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A Diagnostic Analysis of the Impact of Complex Terrain in the Eastern Tibetan Plateau, China, on a Severe Storm

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Abstract

With mesoscale data from a high-resolution numerical model, this paper analyzes the impact of the complex mesoscale terrain at the eastern edge of the Tibetan Plateau on the formation and development of a local severe storm. The result shows that the dynamic blocking effect of the Tibetan Plateau terrain affects the moisture transfer channel in this heavy rain scenario and brings about the formation of a strong water-vapor convergence center in northwest Sichuan and the upper branch of Huang He (Yellow River). The terrain structure of the east side of the Tibetan Plateau places a high energy tongue and energy front in the lower layer of the troposphere of Sichuan Basin and helps establish unstable potential energy stratification in the lower troposphere of the Sichuan Basin. The accumulation of water vapor in the lower troposphere in the Sichuan Basin is the major reason for the establishment of unstable potential energy stratification. The steep terrain of the east side of Tibetan Plateau strengthens the ascendant motion. The strongest updraft movement occurred in the convergence area of the vertical shear of east and west wind and the steep landform, stimulating the unsteady release of energy and rapid development of the strong convection. The process is also accompanied by a mesoscale vortex in the east side of the Plateau. The most significant thermal and dynamic feature of this heavy rain scenario is that high temperature, high humidity, and strong vorticity columns appear only in the lower troposphere, which is very different from Mei-Yu. (''Mei-Yu'' in Chinese and ''Baiu'' in Japanese refers to the frontal precipitation caused by Mei-Yu front, a persistent east-west zone of disturbed weather during early summer which is quasi-stationary and stretches from the east China coast, across Taiwan, and eastward into the Pacific Ocean south of Japan.)

Introduction

The impact of alpine regions on the three-dimensional flow pattern and local strong convective storm rainfall is an issue that has concerned many meteorological experts and scholars. In an international conference, Schmid and Lehre (1998) discussed the relationship between winds and strong storms in alpine regions. They indicated that, within a given synoptic situation, the formation, structure, and development of local strong convection storm rainfall relies on distribution of wind that is affected by the mountains. As a key factor in formation of strong storms, vertical wind shear may be strengthened or weakened locally due to terrain differences.

Stretching as high as the middle layer of troposphere, the Tibetan Plateau is the largest, highest and, most complex plateau in the world, with an average altitude of over 4000 m. To its east is the well-known East Asia Monsoon Region. During the summer monsoon season, it rains heavily in a belt crossing from east China to Japan. Worldwide meteorologists have studied extensively the formation mechanism, structure, and water budget of the strong convection system along the southern side of the Mei-Yu belt (Akiyama, 1973; Gao et al., 1981; Tao and Ding, 1981; Kuo et al., 1986; Ding, 1994; Ninomiya, 1999). (''Mei-Yu'' in Chinese and ''Baiu'' in Japanese refers to the frontal precipitation caused by Mei-Yu front, a persistent east-west zone of disturbed weather during early summer which is quasi-stationary and stretches from the east China coast, across Taiwan, and eastward into the Pacific Ocean south of Japan.) In terms of landforms, southwest China, located in the rugged terrain of the eastern Tibetan Plateau (25–35°N, 102–108°E) is complex, with both the high Yungui Plateau and the low Sichuan Basin in that region. In summer, the southwest monsoon flow from India, the southeast monsoon flow from the South China Sea, and northerly cold flow converge in southwest China, where complex changes are aroused in weather and catastrophic storms often take place. Heavy rain storms in this region studied by Kuo et al. (1986) indicate that the southerly monsoon flow near the Sichuan Basin, the Indian monsoon depression and the passage of a deep mid-latitude trough from the Lake Baikal region, which brought colder, drier air into southwest China, met over the eastern plateau and the Sichuan Basin. A region of large-scale, low-level convergence was created by the three flows. Even in autumn (in September and October), strong local convection arises from the interaction between the terrain and atmospheric circumfluence. However, compared with the summer season, little research has been done on local strong convective storms.

From the night of 18 September to 20 September 2001, Miyang, a city of Sichuan Province, witnessed several periods of particularly strong local convection and heavy rainfall (hereafter referred as 9.18 Storm). The center of the storm was located in a steep transitional area from the Sichuan Basin to the Plateau. The storm rainfall brought about flooding in areas such as Chengdu, Deyang, Mianyang, and Guangyuan, and it caused mudflows and landslides in many places (Chen et al., 2003, Min et al., 2003; Wang et al., 2003). This is the most recent heavy rainfall

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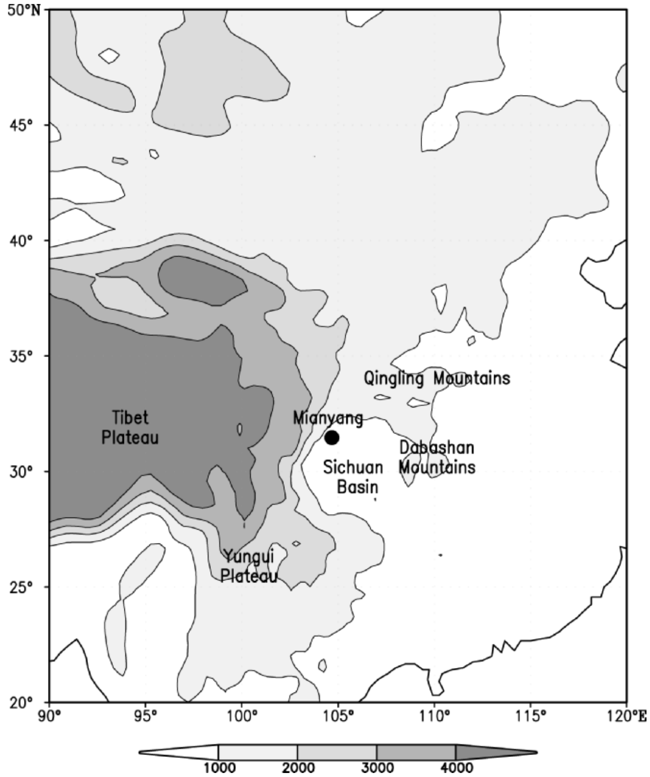


FIGURE 1. Topography of eastern Tibetan Plateau and the surrounding area (contours 1000 m). Station Mianyang (block dot) hourly precipitation, temperature, and pressure will be shown in Figure 3.

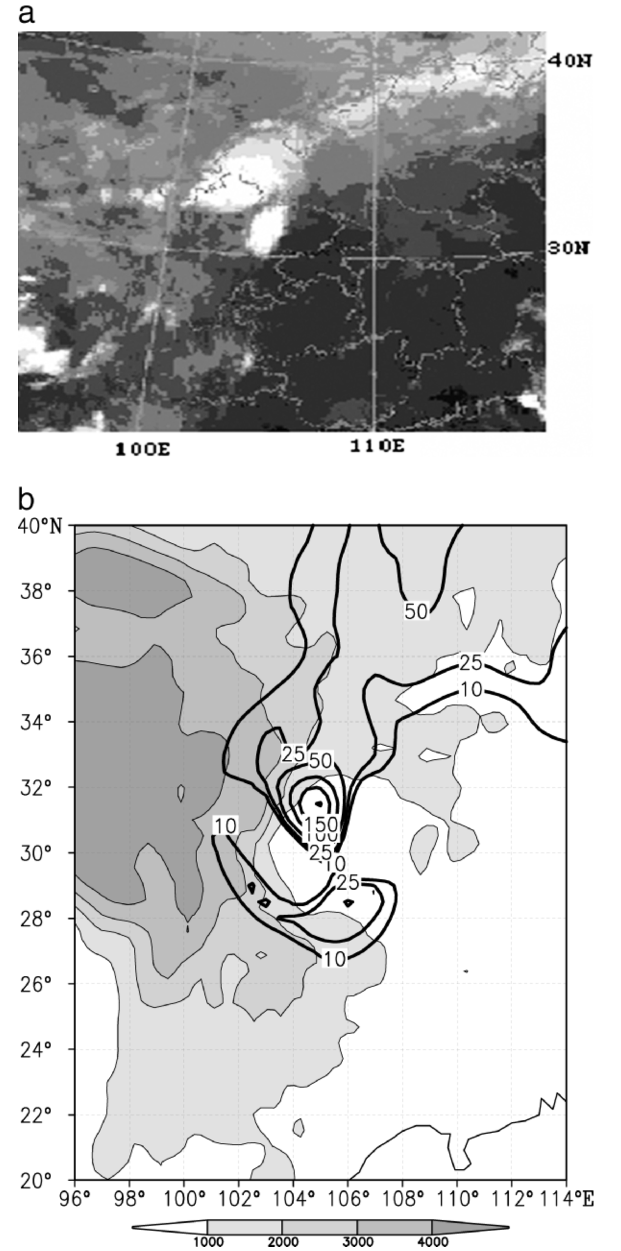


FIGURE 2. (a) GMS meteorological satellite visible range cloud image of the strong convective rainfall on 1600 UTC 18 September, (b) 24-h observed precipitation (contour, unit: mm) from 1200 UTC 18 September to 1200 UTC 19 September, shading shows the terrain height (1000 m contours).

in the weather records of the Sichuan Basin. Based on diagnostic analysis of the strong convection rainfall case, this paper studies the impact of the steep medium-scale terrain of eastern Tibetan Plateau on the emergence and development of strong convection, discusses the physical mechanisms of autumn heavy rainfall processes and seeks to help improve the prediction of such heavy rainfall.

Terrain Features of Eastern Tibetan Plateau

Figure 1 shows topography the eastern Tibetan Plateau. With its main body at over 4000 m, the Plateau is called "the roof of the world." Descending from the Plateau to an altitude of 1000 to 2000 m are the Qinling Mountains, Dabashan Mountains, and Yungui Plateau. The Qinling Mountains exert a significant influence on the regional climate in that it shields eastern China from the dry air from the northwest. The Yungui Plateau separates the subtropical southwest area and the eastern coastal area. Between the Yungui Plateau and the Qinling Mountains lie the lowlands of the Sichuan Basin. As shown in Figure 1, the terrain of the eastern edge of the Tibetan Plateau is very complicated, with the steepest topography in western Sichuan Basin. Particularly, in northwest Sichuan Basin, the elevation rises from 500 m to over 3000 m over less than 100 km from west to east, forming a steep ascending terrain.

Data and Methodology

The data used are the real-time rain observations of 24-h accumulated rainfall measurements, by observers, from rain gauges and distributed once a day to a local meteorological observatory of China Central Meteorological Observatory, and 1-h interval observations, including measurements of 1-h accumulated rainfall by self-recording rain gauge, pressure by self-recording barometer, and temperature by self-registering thermometer at the station Mianyang from 1300 UTC 18 September to 1300 UTC 19 September. Mesoscale grid data were produced by blending the global analysis data from National Meteorological Center (T106L19) of China with eastern Asia surface and rawinsonde data from 17–21 September 2001. The objective analysis approach was Cressman's gradual correction method of banana weighted coefficient analysis provided by a nonhydrostatic version of the Pennsylvania State University–National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model version 5 (MM5) (Grell et al., 1994). The MM5 modeling system was used

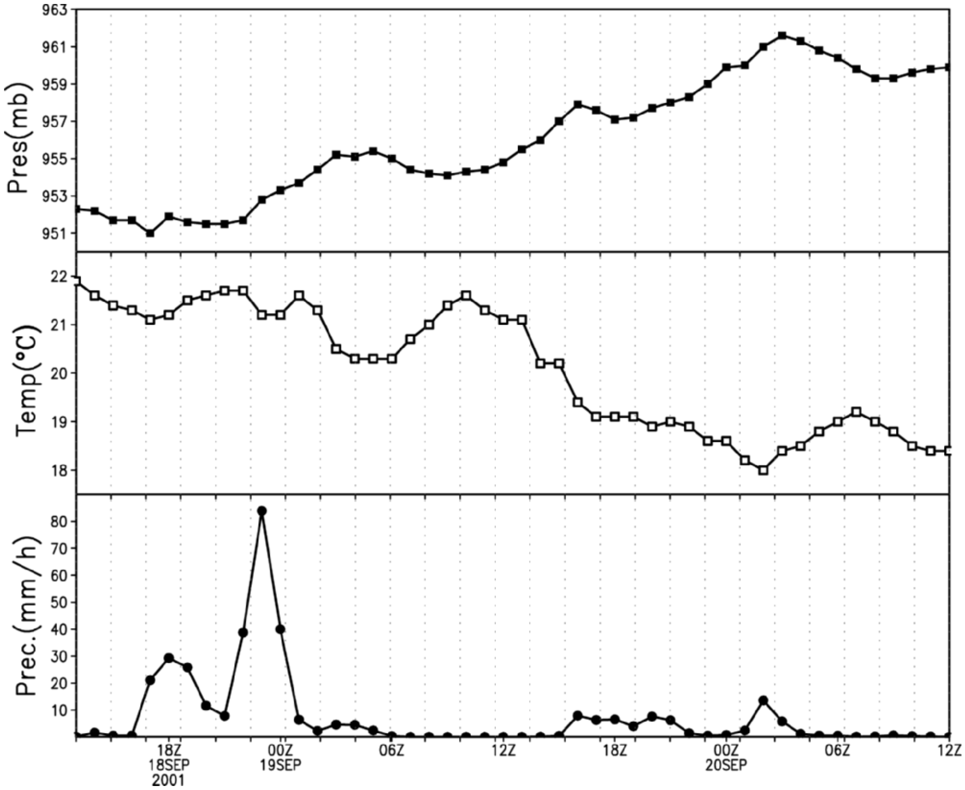


FIGURE 3. Hourly precipitation, temperature, and pressure in Mianyang from 1300 UTC 18 September to 1300 UTC 19 September.

only for data assimilation and diagnostic analysis purposes. The horizontal grid spacing is 54 km and 18 km, respectively.

The Time and Spatial Distribution Feature of 9.18 Strong Convection Rainfall

Figure 2 is a GMS meteorological satellite visible range cloud image of the strong convection process at 1600 UTC 18 September 2001 and the 24-h observed precipitation from 1200 UTC 18 September to 1200 UTC 19 September 2001. It illustrates a northeast to southwest wind zone from northeast China to Tibetan Plateau, which developed some convective cloud cluster in east Tibetan Plateau and some northeast to southwest strong convective cloud clusters in west Sichuan Basin. Similar to the topographic contours, the heavy rainfall band runs northeast to southwest. Its center is located in Mianyang (31.47°N, 104.68°E), Sichuan Province on the steep rising area. In Mianyang and Deyang (31.15°N, 104.38°E), the volume of rainfall amounted to 281.5 and 283.1 mm, respectively.

Figure 3 shows hourly precipitation, temperature, and pressure in Mianyang during 1300 UTC 18 September to 1300 UTC 19 September. It is night in the Sichuan Basin from 1300 UTC to 2300 UTC; under normal diurnal warming and cooling, the temperature should drop slowly overnight. But in this case, the hourly temperature reveals that this diurnal pattern is disrupted during the strong precipitation phase and precipitation has a big impact on temperature and pressure. Heavy rainfall consisted of two pulses at night. The first heavy rainfall pulse was from 1700 to 1900 UTC, 18 September, with an amount at 1900 UTC reaching 30 mm. The second heavy rainfall pulse was from 2200 to 2400 UTC, 18 September an amount at 2300 UTC exceeding 80 mm. Typically, thunderstorms are associated with cool downdrafts owing to evaporation of raindrops in unsaturated downdrafts. So it is common for surface temperatures to decrease in areas affected by the downdraft and outflow. The lowest temperature occurred during the second, stronger pulse of rain on the night of 18 September.

An Overview of Large-Scale Circulation and Mesoscale System

LARGE-SCALE CIRCULATION

Figure 4 shows the synoptic situation at 500-hPa and 850-hPa levels in Asia on 1200 UTC 18 September from the MM5 analyses using the 54-km grid.

During a heavy rain phase, the westerly belt in Asia at 500 hPa level is characterized by a high ridge over the Mongolian Plateau and two deep troughs at Lake Balkhash and Yakutsk to Okhotsk Sea (latter not shown) with features almost fixed in location and amplitude. On the north end of the trough are two low. When some cold air splits from the trough at Lake Balkhash and moves south, it forms a trough in the eastern Plateau and reaches the northern Sichuan Basin. The characteristics of subtropical circulation are that, in the middle and low latitudes of Asia, there is a deep and active trough in the Bay of Bengal, which helps transfer warm and humid air by the southwest monsoon to the eastern Tibetan Plateau. The eastern Tibetan Plateau and western China are controlled by the warm and humid southwest flow from the Bay of Bengal trough. Cold air from Lake Balkhash was blocked by the topography of the Tibetan Plateau, forming a strong temperature front at 40–50°N. Meanwhile, the Qinling Mountains also have an important effect on the formation of temperature front. On the one hand, the mountains block the transmission of warm and humid southwest flow, resulting in warm air accumulating in the Sichuan Basin; on the other hand, the Qinling Mountains also prevent the northern cold air from moving south. Convergence of the cold and warm flows in the Sichuan Basin and the upper area of the Huang He (Yellow River) forms a quasi-stationary front (Fig. 4b). On the 18

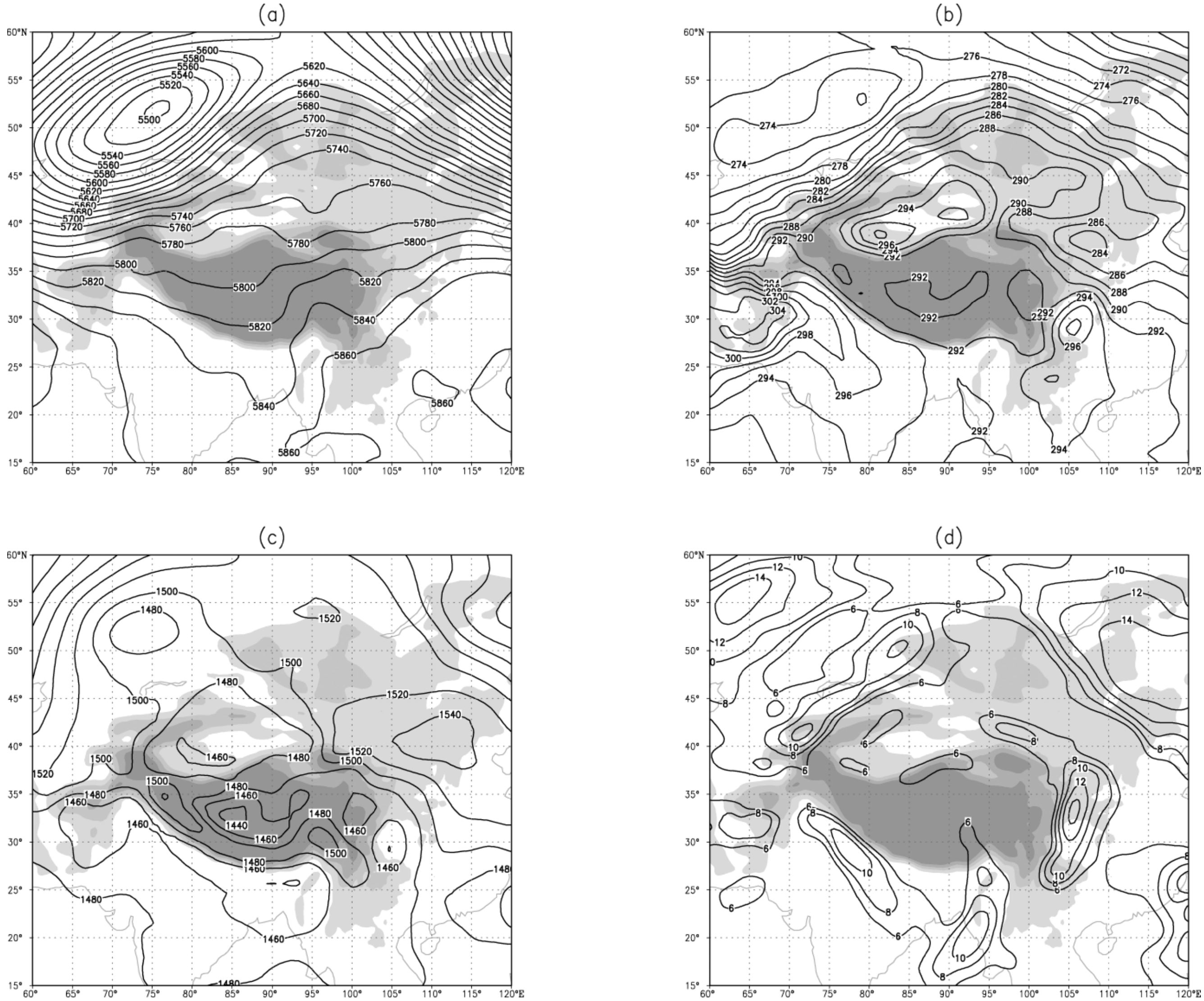


FIGURE 4. The synoptic situation in Asian Area on 1200 UTC 18 September 2001. (a) The height at 500 hPa level (geopotential meter), (b) temperature at 850-hPa level (K), (c), height at 850-hPa level (geopotential meter), (d) wind speed at 850-hPa level (m s^{-1}). Shading delineates the Tibet Plateau over 1000 m.

September and 19 September the low trough moved east onto the Plateau region, arriving at 100–105°E on 18 September while the 16th Typhoon (Nari) (named Baihe in China) was moving from Taiwan island to South China. The west-moving typhoon caused the transformation of the west Pacific subtropical high and westward displacement of the ridge point. The shortwave trough that moved east from the Plateau slowed down and stagnated in the Sichuan Basin. Heavy rain came into being under such a situation.

LOWER ATMOSPHERE JET FLOW AND MESO-α-SCALE LOW PRESSURE

Figure 4d shows that at 1200 UTC 18 September, two jet flows at low levels of troposphere were established. One was the jet flow of the east wind to the north of the 16th Typhoon (Nari) with the center located at (26°N, 121°E), and the other was the jet flow of south by southeast wind to the east of the Plateau (not shown). There were two high wind-speed areas in the southeast jet flow, one in Shanxi and the other in the Sichuan Basin. The lower atmospheric jet flow in the Sichuan Basin was located near (30°N, 106°E) with the highest wind speed at 14 m s^{-1} and the heavy rain area located just in convergence-rising area, the left front of the axis of the highest wind speed.

Another system that is directly related to the heavy rain is the meso-α-scale low-pressure system that remains steady near the lower layer of the troposphere at (29°N, 105°E) (not shown). At the 850-hPa level, there was a closed low-pressure center in Sichuan Basin at 1200 UTC 18 September. Its central value was lower than 1440 geopotential meters. During the heavy rain the meso-α-scale low pressure was stable and even strengthened, maintaining a convergence-rising current at the boundary layer of Sichuan Basin and promoting the development of convection.

The Impact of Plateau Terrain on Water Vapor Supply in Heavy Rain Area

Adequate water vapor supply is a precondition for the formation of particularly heavy rain. Here we will discuss the

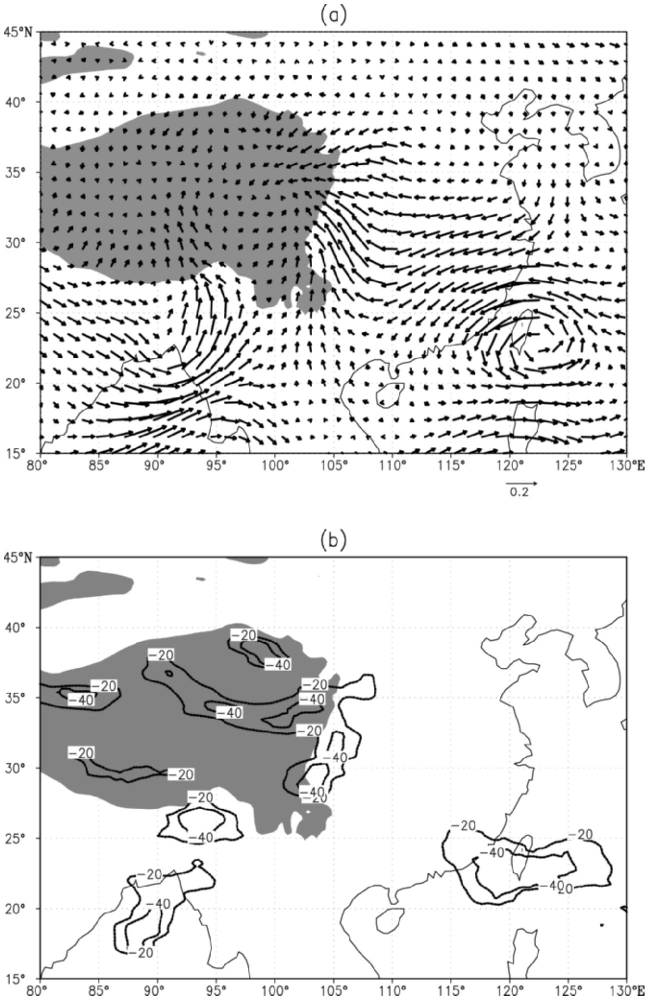


FIGURE 5. (a) The moisture flux ($g\ s^{-1}\ hPa^{-1}\ cm^{-1}$) and (b) moisture flux divergence contours ($10^{-8}\ g\ s^{-1}\ hPa^{-1}\ cm^{-1}$) at 850 hPa at 1200 UTC 18 September 2001. Shading shows the Tibetan Plateau above 4000 m.

water vapor conveyance in this heavy rain scenario. The moisture flux and moisture flux divergence at 850-hPa level at 1200 UTC 18 September clearly shows two moisture transfer belts (Fig. 5). One is the warm and humid southwest current from the Bay of Bengal, which divided into two branches when it was conveyed to the southeast Tibetan Plateau and blocked by the Yungui Plateau. One of the branches went northward along the southeast Yungui Plateau and reached the Sichuan Basin in the east of the Plateau. The other moisture source originated from the east by winds off the East China Sea, which turned northward to northeast Sichuan and the upper branch of the Huang He (Yellow River), blocked by the Plateau from going to the west. It converged with the warm and humid current from the Bay of Bengal and formed an obvious water vapor convergence area in the northeast side of the Tibetan Plateau and the upper branch of the Huang He (Yellow River). The mean value of the moisture flux divergence amounted to $-40 \times 10^{-8}\ g\ s^{-1}\ hPa^{-1}\ cm^{-1}$. Heavy rain occurred in the convergence area of the two moisture transfer belts. Therefore, the Tibetan Plateau played an important role as a blocking dynamic force in the formation of the moisture transfer belt and water vapor convergence center during this heavy rain scenario. It helped the formation of a strong moisture convergence on the southeast side of the Plateau, which was very favorable for the occurrence of heavy local rainfall.

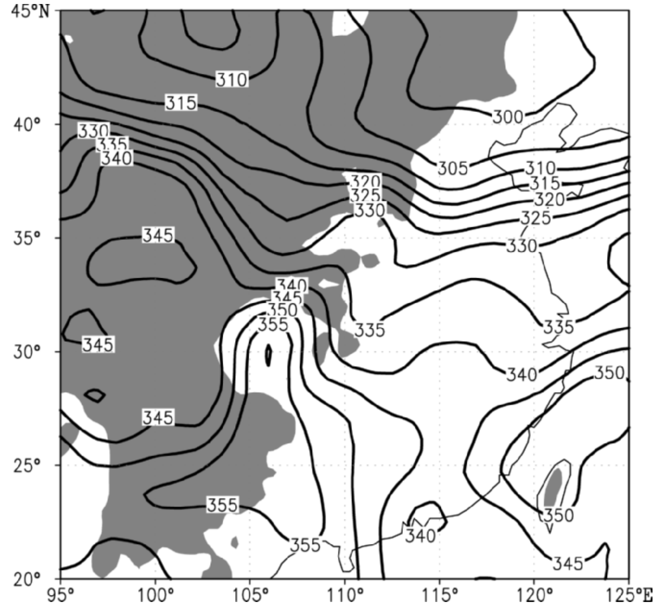


FIGURE 6. The pseudo-equivalent temperature (in K) at 850-hPa level at 1200 UTC 18 September 2001. Shading shows topography above 1000 m.

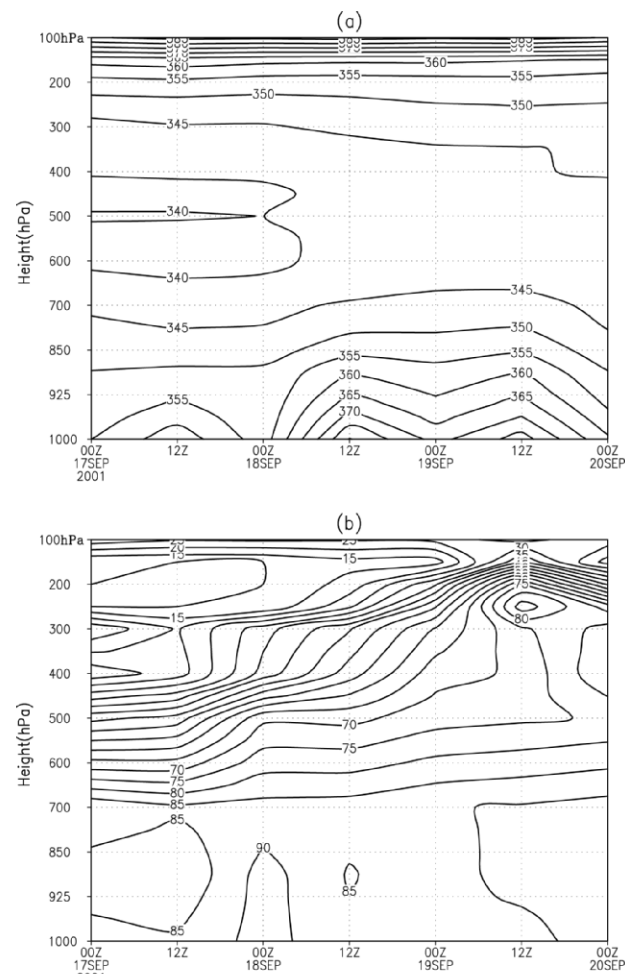


FIGURE 7. The evolution of θ_{se} (contour interval 5 K) (a) and relative humidity (contour interval 5%) (b) of the heavy rain at center Mianyang (31.5°N, 104.5E°) from 17 to 20 September 2001 in terms of height and time.

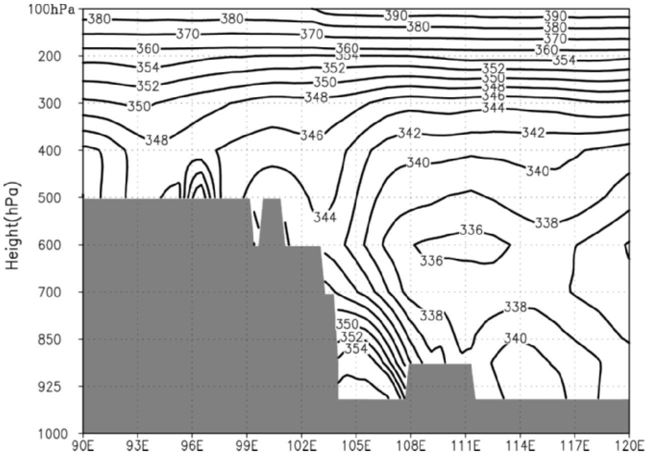


FIGURE 8. Zonal-height (in hPa) section of pseudo-equivalent temperature (in K) across the heavy rain center at 31°N at 1200 UTC 18 September 2001. Shading represents topography.

The Impact of the Plateau Terrain on the Energy

THE IMPACT OF THE TERRAIN ON THE ENERGY

Pseudo-equivalent temperature (θ_{se}) (Bolton, 1980) is a good reference value to evaluate the variations of atmospheric energy. Pseudo-equivalent temperature at 850-hPa level at 1200 UTC 18 September (Fig. 6) shows that high θ_{se} values are centered on the Sichuan Basin. The highest values over Sichuan exceed 360K while θ_{se} is relatively low in east and north China. In such a case, an Ω-shaped high energy tongue and strong energy front area emerged between 102 and 108°E. Its emergence is closely related to the mesoscale terrain of the Tibetan Plateau. On the one hand, Qinling Mountains and Dabashan Mountains obstructed the water vapor carried by the warm and humid southwest and southeast current from being conveyed to the north; on the other hand, it resisted the dry and cold air from the north from invading the Sichuan Basin. At 1200 UTC 18 September, as the south by southwest wind strengthened, warm and humid air from the Bay of Bengal quickly advected to the Sichuan Basin. At the same time the cold air from the north also quickened its movement to the south, forming an obvious gradient in θ_{se} and different stratified air on the two sides of Qinling Mountain and also a high energy tongue and strong energy front area.

IMPACT OF TERRAIN ON POTENTIAL UNSTABLE STRATIFICATION

The analyses on the energy evolution were based upon data assimilation/OA at 12-h intervals valid at 0000 and 1200 UTC, with linear interpolation between those two times. What follows is

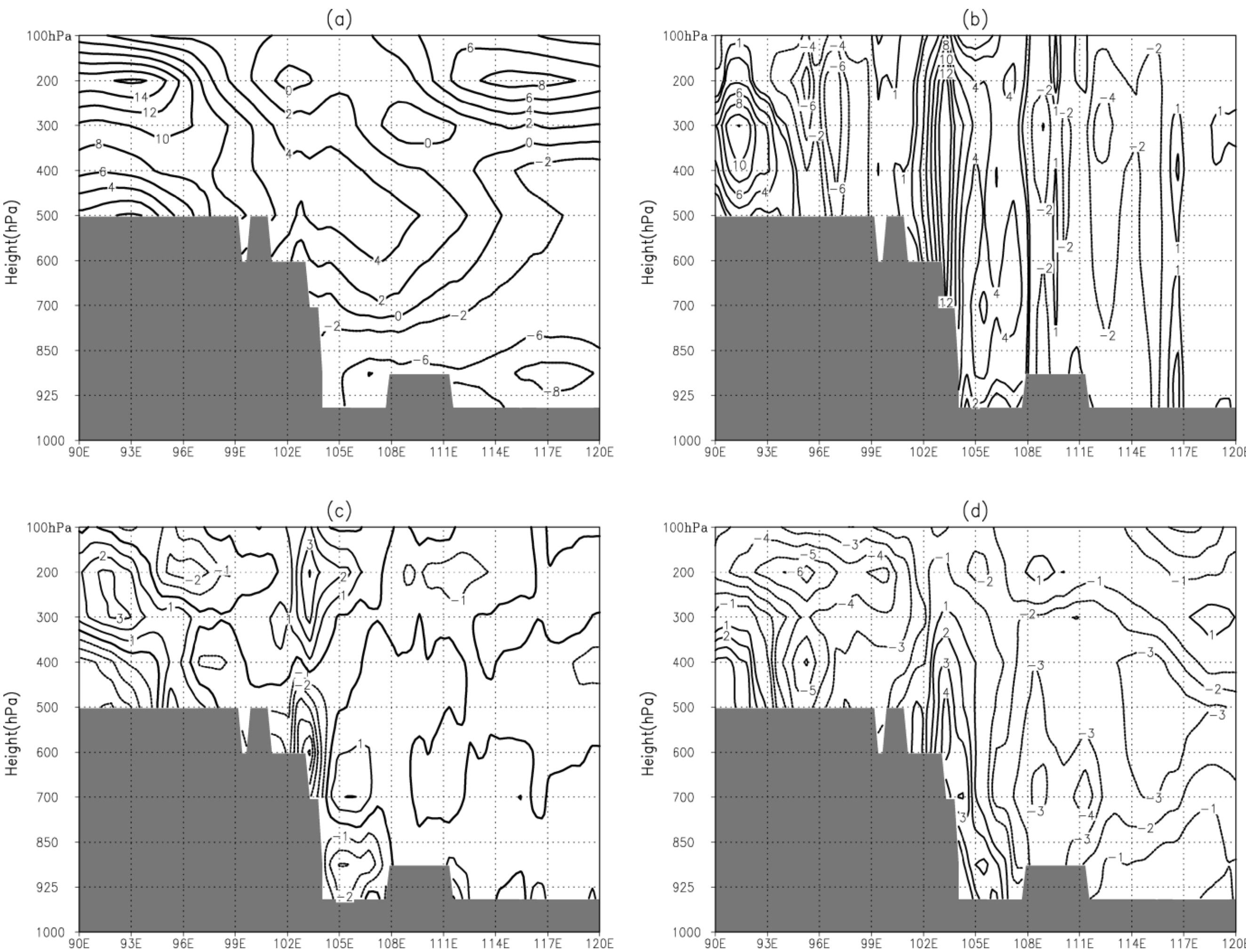


FIGURE 9. The zonal section of the physical field along 31°N at 1200 UTC 18 September 2001, (a) u component wind (m s^{-1}), (b) vertical speed (m s^{-1}), (c) divergence (s^{-1}), (d) vorticity (s^{-1}). Shading represents topography.

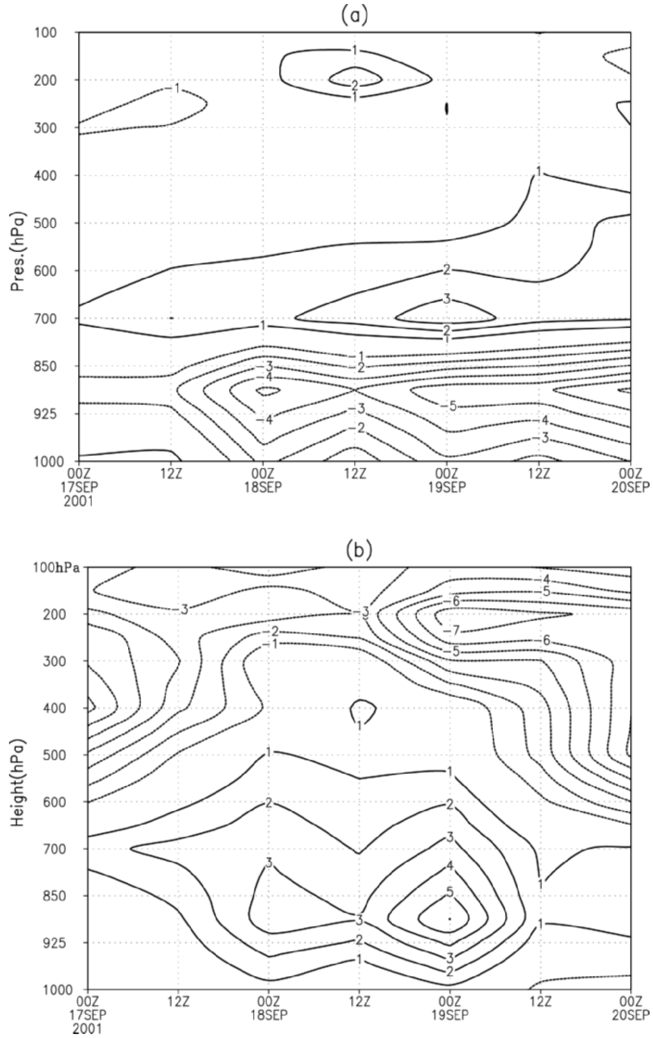


FIGURE 10. The temporal evolution of height cross section at (31.5°N, 104.5°E) from 17 to 20 September. (a) divergence (10^{-5} s^{-1}), (b) vorticity (s^{-1}).

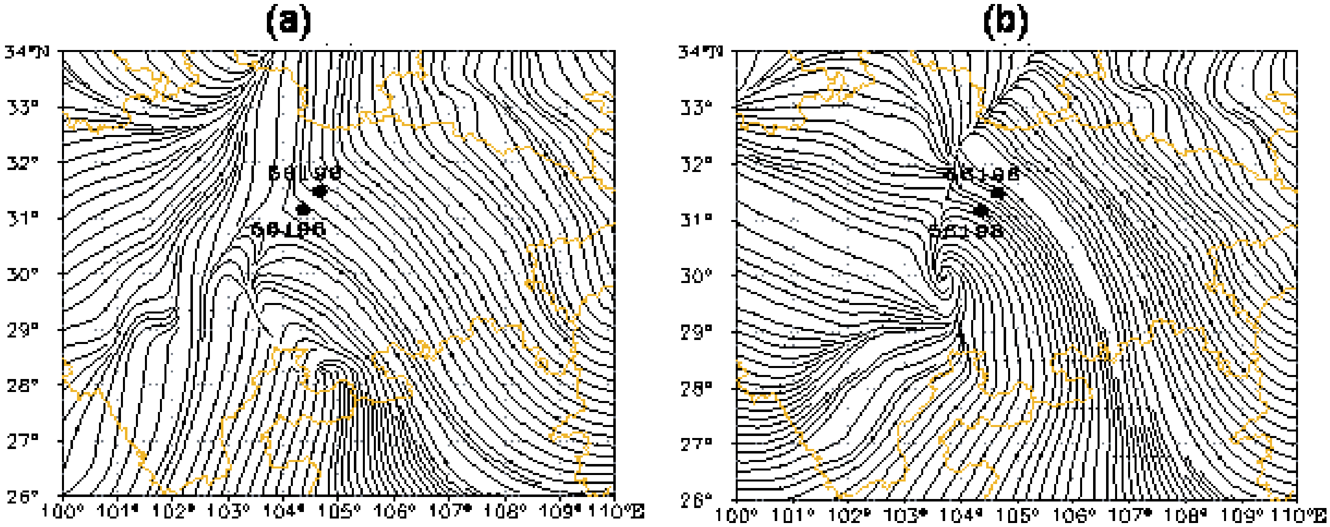
a description of temporal evolution of potential pseudo-equivalent temperature, θ_{se}, and relative humidity at Mianyang from 17 to 20 September with a 12-h resolution (Fig. 7). The θ_{se} of the lower level troposphere fluctuated greatly before and after the heavy rain. On 0000 UTC 17 September and 1200 UTC 17 September, middle layers were 340 to 345 K similar to stable stratification, and lower layers were 345 to 360 K similar to weak unstable stratification. At 2000 UTC 18 September, the θ_{se} at the lower and middle troposphere increased considerably, with a maximum value of over 350 K located near the ground. Potential energy unstable stratification ($\theta_{se}/p > 0$) was established below 600-hPa level and quasi-neutral stratification between 600 and 400 hPa; the relative humidity is over 80%, indicating ample water vapor. The thermal structure with unstable stratification and high humidity lasted until 0800 UTC 18 September. It is also found that from 19 to 20 September, the relative humidity of middle and upper troposphere was over 70% due to the development of convection, forming a thick humid layer (Fig. 7b). Due to the effects of convection activities, release of the latent heat of condensation as well as convective scale mixing, the unstable potential energy stratification of the lower layer began to be weakened with value of θ_{se} dropped from 365 K to 355 K from 0000 UTC 19 September to 0000 UTC 20 September and that of the middle layer ($\theta_{se}/p < 0$) became stable on 20 September.

The establishment of the unstable potential energy stratification is a result of moisture transfer in the lower troposphere. As there is no sounding data for Mianyang, we analyzed the evolution of temperature and dew point temperature at 850-hPa level in course of time at the nearest rawinsonde station Chengdu (30.7°N, 104°E) (not shown). The temperature fluctuation was small in Chengdu from 0000 UTC 17 September to 1200 UTC 18 September rising from 17.5 to 18.5°C while the dew-point temperature increased significantly from 13.8 to 17.2°C and the dew-point depression nearly fell to 1.3 from 3.7°C. Before the heavy rain the lower air was almost saturated. At the same time, the middle and upper troposphere was relatively dry, with the relative humidity at less than 30% above 400 hPa at 000 UTC 17 September. Between the lower and upper layer an obvious gradient developed. Therefore, because of the impact of the Plateau terrain, lower humid air continued to pile up, building energy conditions in heavy rain area favorable for the mesoscale convection activities and the emergence of heavy rain and establishing unstable potential energy stratification in lower troposphere.

It is found in the study of the thermal structure of the convective heavy rain of the Mei-Yu front in East Asian monsoon area that the heavy rain occurs in the region of saturated air with high temperature and high humidity in the whole air column, and where potential energy stratification becomes strong and unstable near ground and remains nearly neutral above 850 hPa (Chen and Feng, 2001). This heavy rain scenario, however, shows that due to the influence of the abruptly rising terrain of the eastern edge of the Tibetan Plateau, the thermal structure of the environment associated with the convective system is different from the heavy rain of the Mei-Yu front. Figure 8 is the horizontal section of the potential pseudo-equivalent temperature across the heavy rain center at 31N at 1200 UTC 18 September. The figure shows that the high-temperature and high-humidity region only appeared in lower troposphere, with the unstable potential energy stratification ($\theta_{se}/z < 0$) below 600-hPa level and the stable potential energy stratification above 600 hPa ($\theta_{se}/z > 0$). This is different from the heavy rain of the Mei-Yu front in that the whole air column of the latter has a high-temperature and high-humidity thermal structure.

The Impact of the Terrain on the Dynamic Field

The dynamic structure of the heavy rain of Mei-Yu front is characterized by co-location of strong ascendant motion updraft and high-temperature and high-humidity saturated air column as well as the co-location between the strong divergence and strong vorticity columns from the ground to about 200 mb (Chen and Feng, 2001). The dynamic structure of the heavy rain of Mei-Yu heavy rain contrasts with that of heavy rains caused by the terrain. Under the dynamic effect of the terrain, the east current in the lower troposphere was blocked at 104°E by the Tibetan Plateau (Fig. 9a). Because of the west flow over the Tibetan Plateau, a shear line formed between the east and west wind at the transition from the Sichuan Basin to the Tibetan Plateau. The east draft was forced to lift and formed an extra strong ascendant motion column. Its maximum ascent speed was over 0.14 m s^{-1} near 400-hPa level (Fig. 9b). Figure 9c shows that due to the lift effect of the terrain a strong negative divergence area emerged in the boundary layer at 100 to 105°E. The strongest divergence area was located in the region of strong mesoscale ascent, with the center value at -6×10^{-5} s^{-1}. Furthermore, at the upper troposphere (200 hPa) an extra convective column formed with



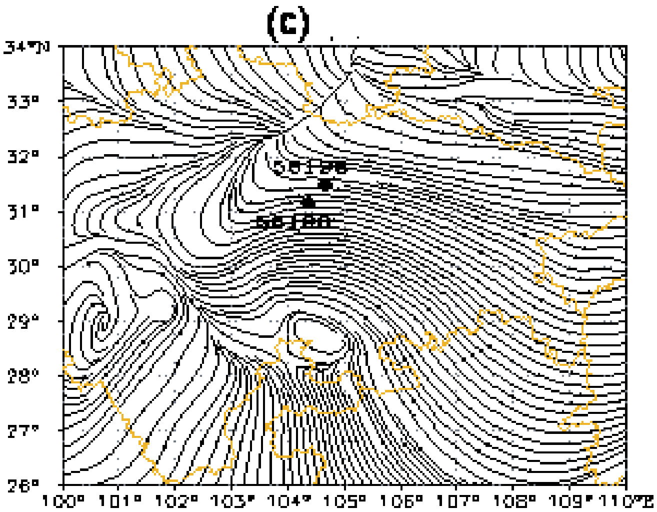


FIGURE 11. The stream field near boundary 925-hPa level from 1200 UTC 18 to 1200 UTC 19 September. (a) 1200 UTC 18 September, (b) 0000 UTC 19 September, (c) 1200 UTC 19 September. The black circles indicate the position of Mianyang (56196) and Deyang) 56198).

the center value higher than 4×10^{-5} s^{-1}, which together with the convergence area formed the extra strong divergence column. The Figure 9d shows that all the positive values of the vorticity center appeared in the lower and middle atmosphere in the abruptly rising terrain region, with all the maximum positive values of the vorticity center over 4×10^{-5} s^{-1}. The positive vorticity in upper atmosphere developed slowly, with the mean maximum positive values of vorticity at only 1×10^{-5} s^{-1}. Strong precipitation occurred only in the strong divergence column and updraft area, indicating that strong ascendant motion occurred in the convergence area of the vertical shear of east and west wind and the steep landform. The very strong divergence column and the strong vorticity column in the lower troposphere are the major dynamic features of this heavy rain scenario.

In order to have a better analysis of the mesoscale circulation feature of this heavy rain scenario, the global analysis data of National Meteorological Center (T106) was further studied by MM5 with an 18-km grid space. In the atmospheric boundary layer divergence values varied from positive on 0000 UTC 17 September to negative at 1200 UTC on 18 September (Fig. 10). A minimum value less than -5×10^{-5} s^{-1} shows that the lower flow pattern changed from divergence to convergence in the heavy rainfall region. When a short wave trough on the Tibetan Plateau moved eastward on 18 September, positive vorticity first developed at 700 hPa, with the strongest positive vorticity column at 0000 UTC 19 September, and maximum values of over 6×10^{-5} s^{-1} at 700 hPa. A strong divergence column and the strong vorticity column in the lower and middle-high layer of the atmosphere were co-located, revealing the major dynamic features.

A mesoscale vortex perturbation occurred and developed in the lower air current from 1200 UTC 18 September to 1200 UTC 19 September (Fig. 11). At 1200 UTC 18 September, there was a southeast current in eastern Sichuan and a southwest current in western Sichuan. The two currents converged on the steep south slope of the Sichuan Basin and formed a convergence line (Fig. 11a). At 000 UTC 19 September, a northwest current appeared in northwest Sichuan, converging with the southeast current to form a current convergence line, where a mesoscale vortex emerged (Fig. 11b). By 1200 UTC 19 September the vortex had continued to develop and move eastward to the southern Sichuan Basin (Fig. 11c) and at 000 UTC 20 September it disappeared (not shown). As shown above, during the process of formation and development of the lower mesoscale vortex, strong precipitation occurred in the northwest part of Sichuan Basin, with the center located at the southeast side of the convergence line, indicating that the strong precipitation was accompanied with the development of lower mesoscale vortex.

Conclusions

With the mesoscale data provided in the high-resolution numerical model, this paper analyzed the impact of the complex mesoscale terrain at the eastern edge of the Tibetan Plateau on the formation and development of strong convective storms in Sichuan Basin and reached the following conclusions:

(1) The dynamic blocking effect of the Tibetan Plateau terrain affects the moisture transfer channel in this heavy rain scenario and brings about the formation of a strong water vapor convergence center in the northwest Sichuan and the upper branch of Huang He (Yellow River).

(2) The terrain structure of the east side of Tibetan Plateau makes a high energy tongue and energy front in the lower troposphere in the Sichuan Basin and helps establish unstable potential energy stratification in the lower troposphere of the Sichuan Basin. The accumulation of water vapor in the lower troposphere in the Sichuan Basin is the major reason for the establishment of unstable potential energy stratification.

(3) The steep terrain of the eastern edge of the Tibetan Plateau strengthens the updraft movement in the convergence flow field and the current incurred by the vertical wind shear. The strongest updraft movement occurred in the convergence area of the vertical shear of east and west wind and the steep landform, stimulating the release of the unsteady energy and rapid development of the strong convection. The process is also accompanied by a mesoscale vortex on the eastern edge of the Plateau.

(4) In terms of the thermal and dynamic structure of the circulation, the heavy rain area at the east side of Tibetan Plateau is different from that of Mei-Yu front in the East Asian monsoon area. For the former, the most significant thermal feature is that the high-temperature and high-humidity area appears only in the lower troposphere and the most significant dynamic feature is that its strong vorticity column also only appears in the lower troposphere.

Acknowledgments

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