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Atmospheric Boundary Layer Circulation on the Eastern Edge of the Tibetan Plateau, China, in Summer

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Abstract

By using radiosonde data in Sichuan Province and Chongqing Municipality of China during May–September from 1982 to 2002, the meteorological significance and evolution patterns of the atmospheric boundary layer (ABL) wind on the eastern edge of the Tibetan Plateau are analyzed. Results show that the ABL wind at Chengdu near the eastern edge of the Tibetan Plateau varies with regularity. Because of the interaction between the circulation and the topography, the wind field alternates between northeast and southwest winds. When northeast ABL winds prevail at Chengdu, the ABL in the Sichuan Basin maintains a cyclonic flow field and corresponds with heavy rain in the Sichuan Basin. When southwest winds prevail, the ABL maintains an anticyclonic flow field and corresponds with rainless, fine weather in Sichuan Basin. With the northeast-southwest–trending topography between the Tibetan Plateau and the Sichuan Basin, the dynamic trigger of the ABL at Chengdu is a very important cause of occurrence and development of severe, convective weather and heavy rain in the Sichuan Basin. The Chengdu station is the key weather station in the Sichuan Basin for weather prediction and understanding physical mechanisms.

Introduction

The Tibetan Plateau is located in South Asia, covering more than one quarter of China; it has an average altitude above 4000 m. It is the highest plateau, with the most complex topography, in the world, and it influences the atmospheric circulation over China, Asia, and even the Northern Hemisphere, and hence affects the formation and evolution of the weather and climate in these areas (Flohn, 1968; Hahn and Manabe, 1975; Yeh and Gao, 1979; Zhang et al., 1988).

The Tibetan Plateau forms a physical barrier to atmospheric circulation, splitting air currents and forcing them to flow around it. This causes confluence and convergence zones, shear lines, and the southwest vortex, which directly influence the weather and the climate in large areas around the Plateau (Yeh, 1950; Yeh et al., 1957; Yeh and Gao, 1979). And the atmospheric boundary layer (ABL) over the Tibetan Plateau also has important effects on atmospheric variation. Yanai and Li (1994) first analyzed the mechanism of heating and the boundary layer over the Tibetan Plateau. Their studies showed that the ABL over the Tibetan Plateau has its own structure and variation, and the thermal and dynamical processes in the ABL have connections with the heating over the Tibetan Plateau. Following their study, many works about the ABL over the Tibetan Plateau have been done (Zhou et al., 2000).

The Sichuan Basin lies close to the eastern Tibetan Plateau, and it is surrounded by mountains. This unique topography is known as the Plateau Basin. Because of the influence of the steep topography, the western Sichuan Basin is a pluvial region in southwest China (Xu, 1991). Even though thermal and dynamic effects in the ABL have key influences on strong convective weather such as heavy rain in China (Tao et al., 1979; Zhao et al., 1982), the circulation of the ABL in Sichuan Basin and its influence is not well understood. Li (1995) analyzed the ABL wind field variation in the Sichuan Basin during May–September from 1982 to 1986 and discovered that the ABL wind moves alternately northeast and southwest at Chengdu, and is closely related to the short-term weather patterns in the region. To understand better the ABL circulation and its significance for weather on the eastern edge of the Tibetan Plateau, further study is needed with a longer time series of data.

The study used 21 yr of observational data and 10 d of intensive in situ observations to characterize the regional ABL circulation on the eastern edge of the Tibetan Plateau, and further determine its influence on weather.

Data and Explanation

The data used in this study are the daily observations from the Monthly Aerological Bulletin of China published by China National Meteorological Center for seven radiosonde stations in Sichuan Province and Chongqing Municipality, on the eastern edge of the Tibetan Plateau. The stations are Chengdu, Yibin, Dazhou, Xichang, Ganzi, Hongyuan, and Chongqing; all are in operational use in China. Among them, Chengdu is an international data exchange radiosonde station of the World Meteorological Organization (WMO), and the other six stations are the domestic data exchange radiosonde stations of China. The data are reliable and used in many studies (Liu et al., 1992).

In addition, the environment surrounding the stations accords with the demands of China's meteorological observing standards. For example, observations at Chengdu, international exchange station (station identification 56294), located in the western suburbs of Chengdu city, began in January 1951. It is located at 30°40′N and 104°01′E, 507.3 m a.s.l. Its surroundings are smooth and open, vegetated land around 1 to 2 km. The data of Chengdu, as with the other stations, is therefore a fair representation of the ABL for analysis and study (Liu et al., 1992).

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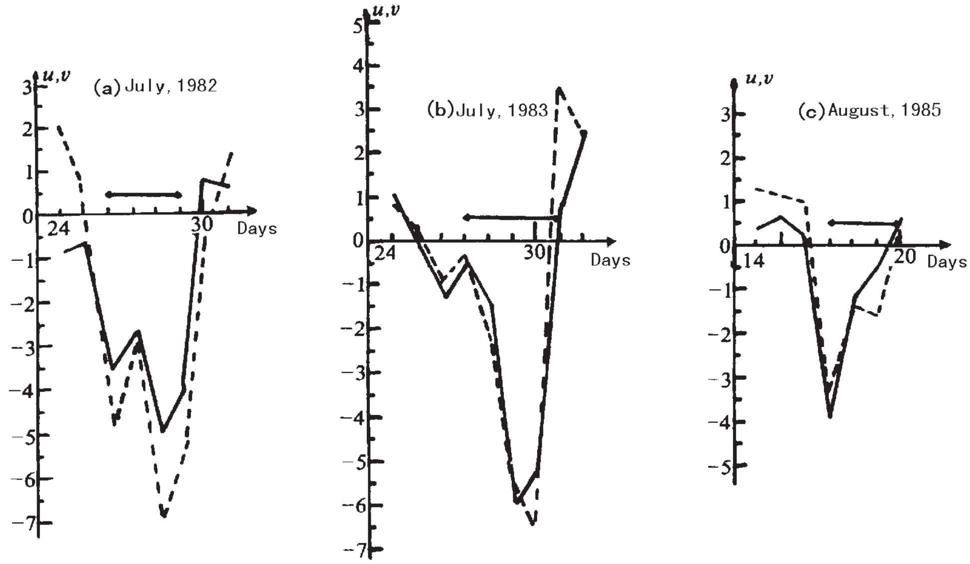

FIGURE 1. Variation of ABL mean wind speed (units: m s^{-1}) at Chengdu at 2300 UTC in relation to three instances of heavy rain in the Sichuan Basin. Solid and dashed lines are U and V components, respectively. Line segments above the horizontal axis denote timing of heavy rain.

We examined the horizontal and vertical distribution and variation of the ABL wind field by using daily data from the seven radiosonde stations. Data were collected daily at 2300 and 1100 UTC between May–September from 1982 to 2002. Wind vector analysis obtained the U and V components. We were specifically interested in the regional characteristics and the evolution of the ABL wind field and its relationship to weather in the Sichuan Basin.

Results

ABL WIND FIELD CHARACTERISTICS

As found by Li (1995), the ABL wind field varies with regional characteristics. ABL wind below 1.5 km at Chengdu, in the western Sichuan Basin, changes regularly during the summer. The U and V components are synchronized in phase, with the same sign and the same intensity. They alternate between northeast ($U < 0$, $V < 0$) and southwest ($U > 0$, $V > 0$) winds (not shown). Furthermore, there is close relationship between the ABL wind and the weather. When the ABL consists of a northeast wind at Chengdu, there is heavy rain in the Sichuan Basin, and when the ABL consists of a southwest wind, the weather in the Basin is dry. The ABL wind changes direction several hours to one day before heavy rain occurs in the Basin, which may be useful in predicting weather in the Basin (see also Li, 1995).

Figure 1 shows ABL wind speed during three instances of regional heavy rain storms in the Sichuan Basin. The average U and V components were 0, 300, 600, and 900 m at Chengdu at 2300 UTC (1100 UTC is similar to 2300 UTC). On 25 July 1982, 25 July 1983, and 16 August 1985, the U and V components become negative, the wind direction began to turn to northeast, and wind speed increased significantly. Anywhere from several hours to more than 40 h later, heavy rain occurred. During 26–29 July 1982, 27–31 July 1983, and 17–20 August 1985, the ABL U and V components at Chengdu were still less than 0, and the wind continued in a northeast direction, which corresponds with severe heavy rain processes in the Sichuan Basin. On 30 July 1982, 31 July 1983, and 20 August 1985, the U and V components became positive and the wind direction changed to the southwest. Afterwards, the heavy rain in the Sichuan Basin ended.

In April 1993, a project studying the atmospheric transfer rule of the boundary layer in the Sichuan Basin carried out a 10-d intensive observation at the same seven radiosonde stations on the eastern edge of the Tibetan Plateau. From 25 April to 4 May, meteorological data were collected from radiosonde stations at 0, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, and 1500 m above ground level. During the intensive observation period, a severe convective storm with heavy rain, hail, and gale-force winds (which are rare in Sichuan) occurred between 30 April and 1 May. Figure 2 shows that prior to the severe weather, from 2300 UTC on 26 April to 1100 UTC on 29 April 1993, the ABL U and V components at Chengdu were small and the wind was mainly from the southwest. But at 2300 UTC on 30 April, the U and V components became negative and the wind turned to the northeast. Five or six hours later, the heavy rain, hail, and gale-force winds occurred. The entire storm corresponded with the strengthening and maintenance of the northeast wind. When the ABL U and V components became positive again (a southwest wind) at 2300 UTC on 2 May, the storm in the Sichuan Basin ended.

In the summer of 1998, heavy sustained rains along the Yangtze River caused flooding and severe economic loss. During that time, the weather in Sichuan Province, located at the upper reaches of the Yangtze River, was extremely abnormal, with heavy rain occurring more frequently than usual, and starting earlier and ending later than usual. These regional and heavy rains directly influenced the flooding along the Yangtze River. Figure 3 shows the variation of ABL mean winds at Chengdu in 1998. During the summer of 1998, the ABL wind field at Chengdu varied with obvious regularity, alternating between a northeast wind ($U < 0$, $V < 0$) and a southwest wind ($U > 0$, $V > 0$). The northeast wind was much stronger than the southwest wind. During the 92 d of summer, when the ABL at Chengdu consisted of a northeast wind, there was severe rainfall in the Sichuan Basin. When the ABL consisted of a southwest wind, there was dry weather in the Basin. The formation, intensification, and disappearance of the ABL northeast wind at Chengdu indicate the occurrence, development, and the end of the severe convective weather in the Sichuan Basin.

A composite analysis (Fig. 4) shows that during the 92 d of summer in 1998, the composite wind field below 5000 m of the 33 rain days (27–28 June; 9–14, and 19–20 July; 1–4, 9–15, and 18–27 August) had the opposite vertical structure to that of the 20 rainless days (1, 4, 8–9, 16, 19–20, and 25–26 June; 2, 17–18, and 28–29 July; and 9, 16–17, and 29–31 August). The composite wind field of rain days at 2300 UTC exhibits obvious vertical shear, with

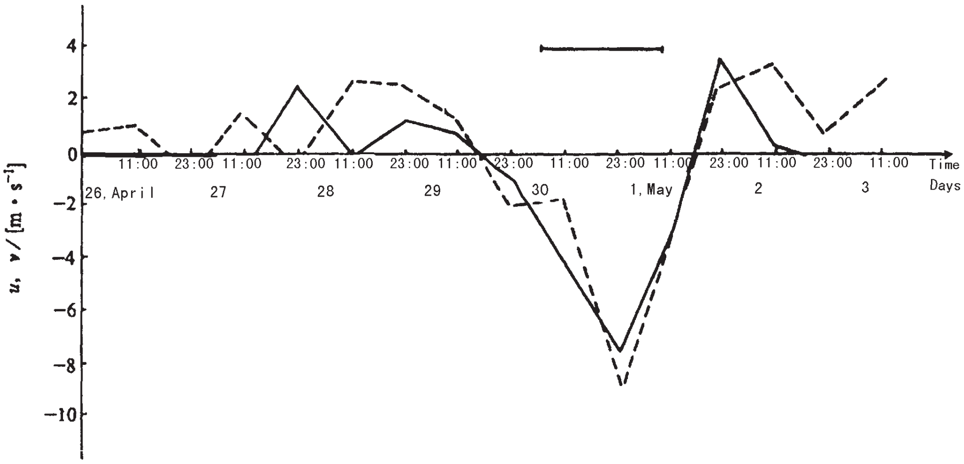

FIGURE 2. Variation of ABL mean wind speed (units: m s^{-1}) at Chengdu from 26 April to 3 May 1993. Solid and dashed lines are U and V components, respectively; the line segment above the horizontal axis denotes the timing of heavy rain, gale, and hail.

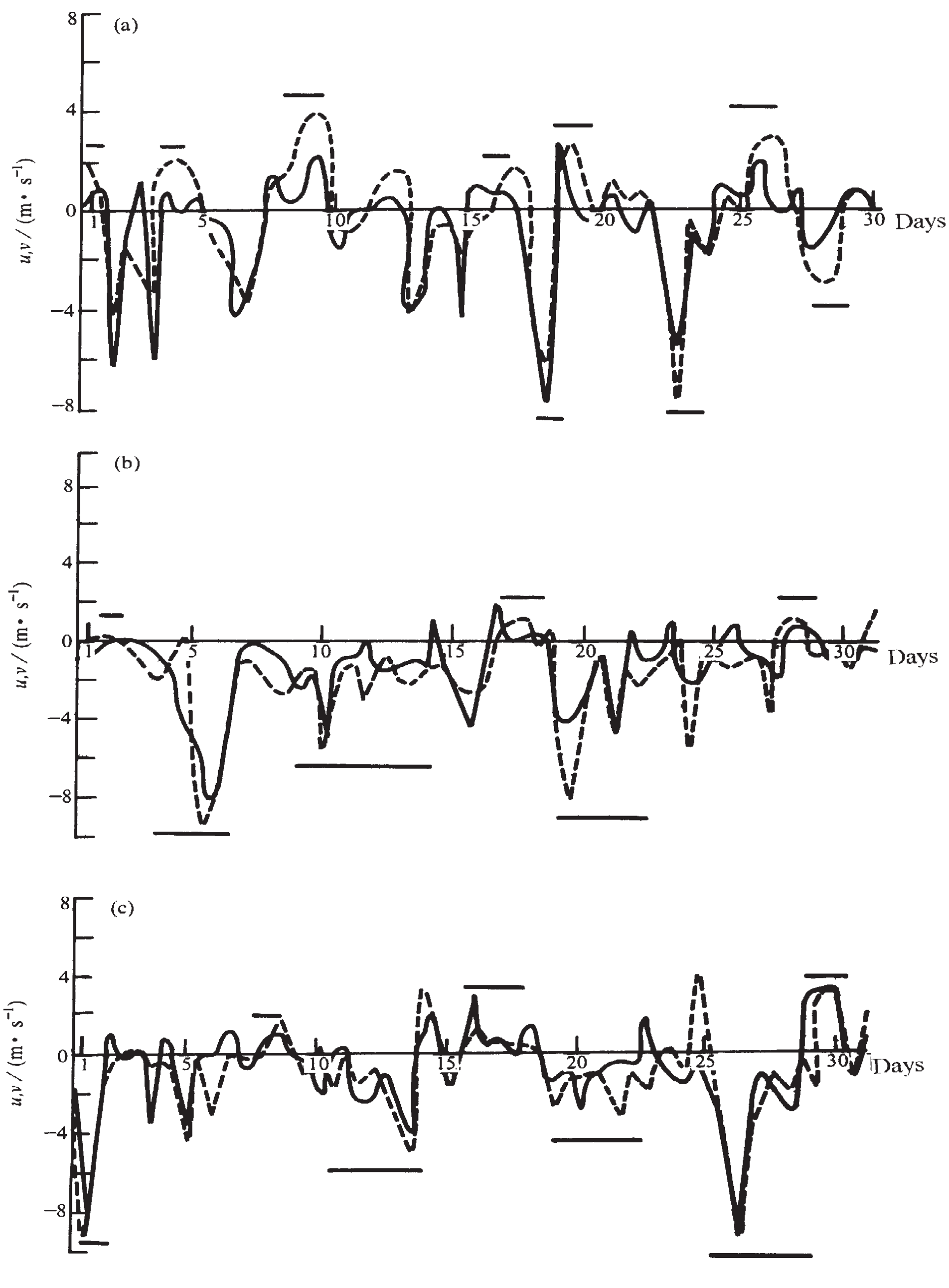

FIGURE 3. Daily variation of ABL mean wind field (units: m s^{-1}) at Chengdu in the summer, (a) June, (b) July, and (c) August, of 1998. Solid and dashed lines are U and V components, respectively; line segments above and below the horizontal axis indicate the main rainless days and heavy rain days, respectively.

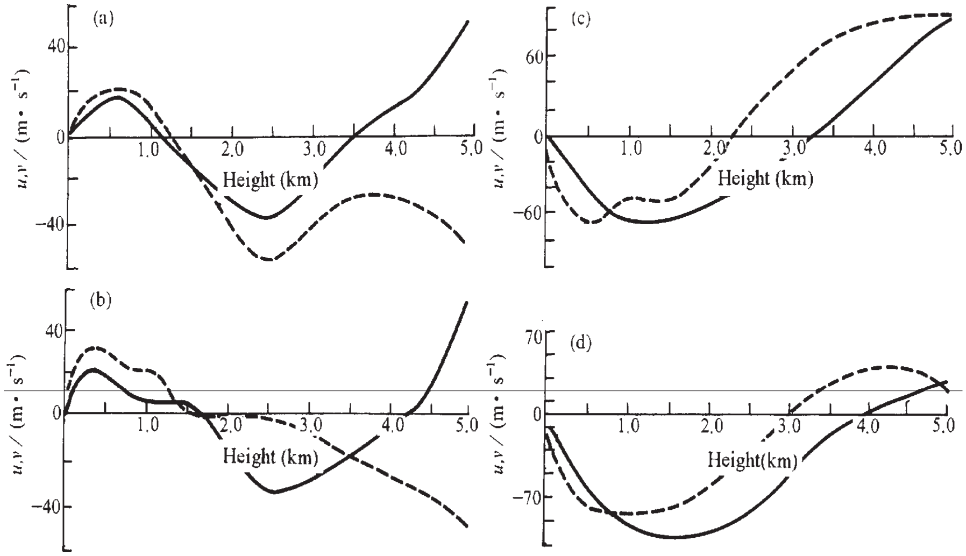

FIGURE 4. Vertical distribution of the composite wind field for 20 rainless days at (a) 2300 and (b) 1100 UTC, and for 33 rain days at (c) 2300 and (d) 1100 UTC at Chengdu. Solid and dashed lines are U and V components, respectively.

northeast wind below 3000 m and southwest wind above it (the ABL is the northeast wind).The wind field at 1100 UTC on rain days is similar to that at 2300 UTC. However, the composite wind field of rainless days at 2300 UTC also exhibits obvious vertical shear, with the southwest wind below 2000 m and the northeast wind above it (the ABL is the southwest wind). Therefore, during rainy (rainless) days in the Sichuan Basin, the wind field exhibits a vertical shear between a northeast (southwest) wind and a southwest (northeast) wind below 5000 m, and the northeast (southwest) wind prevails in the ABL at Chengdu.

We emphasize that during May–September of other years, the ABL wind field at Chengdu also shows the above characteristics, and a close relationship with weather variations. The ABL wind field at Yibin, Dazhou, Xichang, Ganzi, Hongyuan, and Chongqing stations have not shown the regular changes that are seen at the Chengdu station.

ABL FLOW FIELD CHARACTERISTICS

The regular change between the northeast and southwest winds in the ABL of Chengdu, and their association with severe weather, indicate that the wind directions in the ABL at Chengdu represent spatial-temporal changes of regional circulation in the Sichuan Basin. When the southwest wind is prevails at Chengdu, the ABL in the Sichuan Basin is controlled by an anticyclonic flow field, and when the northeast wind prevails, the ABL is controlled by a cyclonic flow field. Under the favored cyclonic flow field, there are obvious positive vorticities, a powerful convergence, and a strong ascending motion in the ABL of the Sichuan Basin. This dynamic configuration causes the formation of low-pressure weather systems, strengthens the heat and vapor transport of the ABL to the free atmosphere, and maintains severe convective weather such as heavy rain (Li, 1996). Furthermore, the formation, maintenance, and disappearance of the ABL cyclonic flow field in the Sichuan Basin are closely related to the appearance, persistence, and end of the ABL northeast wind at Chengdu.

During the severe storm in the Sichuan Basin between 30 April and 1 May 1993, the ABL flow field in the Sichuan Basin correlated with the variation of the ABL wind field at Chengdu. At 2300 UTC on 30 April, the ABL in the Sichuan Basin was controlled by cyclonic flow field, corresponding with the northeast ABL wind at Chengdu. About five or six hours later, a storm occurred in the Sichuan Basin with heavy rain, hail, and gale-force winds. During this storm (from 2300 UTC on 30 April to 1100 UTC on 1 May), the ABL northeast wind at Chengdu and the cyclonic flow field in the Sichuan Basin strengthened. At 2300 UTC on 2 May, the ABL wind at Chengdu turned to the southwest, the ABL in the Sichuan Basin became an anticyclonic flow field, and the storm ended. In the summer of 1998, the ABL wind field in the Sichuan Basin exhibited clear regularity, corresponding to the ABL wind field changes at Chengdu (Fig. 5). During rainy periods, with an ABL northeast wind at Chengdu, the ABL flow field in the Sichuan Basin was a cyclonic circulation that curved along the Plateau Basin topography. In rainless periods, with an ABL southwest wind at Chengdu, the ABL flow field in the Sichuan Basin was anticyclonic. The formation, maintenance, and disappearance of the cyclonic flow field corresponded with the occurrence, development, and end of heavy rain in the Sichuan Basin.

Reasons for ABL Wind Variation at Chengdu

We believe that the regular variation of the ABL wind field at Chengdu, which does not occur at other stations, may be related to the geographical position of the Chengdu station within the unique Plateau-Basin topography.

The Sichuan Basin is located on the eastern edge of the Tibetan Plateau and is surrounded by mountains on all sides. The mean elevation in the Sichuan Basin is about 200 to 750 m (Xu, 1991). However, Chengdu is located on the Chuanxi Plain of the western Sichuan Basin, close to the Chuanxi mountainous region on the eastern Tibetan Plateau. The boundary between the Basin Plain and the Plateau Mountain topographies runs from northeast to southwest, which can be seen in the 1000 and 3000 m topographic contours. Chengdu Station is just to the right of the boundary (Fig. 6). The northeast and southwest ABL prevailing winds at Chengdu are the result of the unique geographical environment and indicate an interaction between the large-scale topography and general circulation.

Wang (1981) points out that above 3 km altitude on the Tibetan Plateau, the low-level western air current will flow around the south and north side of the Tibetan Plateau and will form a convergence or shear line at the east edge of the Plateau. Further theoretical research shows that when the altitude of the Plateau is above 1 km, the topography forces the low-level air current to

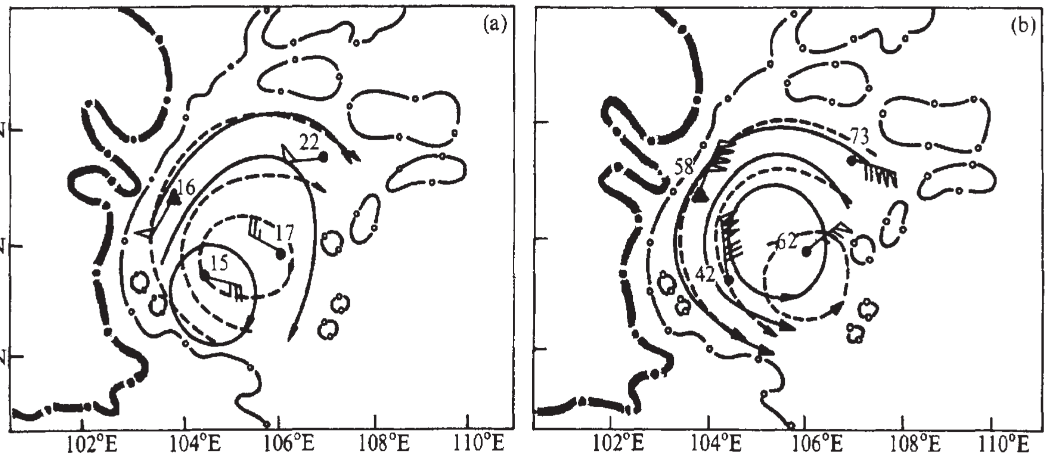

FIGURE 5. Composite distributions of the ABL mean flow field for 20 rainless days (a) and for 33 rain days (b) in the Sichuan Basin in the summer of 1998. Solid and dashed lines are at 2300 and 1100 UTC, respectively. The numbers beside stations are the composite wind speed at 2300 UTC, wind vectors are the composite wind speed at 1100 UTC. The thick and the thin dot-and-dashed lines are the 3000 and 1000 m topographic contours, respectively. Triangle denotes the Chengdu station.

flow around the Plateau. The higher the topography, the greater the forcing effect. Otherwise the air current will mainly flow past the Plateau (Wu, 1984). The Plateau topography forces cold air southward; when cold air pass along the north side of the Plateau, there is often a thin layer of cold air that flows along the Plateau's edge to south. The presence of the Tibetan Plateau strengthens the flow of low-level cold air (Luo et al., 1988). Because of the detaining effect of the Plateau, high-latitude cold air flows around the Plateau into the Sichuan Basin, moving along the eastern edge of the Plateau and entering the Sichuan Basin from the north in the low or middle levels of the troposphere. Therefore, the northeast ABL wind at Chengdu is a reflection of the cold advection invading the Sichuan Basin. But when the ABL at Chengdu consists of a southwest wind, the Sichuan Basin is controlled by a warm air mass (no cold air outbreak) and the weather is dry in the Sichuan Basin.

Because of the barrier effect of the Tibetan Plateau and surrounding mountains, it is very difficult for high-latitude cold air (at the low to middle troposphere) to directly invade the Sichuan Basin from the north, but cold air often flows around the Plateau along its eastern edge into the Sichuan Basin. We believe that the alternating northeast and southwest winds in the ABL of Chengdu are the result of interaction between the topography and the circulation.

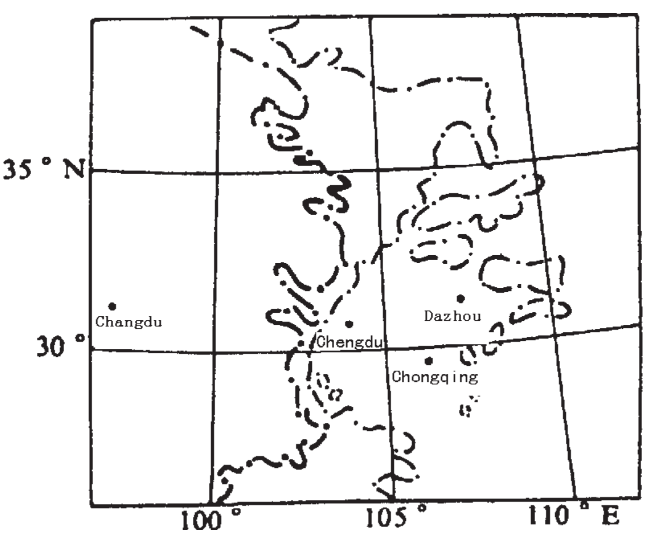

FIGURE 6. The topographic distribution of the Sichuan Basin at the eastern edge of the Tibetan Plateau. The thick dashed line is the 3000 m topographic contour, the thin dashed line is the 1000 m topographic contour. The cities of Chengdu, Dazhou, and Chongqing are within the Sichuan Basin.

Significance of the ABL Wind Variation at Chengdu

Chengdu Station is the key measuring and prediction point for weather changes within the Sichuan Basin. The regular variation of the ABL wind field at Chengdu has significance for the weather in Sichuan Basin.

When the ABL wind at Chengdu is northeast ($U < 0, V < 0$), there will be heavy rain in the Sichuan Basin. When the wind is southwest ($U > 0, V > 0$), there will be dry weather in the Basin. The occurrence, development, and end of heavy rain in the Sichuan Basin correspond to the formation, maintenance, and disappearance of the ABL northeast wind at Chengdu. The ABL wind field in Chengdu changes from several hours to one day before the start of heavy rain, which may allow prediction of such storms.

Due to the unique topographical environment of the Sichuan Basin, and the Tibetan Plateau, the ABL wind field at Chengdu changes regularly. When the ABL at Chengdu consists of a northeast wind, the ABL in the Sichuan Basin will be controlled by a cyclonic flow field, and will maintain convergence, positive vorticity, and ascending motion, which will cause severe convective weather such as heavy rain. When the Chengdu ABL is southwest, the ABL in the Sichuan Basin is controlled by an anticyclonic flow field and is in an unfavorable dynamic configuration. This causes dry weather in the Sichuan Basin.

We suggest the following synoptic model of heavy rain in the Sichuan Basin. Due to the unique northeast-southwest–trending topography of the Plateau Basin, high-latitude cold air invades the Sichuan Basin from the Chuanxi Plain through the ABL. The ABL dynamic trigger is an important mechanism for the occurrence of heavy rain in the Sichuan Basin.

Summary and Conclusions

(1) Due to the unique topography of the Tibetan Plateau and the Sichuan Basin, the ABL wind field at Chengdu (near the

eastern edge of the Plateau) exhibits regional significance. Influenced by the northeast-southwest–trending topography on the eastern edge of Tibetan Plateau, the ABL exhibits alternate northeast and southwest winds. The regular variation between the two winds is the result of the interaction between the topography and the circulation.

(2) Chengdu station is a key measuring and prediction point for severe convective weather, such as heavy rain, in the Sichuan Basin. When the ABL at Chengdu consists of a northeast wind, there will be a cyclonic flow field in the ABL of the Sichuan Basin corresponding with heavy rain. When the ABL at Chengdu consists of a southwest wind, there will be an anticyclonic flow field in the ABL of the Sichuan Basin corresponding with dry weather. The formation, maintenance, and disappearance of the ABL northeast wind at Chengdu predict the occurrence, development, and end of severe convective weather in the Sichuan Basin.

(3) Due to the northeast-southwest–trending topography of the Tibetan Plateau and the Sichuan Basin, high-latitude cold air invades the Sichuan Basin along the Chuanxi Plain near the eastern edge of the Plateau, through the ABL. The ABL dynamic trigger is related to the occurrence and development of severe convective weather in the Sichuan Basin.

The ABL wind field on the eastern edge of Tibetan Plateau is in the focus of this paper. This work highlights the importance of including air temperature and humidity of the ABL in future work.

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