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Analysis of '9.4' unusual rainfall in Beijing during autumn 2015

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ABSTRACT

In this paper, an unusual rainfall in Beijing that occurred on 4 September ('9.4') 2015 is studied to clarify the reasons for such a strong rainfall in autumn. It was indicated that various factors, including stationary westerlies disturbance (i.e. low in the west and high in the east), forward-titling trough, warm shear line, unstable stratification and convective available potential energy release, low level jet as well as a series of mesoscale convective systems produced the strong rainfall. Ordinarily, this situation is uncommon in autumn.

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Heavy rainfall; forward-titling trough; warm shear line; autumn; Beijing

1. Introduction

The rainy season of the Beijing area is concentrated mainly in summer, especially in late July and early August. After mid-August, the rainfall decreases gradually even though some light rainfall may still appear. Typically, it is clear and warm in Beijing during autumn, a period that has been called 'clear and crisp autumn air' ('Qiu Gao Qi Shuang' in Chinese) and 'autumn tiger' when it approaches above normal temperatures. In North America, such weather has been called 'Indian Summer', which describes a period of unseasonably warm, dry weather with above normal temperatures occurring in autumn (Matthews 1902). Similar weather conditions, with local variations, also exist in other places throughout the world. Primarily, there is less precipitation in autumn than in the other seasons.

Research on summer precipitation systems in Beijing has been conducted (Tao 1980; Ding et al. 1980; Sun et al. 2005, 2013; Zhao and Sun 2013). It was found that precipitation systems in Beijing in summer can be divided into six categories (Tao 1980): short wave trough and cold front, vortex, warm shear line, cyclone, inverse trough of typhoon, and typhoon (especially the interaction between middle-lower latitude systems). They are quite different from the band-shaped precipitation area of the Meiyu front in the Yangtze River Valley and the stationary front in South China, with circulation of zonal westerlies with fast-moving and small amplitude troughs resulting in the frequent weather changes observed in Beijing in autumn and the light rain and moderate rain that can sometimes be found when a trough with a cold front passes.

From 0100 UTC 4 to 0900 UTC 5 September 2015, average precipitation amounts of 55.3 mm in the Beijing region and 67.7 mm in its urban area were reported. Among them, the accumulated precipitation amounts from 26 stations were larger than 100 mm, with the largest one being 179.5 mm in Xiangshan, Beijing (Figure 1). Therefore, this was an uncommon precipitation event during autumn.

Special attention was paid to the weather systems during early September 2015 because a formal parade took place in Beijing's Tiananmen Square on 3 September 2015. Fortunately, the weather was fine on the 3rd of September because an upper level ridge predominated over Beijing, and just one day later, on 4 September, the strong rainfall occurred. What caused the changes in weather from 3 September to 4 September 2015? The scientific questions should be clarified.

2. Data and methodology

In this study, the National Centers for Environmental Prediction (NCEP) climate forecast system reanalysis data (Saha et al. 2010) were used to analyze the synoptic weather pattern and to calculate the thermodynamic characteristics, such as moisture flux and divergence of moisture flux. This data-set had a horizontal resolution of $0.5° \times 0.5°$ and a temporal interval of 6 h. Three-hourly surface observations and 12-hourly upper air soundings from the Chinese Meteorological Administration were used to analyze the surface system and to evaluate the evolution at atmospheric stratification and convective energy over Beijing. In addition, the Doppler radar echoes and hourly

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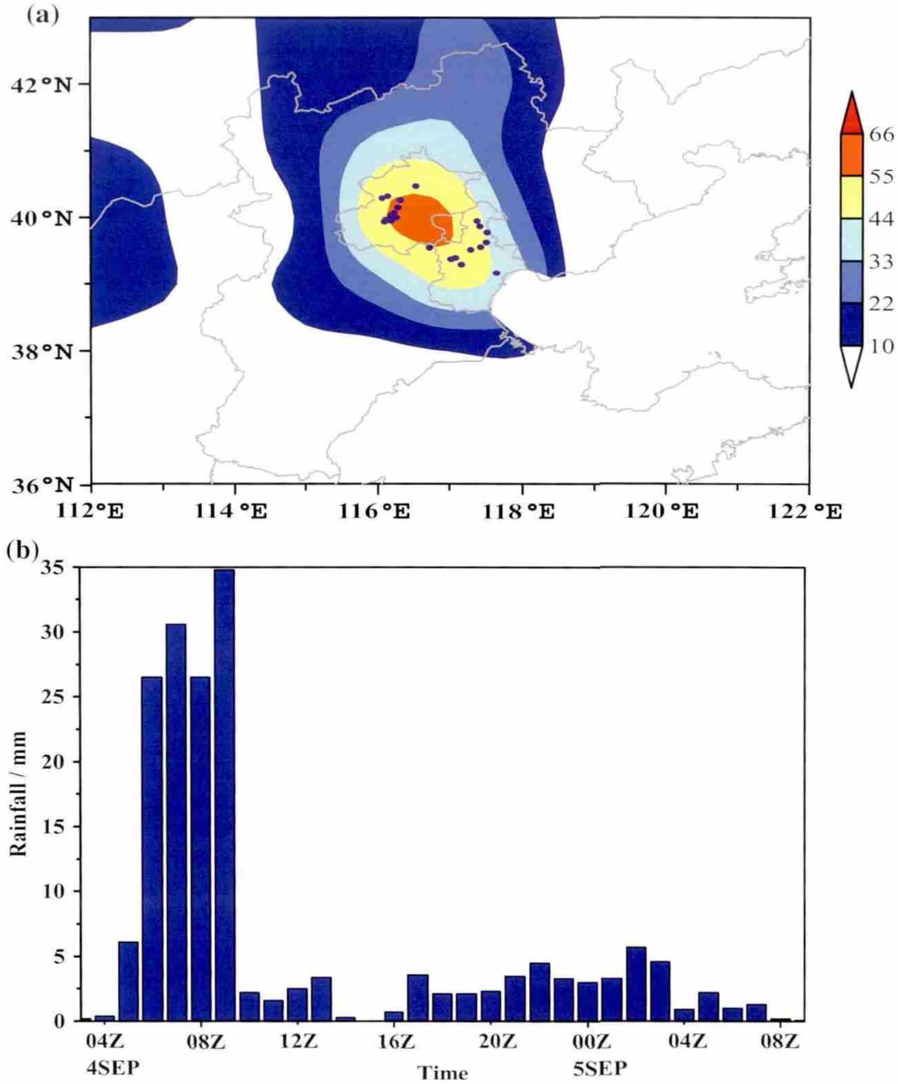

Figure 1. (a) Precipitation amount of automatic weather stations from 0000 UTC 4 to 0000 UTC 5 September 2015 (units: mm). Precipitation amounts larger than 10 mm are shaded and the purple dots represent precipitation amounts larger than 100 mm. (b) Hourly precipitation amount at Xiangshan, Beijing (units: mm).

precipitation amounts were analyzed to further reveal the characteristics of the mesoscale systems.

3. Main results

3.1. Slowly moving-short wave trough

From the weather charts and surface map, it can be observed that the strong autumn precipitation appeared in a background of unusual atmospheric circulation, which corresponded with the 'high in the east and low in the west' pattern of westerlies. 'Low in the west' was a short trough slowed and stopped by the 'high ridge' in the east (Figure 2). Generally speaking, there was a zonal westerly with small amplitude waves that may produce the light rain. In this case, a small ridge was east of Beijing, and the short trough was west of the ridge, at 500 hPa (Figure 2). This pattern was very favorable to the slow-moving of the trough (Ding et al. 1980; Sun et al. 2013) and even stopped it. Beijing was ahead of the 500 hPa trough where conditions were suitable for maintenance of ascending during a longer period. In addition, it can be seen that a 700-hPa low was near the boundary between Mongolia and China, northwest of the Great Bend of the Huanghe River (Figure 2). Although the low was somewhat far from Beijing, one trough on it extended southeastward to Beijing. The trough has more direct impact on Beijing than the low. Additionally, Beijing was also ahead of the trough at 700 hPa. However, it can be seen that the trough was a forward-tilting trough, which is defined by a trough line in the upper level located to the east of the trough line in the lower level. Therefore, the cold air behind the upper trough line moves fast and overlays the warm air ahead of the lower trough line. In this situation, the atmospheric stratification changes, stability decreases, and the conditions

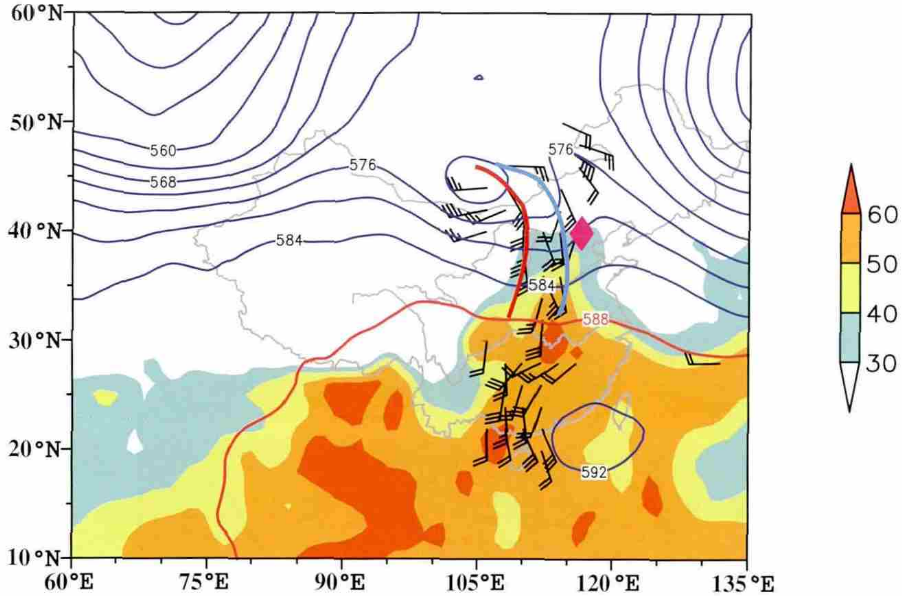

Figure 2. Geopotential height at 500 hPa (units: dagpm) and wind field greater than 8 m s^{-1} at 850 hPa (full bar: 4 m s^{-1}), 0000 UTC 4 September 2015.

Notes: The red and blue bold lines are trough lines at 700 and 500 hPa, respectively. Shaded areas represent perceptible water greater than 30 mm (units: mm). Rhomboid symbol represents Beijing.

become favorable for the formation and development of convective systems.

3.2. Warm shear line in lower layers

In addition, it should be emphasized that during this strong precipitation in Beijing, a warm shear line existed in the lower troposphere. This kind of shear line can sometimes be seen in East Asia, especially in East China. While it is one of the more important systems in China during summer, few can be detected in autumn. Unlike the warm conveyor belts in Europe and North America, a warm shear line with a weak temperature gradient is different from the typical warm front because it is below 850 hPa at most and has a short life cycle. It is sometimes difficult to detect warm shear lines in comparison with warm fronts. Nevertheless, the warm shear line in this case was clearly apparent and was, indeed, related to the strong precipitation. Moreover, a warm shear line can provide not only the favorable environment but also the possible trigger mechanism for strong rainfall. In China, summer warm shear lines have been noticed by some scientists (You 1965; Guo 1977; Hu and Peng 1996; Zhang et al. 2007), as well as those occurring in spring (Liu et al. 2015). Cases in autumn have not been reported in the literature. In our '9.4' case, it can be observed that one continental high combined and merged with another small high to the south of it, which induced the shear line between the southeast and southwest winds. The warm shear line appeared in south Hebei Province at 2300 UTC 3 September (figure not shown), and it approached to Beijing at 0600 UTC 4 September (Figure 3). On the other hand, the cold air from North China is also important. A current of cold air came down along Taihang Mountain southward, where the warm current to the east of the cold current pushed northward to Beijing through Hebei Province (figure not shown). A remarkable interaction occurred between the cold and warm air.

3.3. Low level jet and rich water vapor supply

In summer, moisture from the south contributes significantly to Beijing's precipitation, especially during strong, heavy rain (Wang 1974). Why was the rainfall in autumn of 2015 so strong? Moisture supply should be investigated in detail. It can be seen from Figure 2 that a strong 850-hPa low level jet (LLJ) extended from South China, passed the Yangtze River Valley and North China, and approached Beijing. Precipitable water was approximately 30 mm near Beijing, and in the LLJ upstream area at the Yangtze River Valley, it was even up to ~50 mm.

To further clarify the water vapor impact, the transportation ability as well as the moisture supply ability were discussed. Thus, the moisture flux and divergence of moisture flux were calculated. As shown in Figure 4, a maximum band (larger than 40×10^{-2} kg s^{-1} m^{-1}) extended directly from South China to Beijing, just like a water pipe transporting rich water vapor to North China. The moisture accumulated in the Hebei Province and Beijing and caused strong rainfall as long as it was triggered. Indications

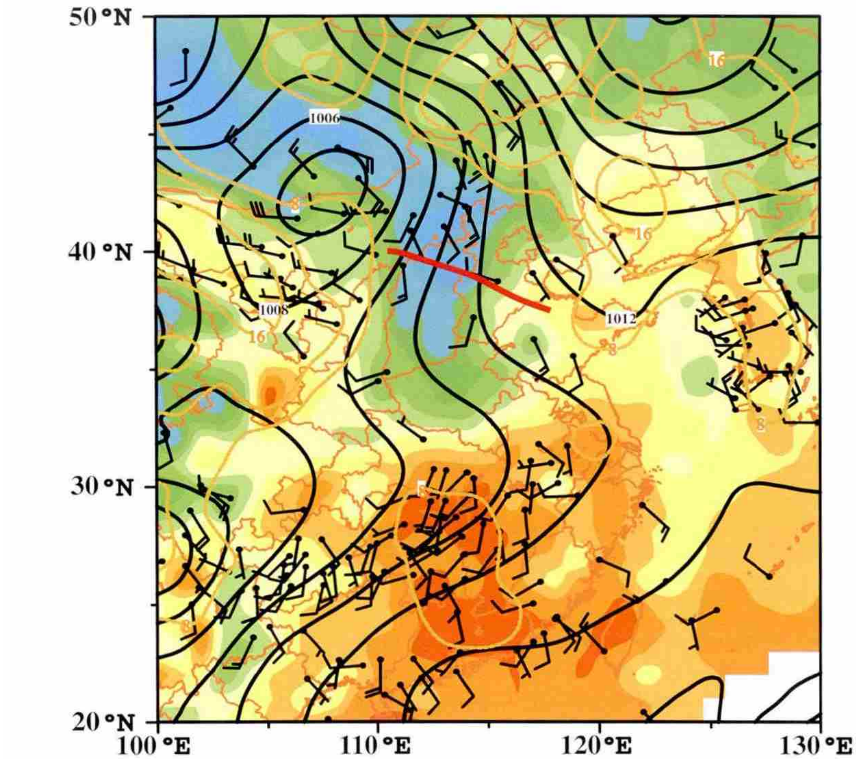

Figure 3. The surface analyses at 0600 UTC 4 September 2015, including sea level pressure (the black solid lines, units: hPa), temperature (color shading, units: °C), and wind field (full bar, 4 m s^{-1}).
Note: The red bold line is the warm shear line.

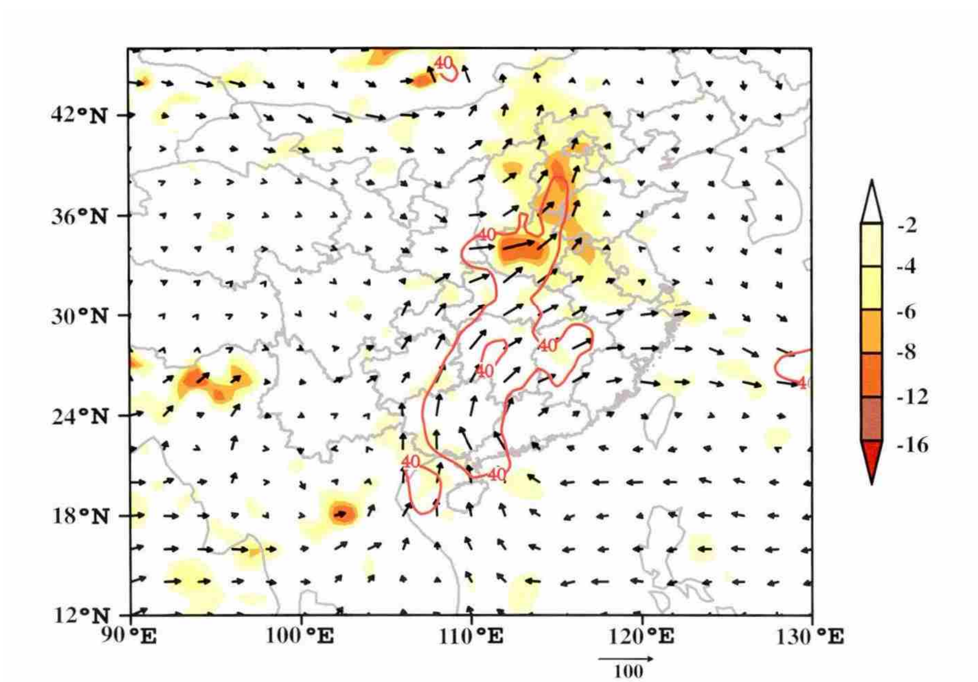

Figure 4. The integrated moisture flux (vector, units: 10^{-2} kg s^{-1} m^{-1}) and divergence of integrated moisture flux (color shaded, units: 10^{-7} kg s^{-1} m^{-2}) from surface to 300 hPa at 0000 UTC 4 September 2015.
Note: The red solid line is the integrated moisture flux with the value 40×10^{-2} kg s^{-1} m^{-1}.

showed similarities to the '7.21' case (Sun et al. 2013), in which the interaction between middle-lower latitude systems seemed to exist. However, the '9.4' case was not accompanied by tropical disturbance and typhoon, and the precipitation amount was weaker than that of the recorded '7.21' case.

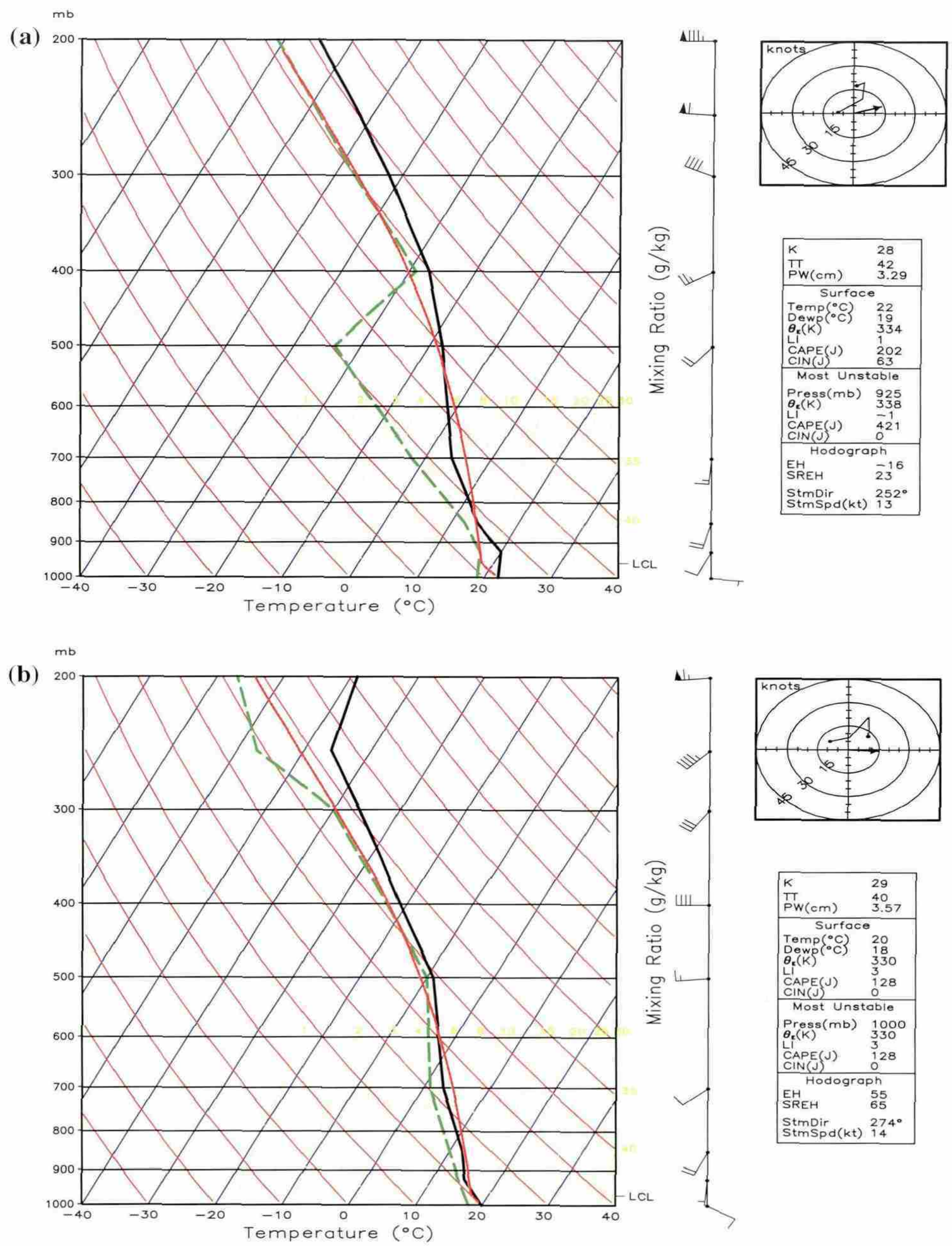

Figure 5. Skew T-log *p* and hodograph (right set) diagram from sounding data at Beijing: (a) 0000 UTC; (b) 1200 UTC 4 September 2015. Notes: Illustration: parallel red curves (dry adiabat), blue lines (isotherm), black parallel lines (isobar), red solid curve (dry adiabat below LCL and moist adiabat above LCL), black solid line (temperature profile), and green dashed curve (dew point profile). Full bar represents 4 m s^{-1}.

3.4. *Unstable stratification and CAPE release*

As mentioned earlier, Beijing was situated ahead of a trough where there was a possibly unstable area. For confirmation, the sounding radio profiles at 0000 UTC and 1200 UTC 4 September 2015 were analyzed (Figure 5). As shown in the thermodynamic diagram (Figure 5), wind direction was in a clock-wise rotation; that is, warm advection predominated in the lower troposphere (surface to 850 hPa) from 1200 UTC 3 to 0000 UTC 4 September 2015, which was favorable to the advance of warm air to Beijing. Southerly wind at 850 hPa and easterly wind at the ground surface were approximately perpendicular to the Yanshan Mountains and Taihang Mountains. It can be qualitatively deduced that the warm air could be lifted by interaction with the related mountains. More quantitative analyses are needed for further proof.

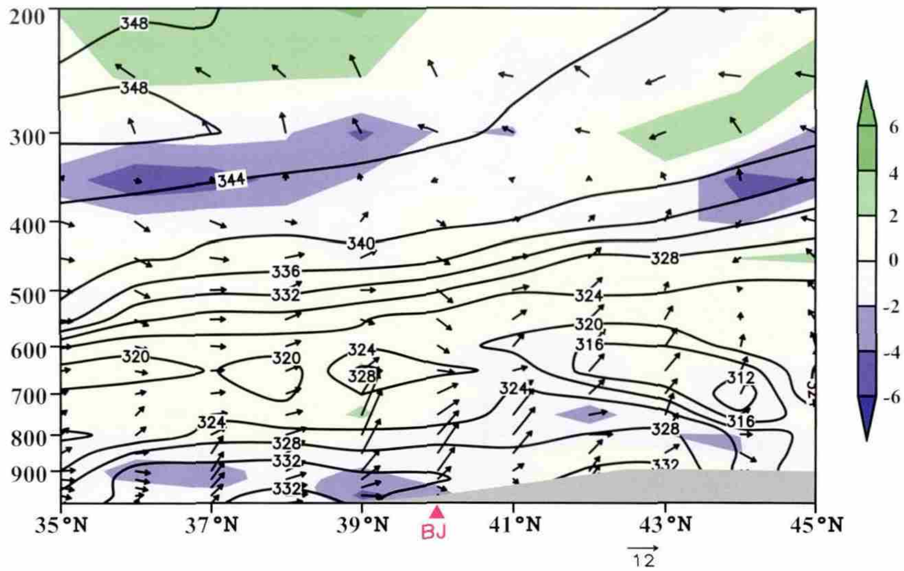

Figure 6. The cross sections along 117°E, including divergence (color shaded, 10^{-5} s^{-1}), pseudo-equivalent potential temperature (black lines, units: K), and meridional circulation (vector: v, $\omega \times 20$, units: v, m s^{-1}; ω, Pa s^{-1}) at 0000 UTC 4 September 2015.
Note: BJ represents Beijing.

In addition, convective available potential energy (CAPE) and convective inhibition (CIN) were analyzed (Lin 2007). In thermodynamic diagram, CAPE is proportional to the area enclosed by the environmental temperature profile and the moist adiabat of the air parcel in between the level of free convection (LFC) and Level of Neutral Buoyancy. Generally speaking, a positive CAPE is a necessary condition for conditional instability to occur, because the air parcel has potential energy for convection. CIN is defined as the negative area (NA) in general, confined by the dry adiabat (below the lifting condensation level (LCL)) or the moist adiabat (above LCL) to the left, and the sounding to the right, from lower level such as surface to its LFC. The NA represents the energy which is needed and has to be supplied to lift vertically up an air parcel. LCL was 825 hPa, CAPE was only 114 J kg^{-1}, and CIN was 37 J kg^{-1}, therefore it was demonstrated that the air parcel was not easily lifted during 1200 UTC 3 September (figure not shown). However, the LCL dropped down to 925 hPa, CAPE increased to 421 J kg^{-1}, CIN decreased to 0 J kg^{-1} at 0000 UTC 4 September. This indicates that the environmental conditions were very favorable to the development of convective systems. No CIN to stop the lifting was present. The air parcels can be lifted to LCL, and, with upward motion continuing to a LFC, CAPE can be released. Later, the system development continued and caused the precipitation in Beijing. At 1200 UTC 4 September, the CIN was still 0 J kg^{-1}, CAPE had decreased to 128 J kg^{-1}, and the thickness of the moist layer with dew point-depression less than 3 °C extended from lower troposphere to mid-upper troposphere. The stratification was approximately neutral. At that time, the precipitation intensity decreased significantly. The rainfall process was over at approximately 0900 UTC 4 September.

The evolution of the stratification can also be discerned from the vertical cross sections. For this reason, the zonal (along 40°N) and meridional (along 117°E) vertical cross sections were drawn, respectively. In Figure 6, the distribution of pseudo-equivalent potential temperature (θ_{se}), divergence and vertical circulation at 0000 UTC 4 September are shown. It can be concluded that the potential instable area between 800 and 700 hPa extended from 35–45°N. Warm air in the middle layer overlaid upon the cold air in the lower layer. A potential instable maximum of 700 hPa and upward motion below 700 hPa were also detected, located approximately 39°N near Beijing.

3.5. Activity of mesoscale convective systems

There were non-uniform spatial and temporal distributions of the rainfall in Beijing (Figure 1). The rain band moved, extending from Southwest to Northeast. It should be emphasized that mesoscale systems were active during the rainfall. Shown in Figure 1(b), the period of the strong precipitation at Xiangshan station was concentrated mainly during 3 h from 0600 UTC to 0900 UTC 4 September. A precipitation amount of 35 mm/hour (0900 UTC) was reported and mesoscale characteristic was clearly observed by radar echo (figure not shown). A strong radar echo moved eastward to northwest Beijing at 0530 UTC 4 September and weakened at 0630 UTC 4 September. Then, other strong mesoscale echoes (larger than 45 dBz) arrived at Beijing from the south at 0650 UTC, persisting there for a longer period until 0930 UTC 4 September (figure not show). The two above mentioned mesoscale convective systems were in agreement with the temporal distribution of the rainy peaks shown in Figure 1(b). This proves that the strong rainfall in Beijing was closely related with the mesoscale systems. However, mesoscale analysis is beyond the scope of this paper and will be presented in detail in another future article.

4. Conclusions

According to statistics, only a few cases of strong rainfall have occurred in Beijing during autumn. Therefore, the precipitation of 4 September 2015 was an uncommon case, even though it was not the only case. Our analyses were completed, and the following conclusions have been drawn: (1) The short wave to the west of Beijing and the ridge to the east of it moved slowly and were almost stationary, providing the favorable environmental conditions for the occurrence of rainfall (i.e. low in the west and high in the east). (2) A forward-tilting trough, where the upper level trough line moved to the east of the lower level trough line, destabilized the air column over Beijing. (3) The warm shear line provided both the favorable environment for rainfall formation and also a possible triggering mechanism. (4) LLJ acted as an important water passage that contributed significantly to the transport of rich moisture to the Beijing area, providing the favorable dynamic and thermodynamic conditions for rainfall formation. (5) Unstable stratification and CAPE release were observed. (6) Mesoscale systems are still sometimes active in the autumn.

In summary, heavy rainfall in autumn can occasionally occur as long as the favorable environmental and triggering conditions exist. Finally, it should be emphasized that the above mentioned results are preliminary, and further study is needed in the future.

Disclosure statement

No potential conflict of interest was reported by the authors.

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