan even though the amount of water vapor was less than that in the lower troposphere in East and South China. In addition, the analysis for three-dimensional air parcel trajectories better revealed and described the source location and the transportation of water vapor to Yunnan.

Key words: heavy rainfall, mesoscale systems, moisture budget, Yunnan-Guizhou Plateau

DOI: 10.1007/s00376-007-0485-z

1. Introduction

Heavy rainfall is one kind of important disastrous weather, causing increasingly severe damage, especially since the economy was developed in China. Meteorologists in China have been paying great attention to the study of heavy rainfall. Tao (1980) researched the circulation conditions and formation mechanism of heavy rainfall according to data from 1953 to 1977 and pointed out that heavy rainfall was the result of interaction between the various scale systems, and that, among these, mesoscale systems are the direct cause of heavy rainfall. Ding (1993) studied extensively the heavy rainfall over the Yangtze-Huaihe River valley,

and focused on the mesoscale convective systems producing heavy rainfall in 1991 that occurred along the shear line and mei-yu front, some of which were associated with mesoscale vortices. Zhou et al. (2004) reviewed the major progresses in mesoscale dynamic research in China since 1999—a study that helps to understand the mechanism of heavy rainfall. In the summer of 1998, a record flood—the biggest since 1954—occurred along the whole of the Yangtze River, the Nenjiang River, the Songhua River, and the Pearl River Valleys. Its circulation background and strong convective systems have been analyzed in detail by Chinese meteorologists (Tao et al., 2001; Zhou et al., 2003; Zhao et al., 2004). In addition, some numerical

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simulations have been conducted to study the structure of convective systems (Cheng and Feng, 2001; Bei et al., 2002; Xu and Gao, 2002). Moreover, the characteristic features of water vapor transport in the planetary boundary layer in China during the mei-yu period have been deeply investigated (Fei et al., 1993; Zhang, 2001; Xu et al., 2003). The above-mentioned demonstrated that heavy rainfalls in the Yangtze-Huaihe River and in South China have been studied, and that some scientific problems have been clarified, such as the triggering by cold air caused heavy rainfall in the warm area the interaction between low-level jet and mesoscale convective systems, the forming of convergence in the planetary boundary layer and the effect on mesoscale convective systems and the transportation and supply of water vapor. This research has helped scientists to better understand the physical mechanism of heavy rainfall formation. On the other hand, some studies have also been carried out on rainfall in West China (including Southwest China), especially in Yunnan near the Plateau. For example, the introduction about meteorological disasters in Yunnan (Qing et al., 2000) and the climatology in the lower latitude plateau area (Qing et al., 1997) have provided whole climate characteristics about Yunnan. Meanwhile, some mesoscale convective systems developing in Yunnan (Duan and Li, 2001; Guo and Lu, 2003) and the water vapor transport feature of the Tibetan plateau (Xu et al., 2002; Chen et al., 2001; Sun et al., 2001) have also been discussed. This research is still very limited in comparison with the research in East and South China. It should be emphasized that the climate in the Yunnan area is quite different from that in East China because of its special location and topography, and the question of water vapor transport on the Yunnan plateau is still in need of further research. For this purpose, this paper will concentrate on the discussion of the various scale systems, and their interaction and moisture source locations during a heavy rainfall in Yunnan.

Yunnan is located in the lower latitude plateau area, which is southeast of the Tibetan Plateau and southwest of the Sichuan Basin (Fig. 1), and is connected with the special geography and climate of this region. The mountainous area in Yunnan is over 90% and the terrain is flexuous, in a ladder style from northwest to southeast. The average altitude in the east is around 2000 m. The famous Hengduan (Transverse) Mountain is in the west, alternating between mountain and gorge, and the difference in terrain is large. The altitude in the north is 3000–4000 m and in the south it is 1500–2200 m. The terrain smoothes gradually, with bayous opening out in the south and southwest of the border area only, where the alti-

tude is around 1000 m, and even below 500 m, and there is a “trumpet-shape” to the entrance of the Red River. The Yangtze River, Pearl River, Red River, Mekong River, Salween River, Irrawaddy River, or their branches, all pass through this area, among which four are international. The water resource in this region is therefore highly abundant.

In addition, Yunnan is located in the area of summer monsoon, and an obvious influence of both heat and water vapor coming from the two tropical oceans (South China Sea and the Bay of Bengal) exists. Monsoon has been studied extensively in China (Kao and Chang, 1957; Yeh and Chang, 1974; Zhao and Mills, 1991; Li and Wu, 2002; Zeng et al., 1994; Zeng and Li, 2002). Zeng et al. (1994) pointed out the causes of seasonal variations of atmospheric general circulation, the cross-equatorial air flows, and the interaction of atmosphere circulations between the Northern and Southern Hemispheres, are primarily due to the seasonal variation of incoming solar radiation. In Asia, the East Asia monsoon and Indian monsoon belong to different sub-systems, and although they are related closely, they are independent from each other. Yunnan is located in a lower latitude plateau, and the monsoon characteristics of this area are different from those in East China. In summer, it is sometimes influenced jointly by the Indian southwest monsoon, the East Asia monsoon, and the weather systems from the middle and high latitudes.

Precipitation characteristics show the existence of a dry and a rainy season in Yunnan. During the dry

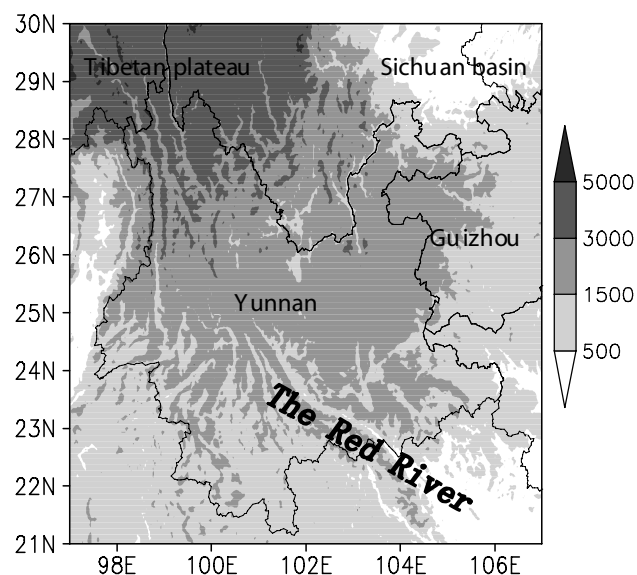


Fig. 1. Terrain in Yunnan, China and adjoining area (units: m).

Though most of the heavy rainfall in Yunnan occurs in mid-summer, some heavy rainfall may appear from May to June, which is different from that in mid-summer. The precipitation amount is less than that in East China, and the precipitation area is local. In addition, because of the higher terrain, the source of water vapor and how it can travel up the mountain are still questions to be clarified. In this paper, a detailed analysis of a heavy rainfall in Yunnan in early summer has been conducted. The purpose is to understand how this kind of heavy rainfall happens, and also to pay special attention to the mesoscale systems and water vapor supply. At the same time, the research results mentioned above will be compared with those in East China. Based on this, the mechanism of heavy rainfall in Yunnan during early summer will be

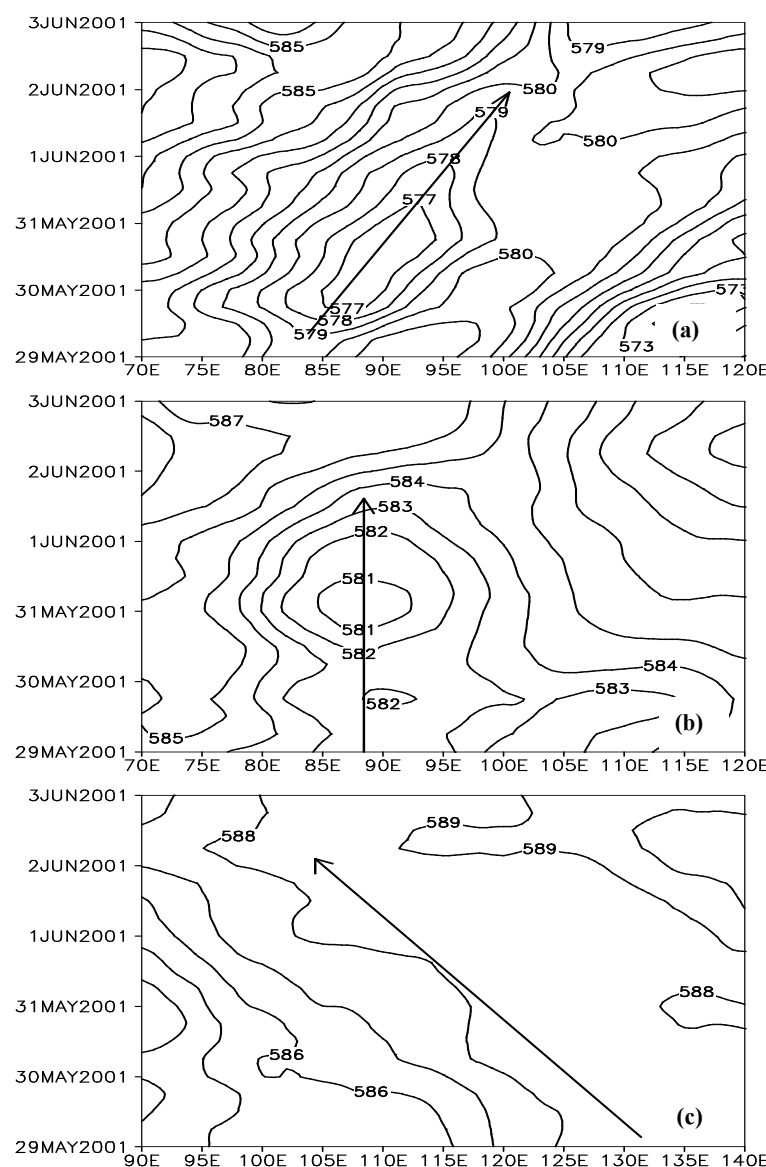


Fig. 3. Temporal-longitude of geopotential height at 500 hPa from 0000 UTC 29 May to 0000 UTC 3 June 2001 (a) along 32°N (the evolution of low); (b) along 25°N (the evolution of the Indian-Myanmar trough); (c) along 15°N (the evolution of the Subtropical High).

proposed.

In May 2001, record heavy rainfalls since 1949 occurred in Yunnan, except in the northeastern area, with the main heavy rainfall process occurring during the three days from 1200 UTC 30 May to 1200 UTC 2 June. From Fig. 2 it can be seen that there are two precipitation maxima in Yunnan (Fig. 2a), near to Nanhua and Tonghai, and that from their hourly change in precipitation amounts the rainfall occurred in two days (Figs. 2b and c). These two precipitation areas in Yunnan province will be analyzed further. In this paper, apart from using $1^\circ \times 1^\circ$ NCEP

data and conventional data, the hourly precipitation data in Yunnan and $0.06^\circ \times 0.06^\circ$ satellite data were also used.

2. Influencing systems

Most heavy rainfall in Yunnan could result from interaction between low and middle latitude systems, especially from that between the southwestern warm moisture current and the westerly trough in the middle latitude (Duan and Li, 2001; Guo and Lu, 2003; Qing et al., 1997; Qing et al., 2000). In the case of

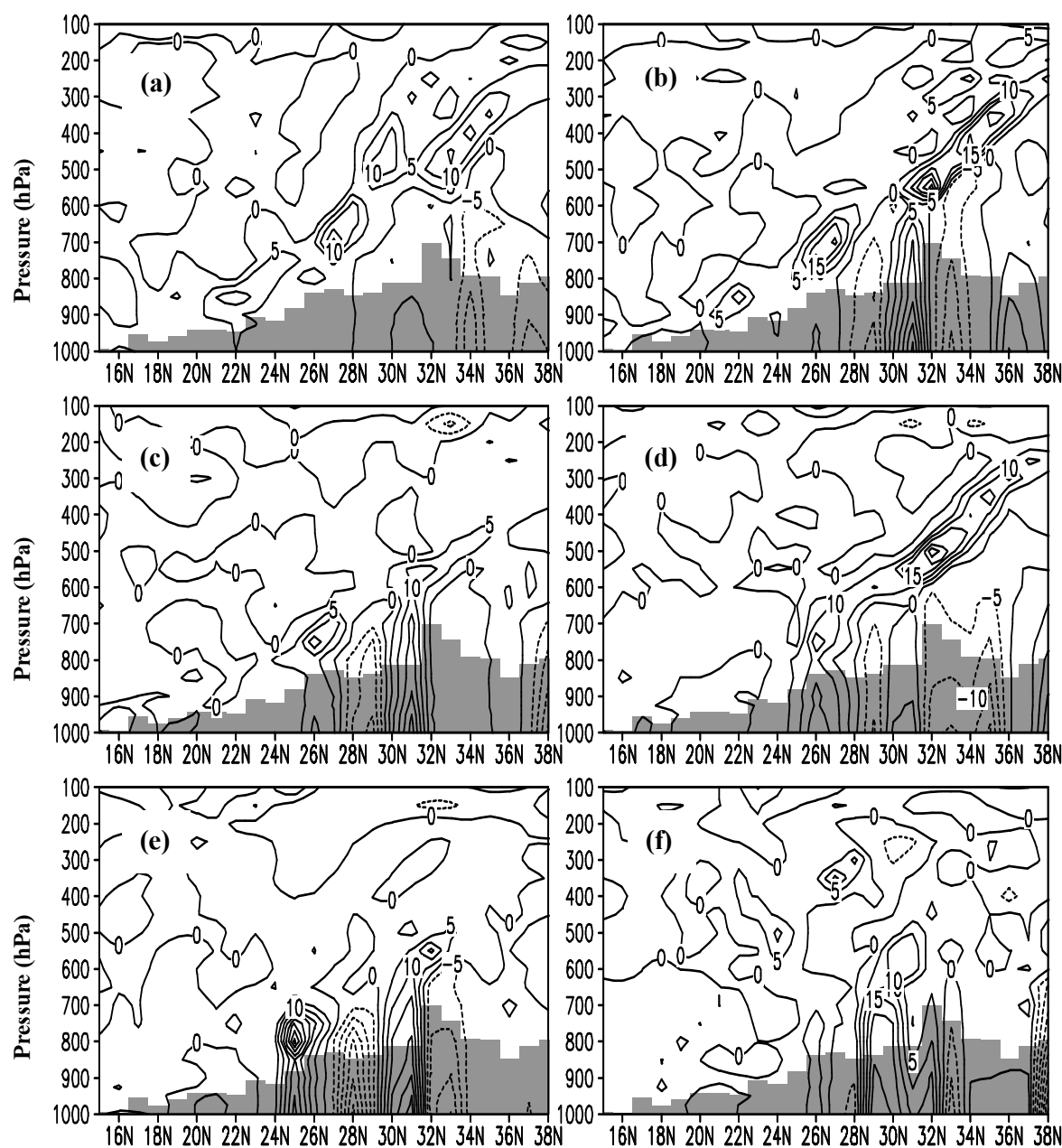


Fig. 4. Vertical profile of $(F_2 + F_3)$ along 102°E (shaded area is the terrain; units: $10^{-10} \text{ K m}^{-1} \text{ s}^{-1}$). (a) 0000 UTC 31 May 2001; (b) 1200 UTC 31 May 2001; (c) 0000 UTC 1 June 2001; (d) 1200 UTC 1 June 2001; (e) 0000 UTC 2 June 2001; (f) 1200 UTC 2 June 2001.

this heavy rainfall, similarly, the interaction between weaker cold air from the north and warm moist air from the southwest provided large-scale favorable conditions. In particular, the maintenance of the Indian-Myanmar trough took an important role in the releasing and rebuilding of convective unstable energy for the heavy rainfall in Yunnan. At the same time, interaction between the upper- and lower-level jets could be found, and moisture transportation as the water vapor supply for the heavy rainfall could also be revealed.

2.1 Warm moist air

It could be found from the circulation at 500 hPa and 700 hPa that the appearance of a southwestern warm moisture current was mainly the result of interaction between the various systems. Figure 3 shows the temporal-longitude at 500 hPa along 32°N , 25°N and 15°N . It is evident that there was a low pressure system that moved continuously from west to east in the area of the Tibetan Plateau, continuously intensi-

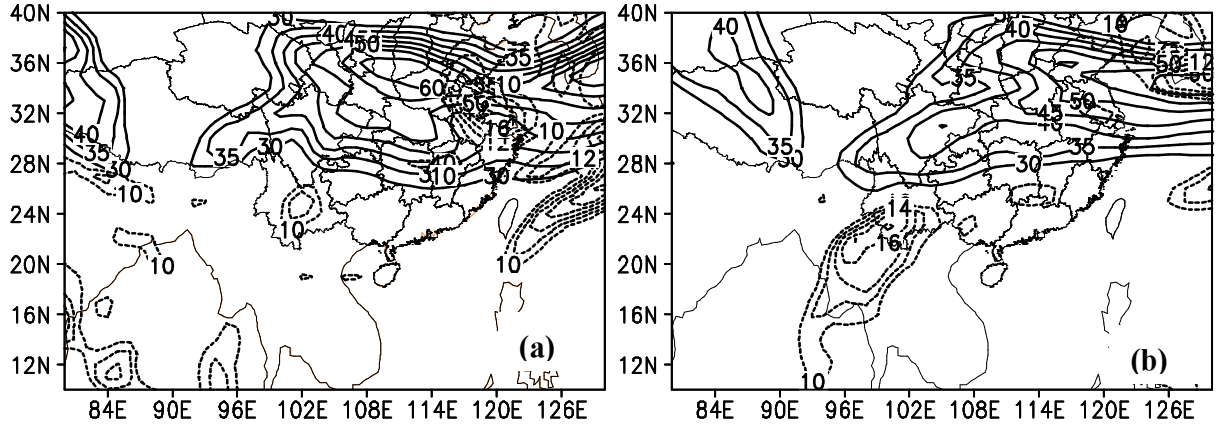


Fig. 5. Horizontal distribution of the upper- and lower-level jets (solid line: at 200 hPa, wind $\geq 30 \text{ m s}^{-1}$; broken line: 750 hPa, wind $\geq 10 \text{ m s}^{-1}$). (a) 0000 UTC 31 May 2001; (b) 0000 UTC 2 June 2001.

fying up to 0600 UTC 31 May 2001, before weakening and moving gradually eastward. Meanwhile, the South Asia High moved continually to the northwest of the Tibetan Plateau (Fig. 3a). Accordingly, there was a trough forming and strengthening significantly in the Indian-Myanmar region (Fig. 3b). On the other hand, the Subtropical High moved westward and strengthened gradually (Fig. 3c), making the convergence strengthen between the Subtropical High and the South Asia High, and also maintaining the axis of the Indian-Myanmar trough at around 88°E . This situation favored the transportation of warm moisture from the Bay of Bengal to Southwest China, and caused the unstable convective energy to be re-buffed gradually. In the later period of precipitation, the Subtropical High continued to move northwestward, strengthening all the while, and the low continued to move eastward, weakening continually. Thus the Indian-Myanmar trough weakened and shrank northward, then warm moist air weakened following it. Therefore, it can be seen that the warm moist air entering Yunnan was connected closely with the Indian-Myanmar trough.

2.2 Invasion of weaker cold air

During the period of southwestern warm moist air strengthening gradually, there was cold air invading continually from northeast of this area. Here, the frontogenesis function was used to analyze the evolution of cold air during the heavy rainfall. The frontogenesis formula is:

$$F = \frac{d}{d\tau} |\nabla \theta_{se}| = F_1 + F_2 + F_3 + F_4$$

where

$$F_1 = \frac{1}{|\nabla \theta_{se}|} \left(\nabla \theta_{se} \cdot \nabla \frac{d\theta_{se}}{dt} \right),$$

$$F_2 = -\frac{1}{2} \frac{1}{|\nabla \theta_{se}|} (\nabla \theta_{se})^2 D,$$

$$F_3 = -\frac{1}{2} \frac{1}{|\nabla \theta_{se}|} \left\{ \left[\left(\frac{\partial \theta_{se}}{\partial x} \right)^2 - \left(\frac{\partial \theta_{se}}{\partial y} \right)^2 \right] A + 2 \frac{\partial \theta_{se}}{\partial x} \frac{\partial \theta_{se}}{\partial y} B \right\},$$

$$F_4 = -\frac{1}{|\nabla \theta_{se}|} \frac{\partial \theta_{se}}{\partial p} \left(\frac{\partial \theta_{se}}{\partial x} \frac{\partial \omega}{\partial x} + \frac{\partial \theta_{se}}{\partial y} \frac{\partial \omega}{\partial y} \right).$$

Here, θ_{se} is potential pseudo-equivalent temperature,

$$A = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}, B = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y},$$

and D is the horizontal divergence. F_1 is the diabatic heating term, and F_2 and F_3 are the horizontal divergence and horizontal deformation terms, respectively. F_4 is the tilting term associated with vertical velocity. Here, only F_2 and F_3 were calculated because the accurate calculation of F_1 and F_4 was difficult.

Figure 4 shows the vertical profiles of $(F_2 + F_3)$ along 102°E from 1800 UTC 30 May to 0600 UTC 2 June. It can be noticed that the frontogenesis was connected with the precipitation during the heavy rainfall. At 0000 UTC 31 May (Fig. 4a), there were two main maxima along the frontal band: one was on the south section of the front from 26° – 28°N at 750 hPa–650 hPa; and the other was on the north section, from 32° – 36°N at 500 hPa–300 hPa. The two maxima then strengthened gradually (Fig. 4b), and at the same time moved from north to south, extending from the upper to the lower level. Correspondingly, stronger precipitation occurred in north Yunnan from 0000 UTC 31 May to 1200 UTC 31 May (Fig. 2b). At 0000 UTC 1 June, the strength of the front weakened

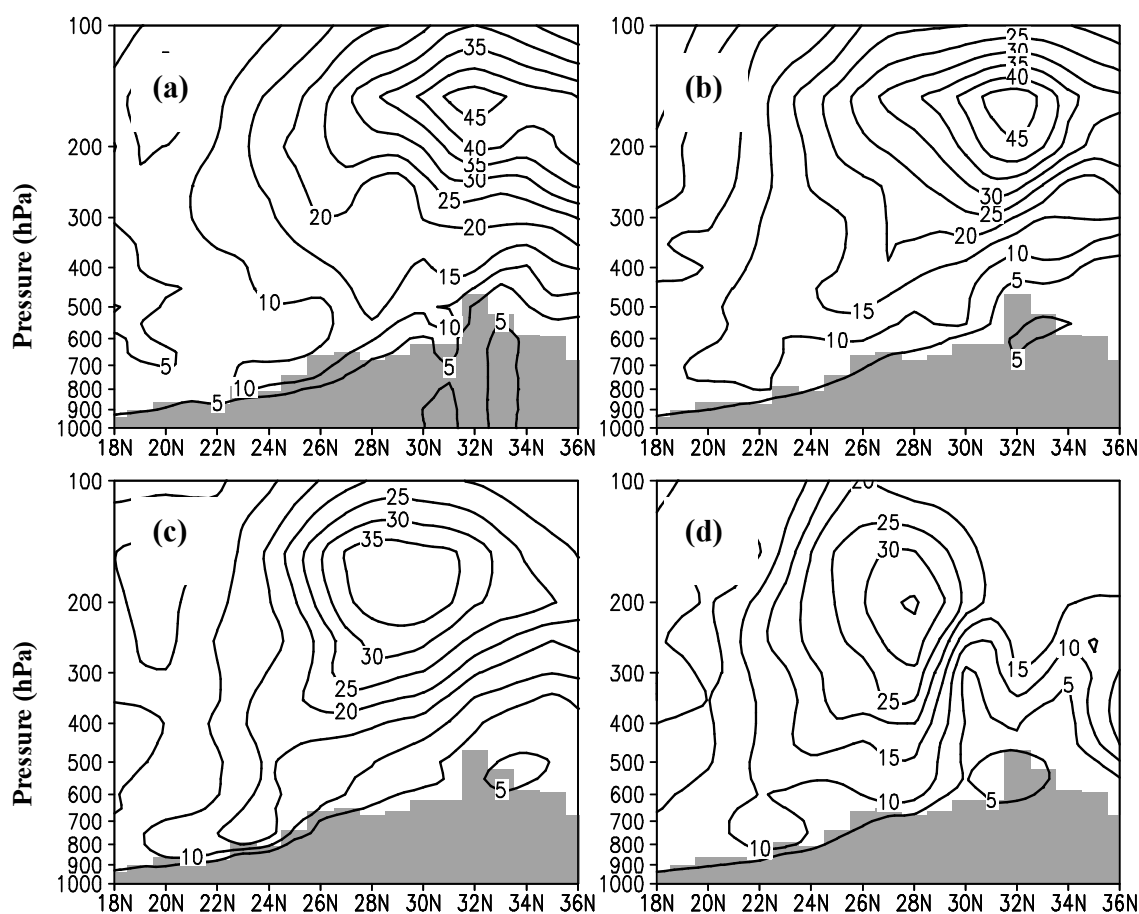


Fig. 6. Vertical profile of horizontal wind along 101°E (shaded area is the terrain; units: m s^{-1}). (a) 0000 UTC 31 May 2001; (b) 0000 UTC 1 June 2001; (c) 0000 UTC 2 June 2001; (d) 1800 UTC 2 June 2001.

(Fig. 4c). The north section of the front then strengthened again, but the south section remained unchanged, and the precipitation weakened during this period, implying there was new cold air moving from the northeast (Fig. 4d). Then, at 0000 UTC 2 June, the south section of the front strengthened greatly and moved to 24° – 25°N , thus causing another strong precipitation event in south Yunnan (Fig. 2c), while the north section weakened gradually (Fig. 4e). Finally, the front zone in Yunnan weakened and disappeared (Fig. 4f).

It can be seen from the above that a stronger frontal zone existed only in the lower levels, around 800 hPa–650 hPa, during the heavy rainfall in Yunnan. The front band was broken, which implies there was not a large amount of cold air entering Yunnan from the northeast, and that the cold air entered Yunnan by means of diffusion. Therefore, it can be seen that the influence of cold air was obvious, even though its strength was less than in East China, and the path of cold air was connected with the special terrain of Yunnan.

2.3 Coupling of the upper- and lower-level jets

Most research regarding heavy rainfall (Tao, 1980; Ding, 1993; Zhou et al., 2003; Zhao et al., 2004) has emphasized that the appearance of heavy rainfall in a larger area is most closely related with the lower-level jet (LLJ) at 700–800 hPa, and sometimes, the LLJ was coupled with the upper-level jet (ULJ) at 200–300 hPa. So, for Yunnan, located in the southeast of the Tibet Plateau, are the heavy rainfalls in this area associated with the coupling between ULJ and LLJ?

Figure 5 shows the horizontal distribution of the ULJ and LLJ at the time of two strong precipitation events occurring during heavy rainfall. It can be seen that the ULJ was basically east-west oriented, and the maximum located northwest of Yunnan. At the same time, there was a stronger LLJ moving toward Yunnan from the southwest. Yunnan is located just to the right of the entrance region of the ULJ, and to the left side of the exit region of the LLJ. The intensification of the precipitation corresponded to the increasing of the LLJ. Thus it seems that the LLJ played an important

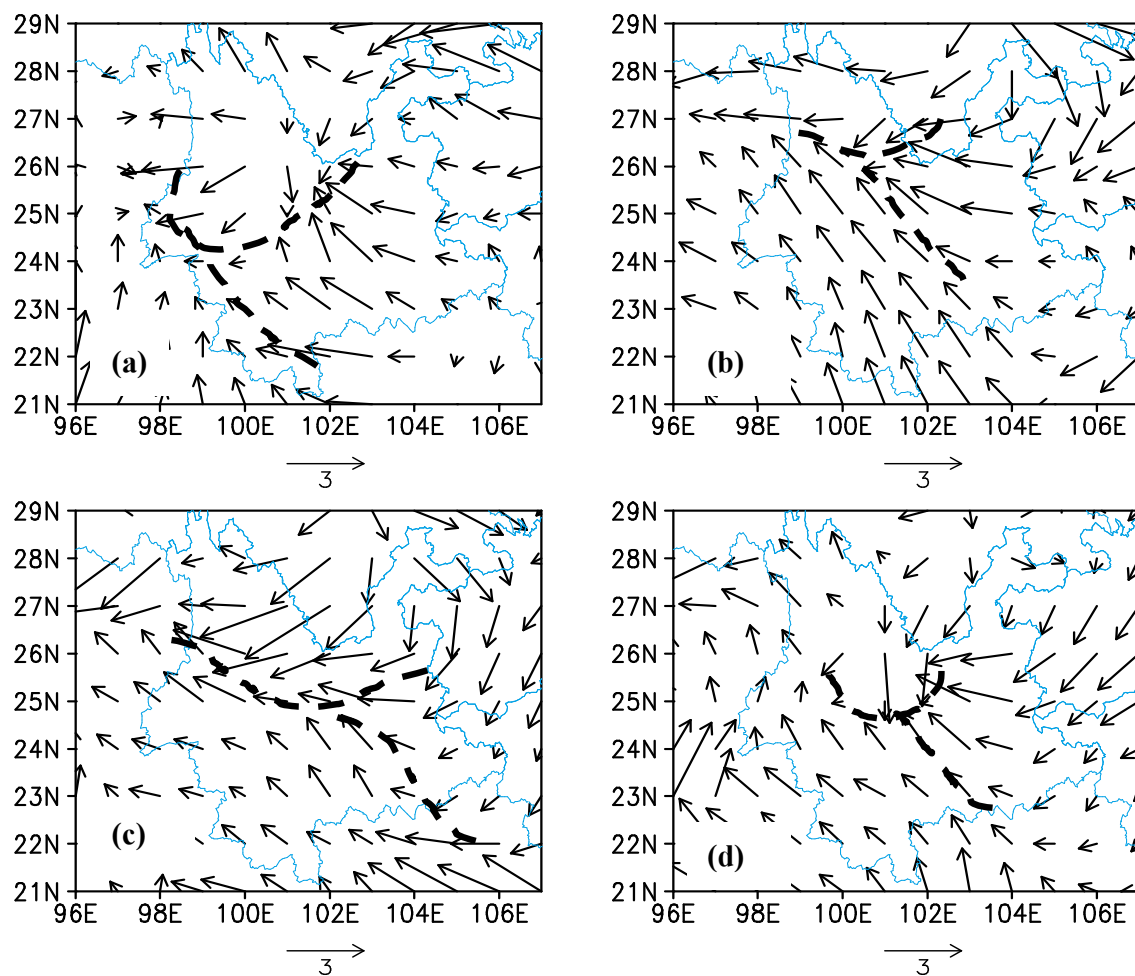


Fig. 7. Streamline at 10 m above ground. (a) 1200 UTC 30 May 2001; (b) 1200 UTC 31 May 2001; (c) 1200 UTC 1 June 2001; (d) 0000 UTC 2 June 2001.

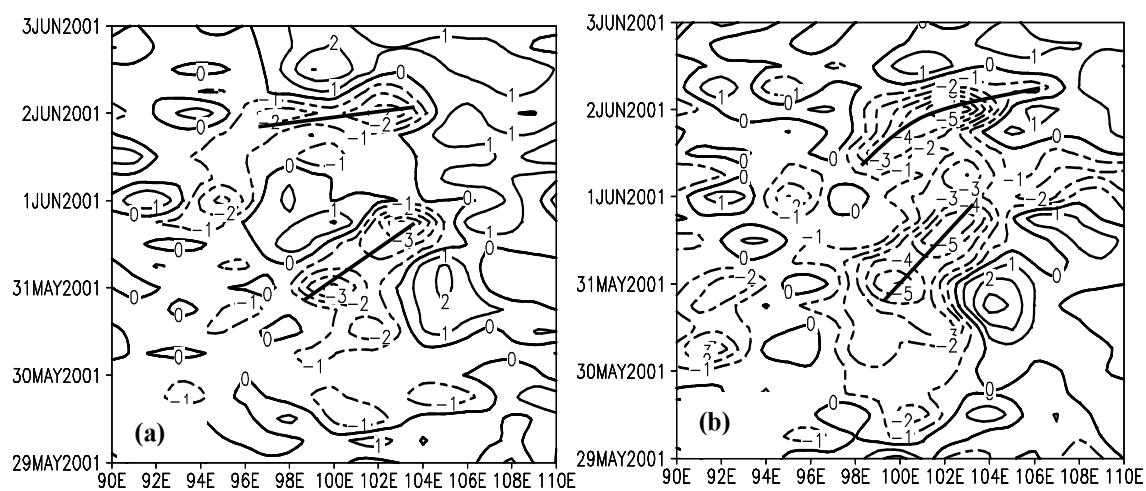


Fig. 8. Temporal-longitude cross section of divergence along (a) 24°N and (b) 25°N at 750 hPa (units: 10^{-5} s^{-1}).

role in the occurrence of the heavy rainfall.

In order to further study the characteristic of the coupling between the ULJ and LLJ in this case, the vertical profile of horizontal wind along 101°E was analyzed (Fig. 6). At 0000 UTC 31 May (Fig. 6a), the maximum of the ULJ located at 150 hPa occurred, and there was a wind zone extending both from the upper to the lower level, and from north to south. In addition, the isotach of 10 m s⁻¹ existed from 27°N to 23°N, around 800 hPa–700 hPa, and the precipitation then occurred in the north of Yunnan with the interaction between the ULJ and LLJ. Then, at 0000 UTC 1 June (Fig. 6b), the LLJ in Yunnan weakened, and the maximum of the ULJ moved down unceasingly, as the precipitation in Yunnan weakened. At 0000 UTC 2 June (Fig. 6c), the maximum of the ULJ moved south continuously and weakened. However, the wind zone extended from the upper level to the lower level, strengthened gradually, and the isotach of 15 m s⁻¹ existed from 24.5°N to 22.5°N, around 800 hPa–700 hPa, and strong precipitation occurred in the south of Yunnan. Thus it can be found that a coupling between the ULJ and LLJ existed. Then, at 1800 UTC 2 June (Fig. 6d), the maximum of the ULJ had moved to Yunnan, and it weakened. Meanwhile, the LLJ also moved away from Yunnan, and the precipitation in Yunnan stopped following it.

3. Mesoscale systems

It has already been noticed that mesoscale systems are the direct influencing systems for heavy rainfall. In this case, where do mesoscale systems appear easily? It is found from the study that the special characteristics of mesoscale systems were quite different from those in East and South China.

3.1 *Mesoscale disturbance in the lower troposphere*

It can be noticed from the precipitation amount (Fig. 2a) that the precipitation distribution possessed characteristics relating to the terrain. Was it related with the special terrain in Yunnan under favorable large-scale conditions? So, the streamline at 10 m aboveground (provided by INCP data) is analyzed because of the complexity of the terrain. It has been revealed that, during the rainfall, there were two main mesoscale convergence lines near to the ground. Moreover, there existed an obvious interaction between them, and heavy rainfall occurred in the area where the two convergence lines met. In the initial stage of heavy rainfall, following the formation of the Indian-Myanmar trough and the East Asian trough moving southward, cold air entered Yunnan along the south-

east edge of the Tibetan Plateau, and a northeast-southwest convergence line formed between the northeast and southeast currents (Fig. 7a). At the same time, on the border of Myanmar and Yunnan, influenced by both the topography and the circulation, there was a convergence line oriented from south to north. There were convective cloud clusters continuously being produced and moving eastward, which formed the precipitation intensity in north Yunnan (e.g., Nanhua: 25.18°N, 101.28°E) reach 5.5 mm from 1700 UTC 30 May to 1800 UTC 30 May (Fig. 2b). The Indian-Myanmar trough then developed and maintained at 88°E, and the southwest current strengthened, making the southwest segment of the convergence line move north and form the east-west convergence line. Meanwhile, a south-north convergence line formed along the Red River (Fig. 7b). Two convergence lines met in Nanhua and created heavy rainfall from 0000 UTC 31 May to 0000 UTC 1 June (Fig. 2b). The Indian-Myanmar trough then weakened and moved slowly, cold air moving continuously from north to south, and the east-west convergence line moved south continually. It should be noted that the cross-point of the two convergence lines moved southward continually (Figs. 7c and d), causing heavy rainfall in Tonghai (Fig. 2c). In the later stage of heavy rainfall, following the weakening of the Indian-Myanmar trough, two convergence lines disappeared and precipitation ceased.

It can be seen from the above-mentioned analysis that the precipitation system in Yunnan was, in certain aspects, different from that in East China. It was neither like the mei-yu front in the Yangtze River, which has a typical east-west shear line and positive vortex zone, nor was it like the heavy rainfall in South China, which interacts with the quasi-stationary front and westerly trough. In fact, it wasn't the same as any kind of front. The systems in the lower troposphere in Yunnan are very complex, and the appearance of this kind of convergence line might be associated with the terrain (Fig. 1). The cold air was weaker than that in East China and it moved into Yunnan by means of diffusion, meaning most of the cold air moved along the terrain of Yunnan. In addition, when the trough in the Bay of Bengal and the Indian-Myanmar trough formed and developed, a southwest current appeared, part of it passing through the Indo-China peninsula and meeting with the cold air in the valley of the Red River to produce a south-north direction convergence line. The rest entered into Yunnan from southwest of the region and met with the northeast current to form an east-west direction convergence line. It can be seen that the place where two convergence lines crossed was favorable for unstable energy accumulation and water

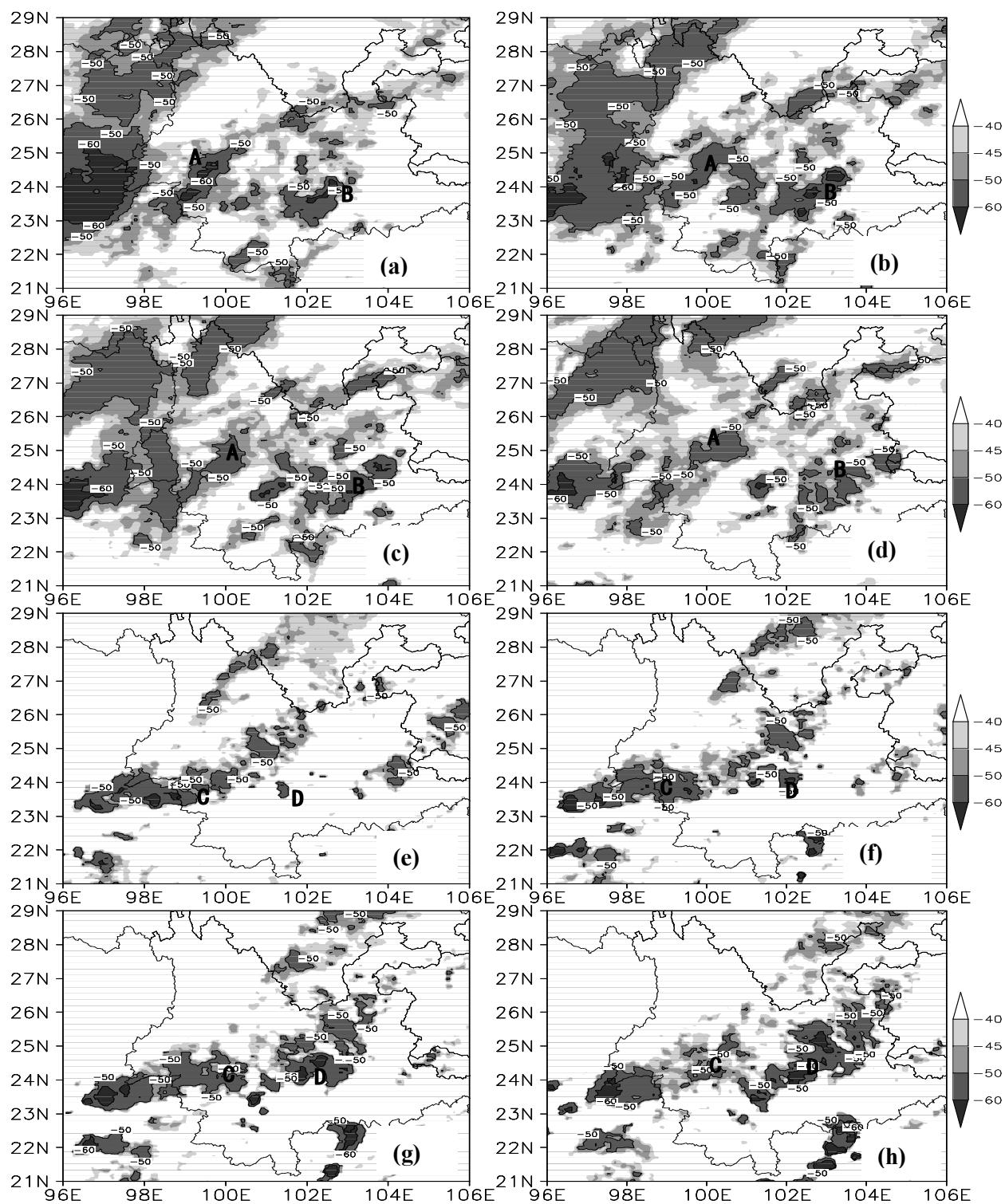


Fig. 9. Successive evolution of TBB 4 times during two days, respectively. (a) 0900 UTC 31 May 2001; (b) 1000 UTC 31 May 2001; (c) 1100 UTC 31 May 2001; (d) 1200 UTC 31 May 2001; (e) 2000 UTC 1 June 2001; (f) 2100 UTC 1 June 2001; (g) 2200 UTC 1 June 2001; (h) 2300 UTC 1 June 2001.

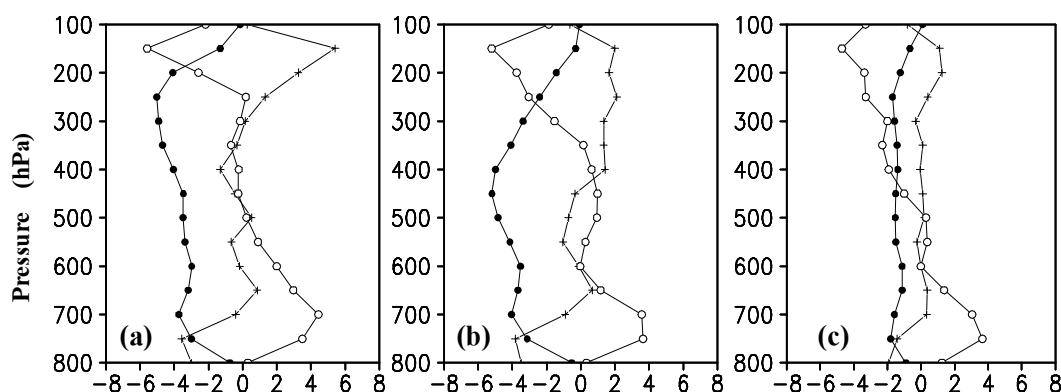


Fig. 10. Vertical profiles of vorticity, divergence and vertical velocity in the area mean (24° – 26° N, 99.5° – 101.5° E) corresponding to cloud cluster A (vorticity: o, units: 10^{-5} s^{-1} ; divergence: +, units: 10^{-5} s^{-1} ; vertical velocity: •, units: $10^{-3} \text{ hPa s}^{-1}$). (a) 0600 UTC 31 May 2001; (b) 1200 UTC 31 May 2001; (c) 1800 UTC 31 May 2001.

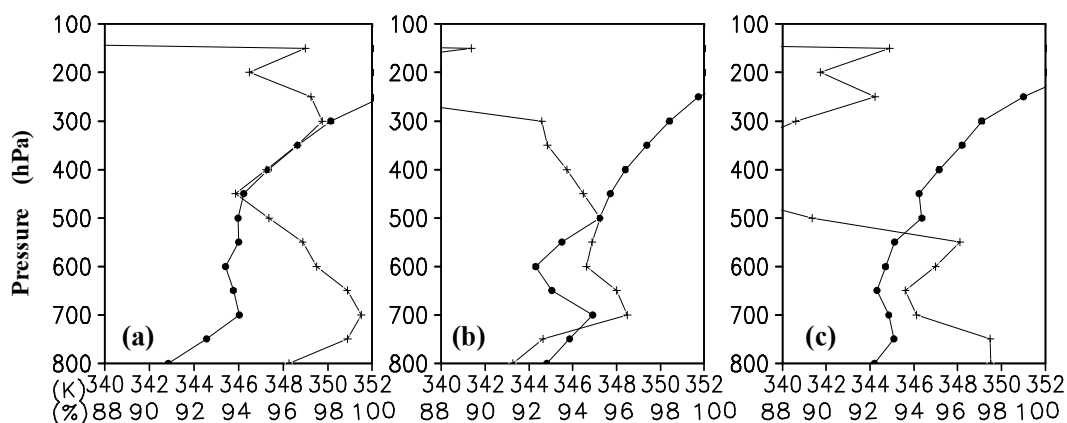


Fig. 11. Vertical profiles of relative humidity and pseudo-equivalent potential temperature in the area mean (24° – 26° N, 99.5° – 101.5° E) corresponding to cloud cluster A (relative humidity: +, units: %; pseudo-equivalent potential temperature: •, units: K). (a) 0600 UTC 31 May 2001; (b) 1200 UTC 31 May 2001; (c) 1800 UTC 31 May 2001.

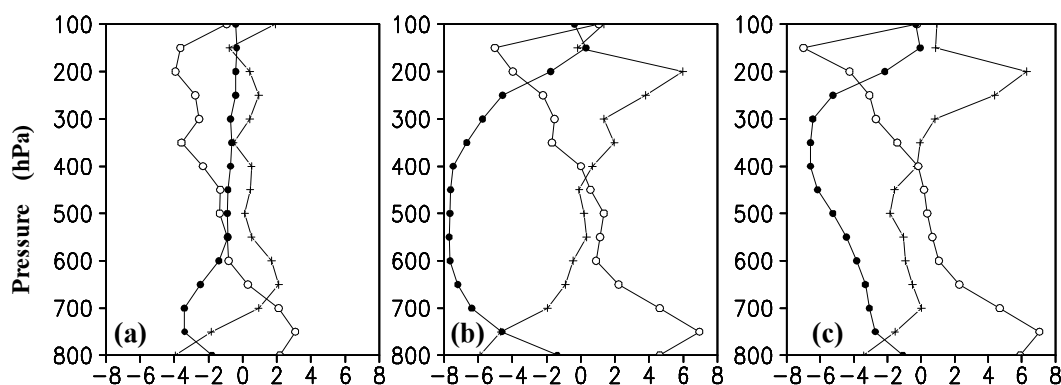


Fig. 12. Vertical profiles of vorticity, divergence and vertical velocity in the area mean (23.5° – 25.5° N, 101° – 103° E) corresponding to cloud cluster D (vorticity: o, units: 10^{-5} s^{-1} ; divergence: +, units: 10^{-5} s^{-1} ; vertical velocity: •, units: $10^{-3} \text{ hPa s}^{-1}$). (a) 1800 UTC 1 June 2001; (b) 0000 UTC 2 June 2001; (c) 0600 UTC 2 June 2001.

vapor convergence, causing heavy rainfall. Therefore, it can be revealed, even though large-scale systems were favorable for heavy rainfall in Yunanan, local heavy rainfall was mainly caused by convergence lines in the lower troposphere, plus some related mesoscale systems produced by the interaction between the convergence lines.

3.2 *Formation of a mesoscale convective system*

The formation of a mesoscale convective system is connected with the convergence in the lower level and divergence in the upper level. To understand further the relation between the distribution of precipitation and the divergence in the lower troposphere, the temporal-longitude cross section of divergence along 24°N and 25°N at 750 hPa has been drawn. It can be noticed from Fig. 8 that the distribution of divergence along 24°N was consistent with that along 25°N, and they were closely related with the distribution of precipitation (Figs. 2b and c). For example, there were stronger convergences during the period of 1800 UTC 30 May to 0000 UTC 31 May 2001, 0600 UTC 31 May to 1800 UTC 31 May 2001 and 1800 UTC 1 June to 0000 UTC 2 June 2001, and at the same time, strong precipitation occurred in some stations in Yunnan (Fig. 2). The distributions were also consistent with the positions of the convergence lines in the lower troposphere, which were associated with the topography of Yunnan (Fig. 8). For example, the convergence maximum at 99°–103°E at 1800 UTC 30 May to 1200 UTC 31 May was near to the merging area of the two convergence lines, and the convergence maximum at 101°–103°E at 0000 UTC 2 June was consistent with the east-west convergence line moving southward, and the convergence line along the Red River. It is possible that the development of convective systems causing the heavy rainfall could be related to topographical characteristics in Yunnan.

It is well known cloud systems can directly produce heavy rainfall. It can be seen from the evolution characteristic of the cloud clusters that there were two cloud systems: one moving from north to southeast, and the other moving from south to northeast. Gradually, these systems then met and become a vortex-shaped cloud cluster located in the southeast of the Tibetan Plateau, before moving slowly eastward. Among them, there were mesoscale cloud clusters which moved continually into Yunnan, maintained and developed in some areas to produce heavy rainfall. Figure 9 shows the successive evolution of TBB (Temperature of Black Body) at one hour intervals over two days. There were two main cloud clusters, A and B, in Yunnan from 0900 UTC 31 May to 2000 UTC 31 May 2001 (Figs. 9a–

d), with cluster A having a tendency to develop along the lower topography and cluster B locating along the Red River. The two cloud clusters moved slowly and caused the local heavy rainfall. Similarly, it can be seen from 2000 UTC 1 June to 2300 UTC 1 June 2001 (Figs. 9e–h) that the cloud clusters C and D caused heavy rainfall the next day. Cloud cluster D developed in an initial area and was located in the region of the Red River. Thus it can further be proven that the special topography of Yunnan can provide favorable conditions for the formation and development of mesoscale convective systems.

3.3 *Structural characteristics of the mesoscale convective system*

As mentioned above, there are two precipitation maxima in Yunnan, and these were caused mainly by two cloud clusters in different days. So, the areas of cloud cluster A and cloud cluster D (mentioned above) were chosen to further study the structural characteristics of mesoscale convective systems causing heavy rainfall. Only the physical quantity distribution above 800 hPa has been analyzed because of the average elevation of Yunnan being 2000 m. It shows, even though there was no obvious system such as the vortex in the mei-yu front of the Yangtze River, that convergence lines only existed in the lower troposphere, however the dynamical and thermal dynamical structure was very obvious during the heavy rainfall process.

Figures 10 and 11 show the vertical profiles of some physical quantities in the area mean (24°–26°N, 99.5°–101.5°E) corresponding to cloud cluster A. It can be seen that the relative vorticity below 500 hPa was positive all the time and it had reached up to 350 hPa at 1200 UTC 31 May. In addition, a strong convergence existed in the planetary boundary layer and the lower troposphere, and, meanwhile, there was strong divergence in the upper troposphere. The whole air column had a strong upward motion, and the vertical motion weakened following convergence in the lower level, weakening at 1800 UTC 31 May. At the same time, the air column was moist, and the relative humidity above 90% had reached 150 hPa, then fell to 300 hPa at 1200 UTC 31 May, and finally to 500 hPa at 1800 UTC 31 May. In addition, there was an inversion layer below 600 hPa, which also weakened at 1800 UTC 31 May.

Figures 12 and 13 show the vertical profiles of some physical quantities in the area mean (23.5°–25.5°N, 101°–103°E) corresponding to cloud cluster D. It can clearly be seen that the structural characteristics of cloud cluster D were similar to cloud cluster A, but that cloud cluster D seemed to be stronger than cloud cluster A. At 0000 UTC 2 June, the maximum of posi-

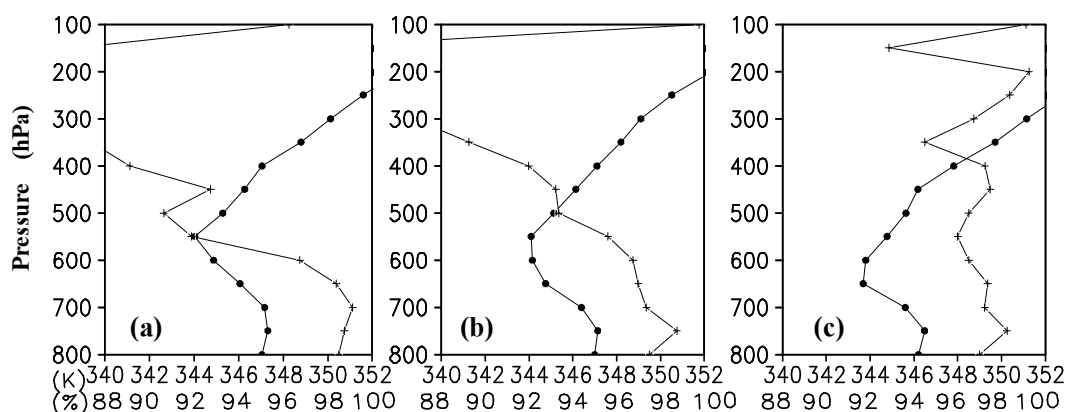


Fig. 13. Vertical profiles of relative humidity and pseudo-equivalent potential temperature in the area mean (23.5° – 25.5° N, 101° – 103° E) corresponding to cloud cluster D (relative humidity: +, units: %; pseudo-equivalent potential temperature: •, units: K). (a) 1800 UTC 1 June 2001; (b) 0000 UTC 2 June 2001; (c) 0600 UTC 2 June 2001.

tive relative vorticity below 500 hPa had reached $7 \times 10^{-5} \text{ s}^{-1}$, the maximum of convergence in the lower level reached $-6 \times 10^{-5} \text{ s}^{-1}$, and the maximum of vertical velocity was $-8 \times 10^{-3} \text{ hPa s}^{-1}$, all the values being larger than those in cloud cluster A. Thus, it can be understood that the precipitation associated with cloud cluster D was stronger than that caused by cloud cluster A (Figs. 2b and c).

4. Water vapor supply for heavy rainfall

Heavy rainfall cannot occur without the convergence of water vapor. Figure 14 shows the successive evolution of the moisture flux (MF) and the divergence of MF in the total column along 101° E. It demonstrates that, in Yunnan, there were two maxima during the periods of 0600 UTC 31 May to 0000 UTC 1 June and 1800 UTC 1 June to 0600 UTC 2 June, respectively, which are consistent with the precipitation maxima occurrences—one in north Yunnan, and the other in the south. It can therefore be presumed that the heavy rainfall resulted from water vapor transportation and convergence.

To analyze in detail the source, import and export of water vapor causing the heavy rainfall in Yunnan, the Yunnan area (21° – 28° N, 98° – 105° E) has been chosen to calculate the water vapor transportation going through each side, and the budget in the area ($7^{\circ} \times 7^{\circ}$).

It is obvious from Table 1 that, generally speaking, water vapor was imported from the west and south sides of Yunnan, and exported from the east and north sides. Moreover, the amount imported was larger than that exported from Yunnan. However, the situation was different at different stages. In the initial stage of precipitation at 0000 UTC 30 May, import and export of water vapor were small, and water va-

por convergence was also weak. Water vapor convergence then reached $-19.43 \times 10^4 \text{ t s}^{-1}$ at 0000 UTC 31 May. There were two periods when water vapor increased significantly during the heavy rainfall: at 0000 UTC 31 May to 1200 UTC 31 May; and 0000 UTC 1 June to 0000 UTC 2 June, and these were the times when heavy rainfall occurred and the strong precipitation appeared. The computational results show that water vapor converged both in the east-west and in the south-north, and the convergence quantity was approaching the value for East Asia. For example, after the “secondary stage of mei-yu” ended in summer 1998, the perturbation on the quasi-stationary front over the Yangtze River developed continually and became a cyclone, before moving to Korea and producing heavy rainfall. The maximum water vapor convergence in Korea reached $-37.28 \times 10^4 \text{ t s}^{-1}$, and caused more than 130 mm of precipitation in 24 hours (Zhang and Zhao, 2004). In this case, the maximum water vapor convergence reached $-29.06 \times 10^4 \text{ t s}^{-1}$, and precipitation was less than the former, probably because of the higher altitude preventing rich water vapor from easily reaching there. If the total quantity of water vapor convergence from 0000 UTC 31 May to 0000 UTC 2 June was distributed averagely across the Yunnan area, then the average precipitation was approximately 50 mm in 48 hours, and it can be seen from the distribution of observational precipitation (Fig. 2a) that the precipitation in most of Yunnan had reached the mentioned-above amount with the two precipitation maxima. It can also be seen (Table 1) that the quantity of moisture convergence in Yunnan corresponds to the precipitation amounts in this area. Furthermore, from the import and export data from each side of the region, we can see that water vapor mainly comes from the southwest, that is, the Bay of

Table 1. Water vapor transportation (1000–100 hPa) in the Yunnan area from the east, west, south, and north directions, at 12-hour intervals, from 0000 UTC 30 May to 1200 UTC 2 June 2001. units: 10^4 t s^{-1} .

Time	Lateral boundary						Total sum in the area
	West	East	North	South	Sum (east–west)	Sum (north–south)	
0000 UTC 30 May	4.30	4.05	3.45	6.20	–0.24	–2.74	–2.99
1200 UTC 30 May	1.88	–3.50	7.25	11.37	–5.38	–4.12	–9.50
0000 UTC 31 May	8.63	–2.52	8.27	16.55	–11.15	–8.28	–19.43
1200 UTC 31 May	11.96	4.95	8.09	30.14	–7.01	–22.05	–29.06
0000 UTC 1 June	15.93	17.10	3.58	18.83	1.17	–15.26	–14.08
1200 UTC 1 June	24.42	13.48	2.94	15.39	–10.94	–12.45	–23.39
0000 UTC 2 June	24.77	16.50	5.80	20.68	–8.28	–14.88	–23.15
1200 UTC 2 June	26.13	22.23	9.50	11.70	–3.90	–2.20	–6.10
Explanation	> 0	> 0	> 0	> 0	< 0	< 0	< 0
	import	export	export	import	convergence	convergence	convergence

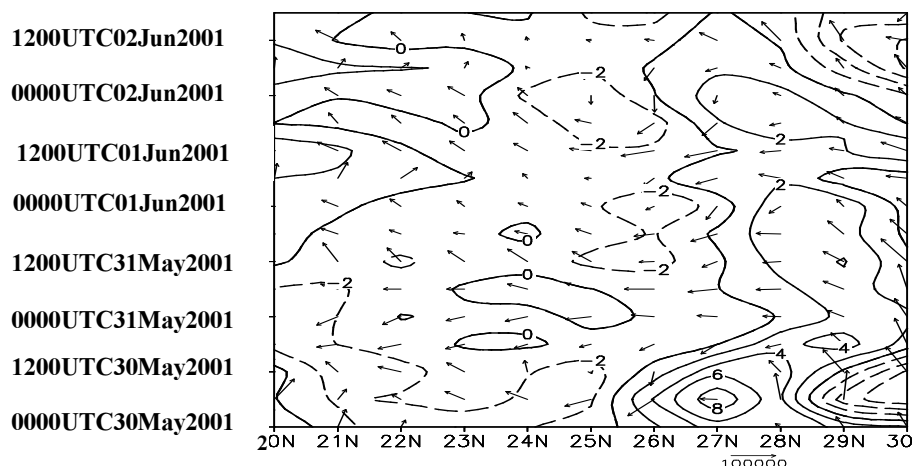


Fig. 14. Temporal-latitude cross section of Moisture Flux (MF) (shown by vector, units: $\text{g s}^{-1} \text{ cm}^{-1} \text{ hPa}^{-1}$) and Divergence of MF (units: $10^{-1} \text{ g s}^{-1} \text{ cm}^{-2}$) in the total layer along 101°E .

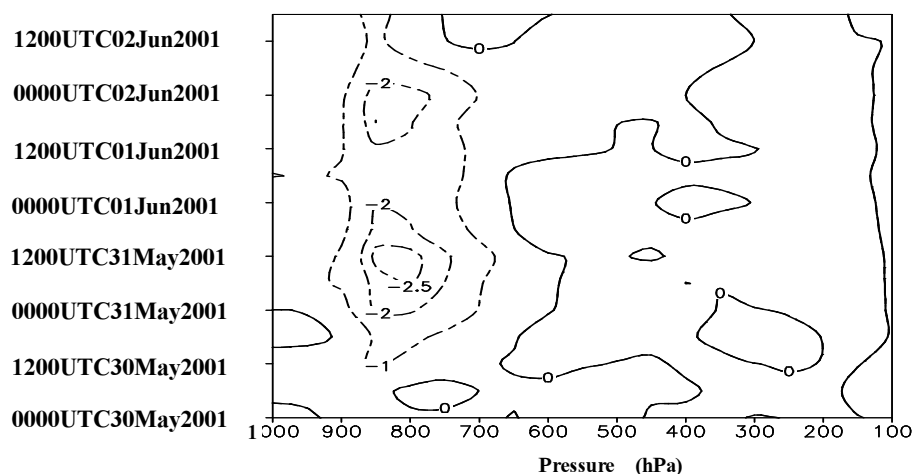


Fig. 15. Temporal-pressure cross section of the divergence of moisture flux in the area mean ($21^\circ\text{--}28^\circ\text{N}$, $98^\circ\text{--}105^\circ\text{E}$) (units: $10^{-7} \text{ g s}^{-1} \text{ cm}^{-2}$).

Bengal. The above-mentioned results are reasonable.

In order to further clarify the average water vapor of each layer in Yunnan, the temporal-pressure of divergence of moisture flux in the mean area (21° – 28° N, 98° – 105° E) is shown in Fig. 15. This demonstrates that the water vapor convergence concentrated in the lower level, from 900 hPa to 700 hPa, and the maximum at around 800 hPa. There was even a little water vapor transportation from 700 hPa to 600 hPa at 1200 UTC 31 May, and from 700 hPa to 400 hPa at 0000 UTC 2 June. Therefore, it can be surmised that water vapor could be transported to Yunnan by accompanying the climbing current layer of the stronger southwest wind, even though the terrain is higher in Yunnan, and meanwhile, the terrain in the southwest of Yunnan is lower and there is a “trumpet-shaped” terrain in the valley of the Red River, which is also favorable for water vapor transportation. Similarly, it can clearly be seen that there were two maxima of water vapor convergence during the heavy rainfall, which corresponds to the forming of the two precipitation maxima.

5. Three-dimensional trajectory of air parcels

In order to further validate the source location and transportation of water vapor, the Vis5D software is used to trace air parcel trajectories. The air parcel trajectories were drawn and it is, in many ways, similar to smoke trajectories in a wind tunnel. When the time interval, direction and speed of a variable are given, future air parcel trajectories can be described and then traced back from the final to the first step.

Three groups of air parcel were chosen and they were located, respectively, in the west, south and east of the Yunnan Plateau (it cannot include all the trends of particles because the choice is partial), with 0000 UTC 31 May as the current time step, and the interval time as six hours ($1^{\circ} \times 1^{\circ}$ NECP data was used). The air parcels were then traced from 0000 UTC 28 May to 1200 UTC 2 June 2001 in order to observe, respectively, where they came from and continued to. It can be revealed that the air parcels in the west and south of the Yunnan-Guizhou Plateau came mainly from the Bay of Bengal and the North Indian Ocean, and the air parcels in the east of the Yunnan Plateau were related with the south and north currents. Warm moist currents came from the north part of the South China Sea and the Bay of Bengal, and the cold air came down from the Sichuan Basin, surrounding the southeast of the Tibetan Plateau. Air parcels in the west moved along the Irrawaddy River and climbed over Yunnan, before moving northeastward. Air parcels in the south moved along the valley and uplifted grad-

ually. Air parcels associated with the convergence of two currents in the east moved along the Red River valley, uplifted gradually, met with air parcels coming from southwest, then moved eastward. In Fig. 16, the air parcel trajectories are seen in both top and side views. The figure shows that there were two currents from the south and north, along the Red River valley, with cold air coming from the north and warm moist air coming from the south. The merging and uplifting of the two currents must result in the release of unstable energy, and that was the main reason why heavy rainfall could occur in these areas.

6. Discussion and conclusions

Through the use of various conventional and non-conventional data, the analysis during the strong precipitation process in Yunnan shows that the heavy rainfall was under the favorable large-scale conditions and it was caused by a series of mesoscale systems. Generally speaking, the multiscale systems were favorable to the occurrence of heavy rainfall like those in East China. However, the particular terrain, low latitude environment, Tropical Ocean and special influencing weather systems in Yunnan are different from the precipitation in East China (Zhao et al., 2004; Sun et al., 2005). Therefore, a detailed analysis of the circulation situation, the information and structure characteristics of the mesoscale convective system, and water vapor supply has been conducted and the following conclusions can be drawn:

(1) Certain kinds of interactions existed between warm moist air and cold air, providing favorable large-scale circulation conditions for heavy rainfall occurrence in Yunnan. The forming of the Indian-Myanmar trough played an important part in the transportation of warm moist vapor. In addition, the influence of the westerly system (e.g., cold air activity) was still obvious, but its path was connected with the special terrain of Yunnan. At the same time, the coupling between the upper- and lower-level jets could not be ignored, and this supplied the source of water vapor for the occurrence of heavy rainfall.

(2) The mesoscale convergence lines and interaction between them may be an important triggering mechanism for the heavy rainfall appearance. The analysis in the near-surface layer shows that these convergence lines could be induced by the special topography of Yunnan and its surrounding region, and there were cloud cluster appearances around the convergence lines that caused the development of mesoscale convective systems. The effect of topography is important, and should be considered.

(3) The analysis of the structural characteristics of

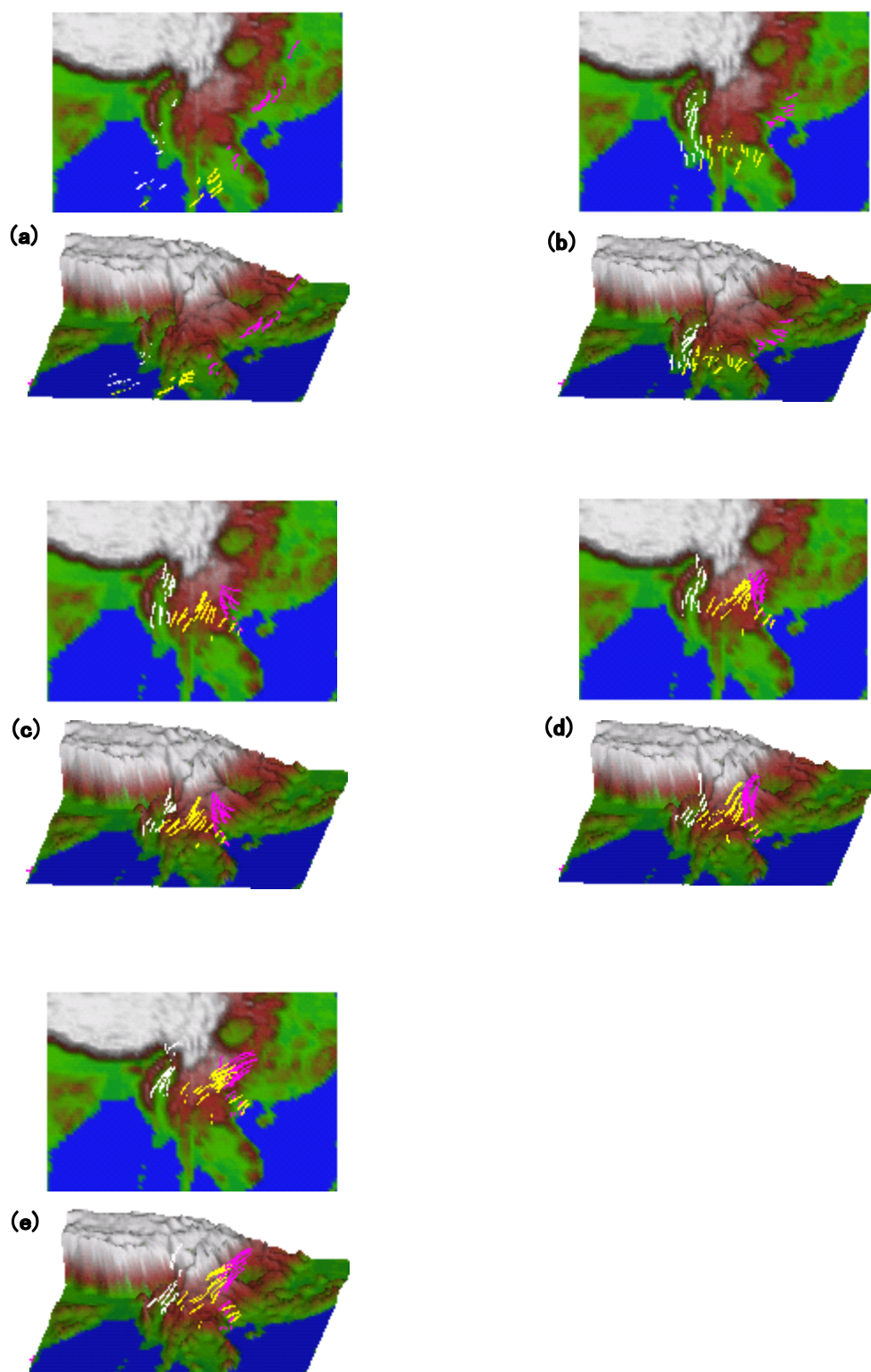


Fig. 16. Air parcel trajectories. (White groups, yellow groups and red groups denote, respectively, the air parcel in the west, south and east of the Yunnan plateau. There are two figures at each time, which, respectively, are the top view and side view). (a) 0000 UTC 30 May 2001; (b) 0000 UTC 31 May 2001; (c) 1800 UTC 31 May 2001; (d) 0000 UTC 1 June 2001; (e) 0600 UTC 1 June 2001.

the two main mesoscale convective systems, cloud clusters A and D, showed that both were under a favorable large-scale environment where positive vorticity and convergence were strong in the lower troposphere, with a strong upwards motion in the middle troposphere. At the same time, there was instability in the lower layer of the air column, which was moist.

(4) The analysis of water vapor transportation showed that the source location of water vapor during heavy rainfall was, in this case, mainly the Bay of Bengal. Certain regions (e.g., the lower area in the southeast of Yunnan and the “trumpet-shaped” terrain of the Red River) are very favorable for water vapor convergence. The water vapor could be brought into the middle troposphere under a stronger southwest current and cause precipitation. The influence of water vapor convergence could imply, to a certain extent, the appearance and intensification of the heavy rainfall.

(5) The analysis of three-dimensional air parcel trajectories can better reveal and describe the source location and transportation of water vapor to the Yunnan area.

In summary, some facts have been revealed in this paper. The influence of topography and convergence lines are quite different from those on the mei-yu front over the Yangtze River. Mesoscale systems form and develop easily in particular areas. However, in this paper, it has been demonstrated that the factors influencing heavy rainfall are complicated. Some questions should still be clarified, such as, did the topography difference play an important role in thermal forcing? What is the role of the Tibetan plateau? Finally, the influence of the Yunnan terrain upon heavy rainfall in this region should be researched further.

Acknowledgements. The authors are very thankful for the denser precipitation data provided by the Yunnan Meteorological Bureau. Prof. Li Chongyin, Prof. Zhou Xiaoping and Prof. Zhang Qingyun gave important suggestions and comments. Dr. Xiao Ziniu provided valuable advice and help. Prof. Shi Chunxiang and Dr. Yan Hongming gave kind assistance. The research was financially supported by the National Key Basic Research and Development Project of China (Grant No. 2004CB418301) and the National Natural Science Foundation of China (Grant No. 40405008).

REFERENCES

- Bei Naifang, Zhao Sixiong, and Gao Shouting, 2002: Numerical simulation of a heavy rainfall event in China during July 1998. *Meteor. Atmos. Phys.*, **80**, 153–164.
- Chen Hong, Sun Jianhua, Zhao Sixiong, and Zeng Qingcun, 2001: Impact of artificial water channel on the Tibetan Plateau on rainfall in northwest China Part I: numerical simulation for some rainfall cases. *Climatic and Environmental Research*, **6**(4), 371–379. (in Chinese)
- Cheng Linsheng, and Feng Wuhu, 2001: Analyses and numerical simulation on an abrupt heavy rainfall and structure of a mesoscale vortex during July 1998. *Chinese J. Atmos. Sci.*, **25**(4), 465–478. (in Chinese)
- Ding Yihui, 1993: *Study on the Lasting Heavy Rainfalls over the Yangtze-Huaihe River Basin in 1991*. China Meteorological Press, Beijing, 255pp. (in Chinese)
- Duan Xu, and Li Ying, 2001: A case study of mesoscale convective complexes over lower latitude plateau. *Chinese J. Atmos. Sci.*, **25**, 676–682. (in Chinese)
- Fei Jianfang, Qiao Quanming, and Gao Taiping, 1993: A study of vapour transport over Asian monsoon region in mei-yu season of 1983. *Quarterly J. Appl. Meteorol.*, **4**(1), 65–71. (in Chinese)
- Guo Rongfang, and Lu Yabing, 2003: A case analysis of meso scale cold vortex heavy rainfall in Central Yunnan province. *Meteorology*, **29**, 29–33. (in Chinese)
- Kao Yu-hsie, and Chang Ming-lie, 1957: On the monsoon problem of the far east and some of its characteristics. *Acta Geographica Sinica*, **23**(1), 55–67.
- Li Chongyin, and Wu Jingbo, 2002: Important role of the Somalian cross-equator flow in the onset of the South China Sea during summer monsoon. *Chinese J. Atmos. Sci.*, **26**(2), 185–192. (in Chinese)
- Qing Jian, Ju Jianhua, and Jie Mingan, 1997: *The Climatology in Lower Latitude Plateau Area*. China Meteorological Press, Beijing, 210pp. (in Chinese)
- Qing Jian, Jie Mingan, Liu Yu, and Yu Lingxiang, 2000: *Introduction about Meteorological Disasters in Yunnan*. China Meteorological Press, Beijing, 250pp. (in Chinese)
- Sun Jianhua, Chen Hong, Zhao Sixiong, and Zeng Qingcun, 2001: Impact of artificial water channel on the Tibetan Plateau on rainfall in northwest China Part II: numerical simulation for monthly precipitation amount. *Climatic and Environmental Research*, **6**(4), 380–390. (in Chinese)
- Sun Jianhua, Zhang Xiaoling, Qi Linlin, and Zhao Sixiong, 2005: An analysis of a meso- β system in a mei-yu Front using the intensive observation data during CHeRES 2002. *Adv. Atmos. Sci.*, **22**(2), 278–289.
- Tao Shiyan, 1980: *Rainfall in China*. Science Press, Beijing, 225pp. (in Chinese)
- Tao Shiyan, Ni Yunqi, and Zhao Sixiong, 2001: *The Research of Formation Mechanism and Prediction Heavy Rainfall in Summer 1998 in China*. China Meteorological Press, Beijing, 184pp. (in Chinese)
- Xu Xiangde, Tao Shiyan, Wang Jizhi, Chen Lianshou, ZhouLi, and Wang Xiurong, 2002: The relationship between water vapor transport features of Tibetan plateau- Monsoon “Large Triangle” Affecting Real on and Drought-Flood Abnormality of China. *Acta Meteor. Sinica*, **60**(3), 257–267. (in Chinese)
- Xu Xiangde, Miao Qiuju, Wang Jizhi, and Zhang Xue-

- jin, 2003: The water vapor transport model at the regional boundary during the mei-yu period. *Adv. Atmos. Sci.*, **20**(3), 333–342.
- Xu Yamei, and Gao Kun, 2002: Simulation and analysis of Meso- β vortex over middle reaches of the Yangtze River on 22 July 1998. *Acta Meteor. Sinica*, **60**(1), 85–95. (in Chinese)
- Yeh Tu-cheng, and Chang Chieh-chien, 1974: A preliminary experimental simulation on the heating effect of the Tibetan Plateau on the general circulation over Eastern Asia in summer. *Scientia Sinica*, **17**(3), 397–420. (in Chinese)
- Zeng Qingcun, Zhang Banglin, Liang Youlin, and Zhao Sixiong, 1994: The Asia summer monsoon—a case study. *Proc. Indian Natl Sci. Acad. Phys Sci.*, **60**(1), 81–96.
- Zeng Qingcun, and Li Jiangping, 2002: Interactions between the Northern and Southern hemispheric atmospheres and the essence of monsoon. *Chinese J. Atmos. Sci.*, **26**(4), 433–448. (in Chinese)
- Zhang Feng, and Zhao Sixiong, 2004: A study of formation and development of one kind of cyclone on the mei-yu (Baiu) front. *Adv. Atmos. Sci.*, **21**(2), 741–754.
- Zhang Renhe, 2001: Relations of water vapor transport from Indian Monsoon with that over East Asia and the summer rainfall in China. *Adv. Atmos. Sci.*, **18**(5), 1005–1017.
- Zhao Sixiong, and Graham A. Mills, 1991: A study of a monsoon depression bringing record rainfall over Australia. Part II: synoptic -diagnostic description. *Mon. Wea. Rev.*, **119**, 2074–2094.
- Zhao Sixiong, Tao Zuyu, Sun Jianhua, and Bei Naifang, 2004: *The Study of Mechanism of Mei-yu Front Heavy Rainfall in Yangtze River*. China Meteorological Press, Beijing, 281pp. (in Chinese)
- Zhou Xiaoping, Lu Hancheng, Ni Yunqi, and Tan Zhemin, 2004: A review of progresses in mesoscale dynamic research in China since 1999. *Adv. Atmos. Sci.*, **3**(21), 497–504.
- Zhou Xiuji, Xue Jishan, Tao Zuyu, and Zhao Sixiong, 2003: *Study of Rainfall Experiment in South China in 1998*. China Meteorological Press, Beijing, 220pp. (in Chinese)