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Analysis of the Characteristics of the Boundary Layer Jet in the Middle reaches of the Yangtze River during the Meiyu season

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Abstract

The Low-level Jet (LLJ) in the Yangtze River Basin during the Meiyu season is analyzed and studied mostly as the atmospheric circulation background of precipitation, which cannot adequately reflect the characteristics of the jet itself. In this paper a fusion of sounding observations and precipitation data from Wuhan Station during the Meiyu season in 2010 are used to analyze the characteristics of the LLJ in the middle reaches of the Yangtze River. The results show that: the vertical structure of the LLJ is characterized by the predominance of a Boundary-layer Jet (BLJ) with an occurrence height concentrated in the 300-1200 m. The BLJ occurs most frequently at 22:00 at night, but most strongly at 01:00 at night, with resultant wind velocities exceeding 14 m/s. A Synoptic-system-related Low-Level Jet (SLLJ) occurs most frequently at 07:00 during the day, but most strongly at 10:00, with resultant wind velocities exceeding 12 m/s. For both the BLJ and SLLJ, the wind direction is characterized by southwesterly winds. However, the wind direction of the SLLJ is more westerly relative to the BLJ, and the northeasterly direction of the SLLJ occurs significantly more frequently. The analysis of four typical cases of heavy precipitation in the middle reaches of the Yangtze River shows that before the onset of heavy precipitation, a LLJ exists in the precipitation center and at its south side. The SLLJ is dominated by southwesterly winds, and the BLJ has more southerly wind component with the BLJ developing earlier than the SLLJ.

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Abstract： The Low-level Jet (LLJ) in the Yangtze River Basin during the Meiyu season is analyzed and studied mostly as the atmospheric circulation background of precipitation, which cannot adequately reflect the characteristics of the jet itself. In this paper a fusion of sounding observations and precipitation data from Wuhan Station during the Meiyu season in 2010 are used to analyze the characteristics of the LLJ in the middle reaches of the Yangtze River. The results show that: the vertical structure of the LLJ is characterized by the predominance of a Boundary-layer Jet (BLJ) with an occurrence height concentrated in the 300-1200 m. The BLJ occurs most frequently at 22:00 at night, but most strongly at 01:00 at night, with resultant wind velocities exceeding 14 m/s. A Synoptic-system-related Low-Level Jet (SLLJ) occurs most frequently at 07:00 during the day, but most strongly at 10:00, with resultant wind velocities exceeding 12 m/s. For both the BLJ and SLLJ, the wind direction is characterized by southwesterly winds. However, the wind direction of the SLLJ is more westerly relative to the BLJ, and the northeasterly direction of the SLLJ occurs significantly more frequently. The analysis of four typical cases of heavy precipitation in the middle reaches of the Yangtze River shows that before the onset of heavy precipitation, a LLJ exists in the precipitation center and at its south side. The SLLJ is dominated by southwesterly winds, and the BLJ has more southerly wind component with the BLJ developing earlier than the SLLJ.

Keywords:Meiyu front, Boundary Layer Jet, Synoptic Low Level Jet,Heavy rain, Middle reaches of Yangtze river

1. Introduction

It is of great scientific significance and social value to study how the LLJ contributes to the occurrence and development of heavy rainfall events, as it is an important factor in causing heavy rainfall [*Chen et al., 1988; Cook et al., 2010; Du and Chen, 2019a*]. A LLJ can be broadly divided into SLLJ and BLJ according to their altitude, which have different spatial and temporal characteristics and formation causes [*Blackaclar, 1957; Wang and Zhang, 2012; Rajewski et al., 2013; Du and Chen, 2018*].

Simply put, a BLJ is a horizontal wind velocity profile maximum occurring in the near-surface layer as a thin layer of fast-moving air at a height of several hundred meters above the ground and usually appears in the stable nocturnal boundary layer

[*Whiteman et al., 1997*]. LLJs can be observed in many parts of the world, and theoretical, observational, and numerical modeling studies have been ongoing for many years. The earliest theoretical analyses began with Blackacdar [1957], who studied the emergence of the LLJ in the stable boundary layer. His study showed that a ground inversion begins to form in the boundary layer after sunset and that the sudden decrease in frictional restraint excites inertial oscillations in the non-geostrophic wind components, leading to the formation of nighttime super-geostrophic wind speed extremes. Some achievements have been made in domestic research on LLJ, mainly focusing on the effect of LLJs on water vapor transport and heavy rainfall [*Sun and Zhai, 1980; Zhang et al., 2019*]. The nocturnal BLJ has also long been of interest in China [*Li et al., 1980; Jin et al., 1983; Fu et al., 2018*]. In Beijing, 30% of the nocturnal observations record a BLJ, which are well correlated with local valley wind circulations under stable boundary layer conditions at night [*Li and Shu, 2008*]. The vertical mixing of the boundary layer during the day and inertial oscillations at night are important processes in BLJs and the diurnal variation of precipitation in the Yangtze River Basin [*Xue et al., 2018*].

The definition of BLJ varies from region to region [*Whiteman et al., 1997; Wei et al., 2014; Vanderwende et al., 2015*]. Hao et al. [2001] define BLJs as events with wind speeds greater than 10 m s-1 at any time occurring at any altitude below 1500 m in the Zhejiang region, lasting for more than one observation time, and with an obvious "nose" protruding in the vertical wind profile. BLJs in the Beijing area generally occur against the background of high daytime temperatures or at night when local heavy rainfall occurs, with significant diurnal variation in intensity and an obvious "nose-like" vertical distribution [*Sun, 2005; Li and Shu, 2008*]. Due to the limitation of the spatial and temporal resolution of the data, most of the studies on LLJ in China only define the maximum wind velocity on a certain isobar surface, but do not specify the vertical shear strength of the wind velocity [*Qian et al., 2004*]. The frequency and intensity of the BLJs in both Shanghai and Tianjin are characterized by a higher daily variation at night than during the day. Due to local topography and weather conditions, Shanghai is dominated by southwesterly and easterly winds while Tianjin by northeasterly and southerly winds, with the former recording a slightly higher in altitude than the latter [*Du et al., 2012; Wei et al., 2014*]. Du and Chen [2018; 2019a] pointed out that convective initiation of warm-sector storms is associated with the upper and lower configurations of double-LLJs, with the BLJ outlet zone providing low-level convergence and the SLLJ inlet zone providing mid-low-level divergence, which produces mesoscale uplift near the South China coast favorable for triggering convection.

According to domestic and international studies, LLJs generally occur overnight and in the early morning (usually between 22:00 local time and 08:00 the next day) [*Bonner, 1968; Astling et al., 1985; Fu et al., 2019*]. However, China's upper-air sounding stations usually observe only twice a day (at 08:00 and 20:00 BJT), which leads to a mismatch between the observation time of conventional sounding data and the occurrence of the LLJ, therefore observing the LLJ is not easy [*Zhang et al., 2007*]. The research on LLJs in China has not yet resulted in a unified and specific standard for defining LLJs. In addition, the complex geographic conditions, large climatic variations, and data limitations in China have not yet led to a complete climate concept of geographic, seasonal, and spatial variability of LLJs [*Hao et al., 2001; Du and Chen, 2019b*].

Few analyses have been conducted to characterize the BLJ in the Yangtze River Basin for heavy rainfall, especially during the Meiyu season. This paper uses intensive sounding and wind profile radar data during the Meiyu season to reveal the existence and daily variation of the BLJ in the middle reaches of the Yangtze River and discusses its impact on heavy rainfall. Section 2 gives a preliminary introduction on the data and methods used in this paper and Section 3 describes the methods for selecting the jet observation profiles in the middle reaches of the Yangtze River. Section 4 analyzes the statistical characteristics of the BLJ in the middle reaches of the Yangtze River during the Meiyu season and Section 5 gives examples of heavy rainfall in the Yangtze River basin accompanied by a BLJ. The last section concludes with a summary and discussion.

2. Data and Methods

2.1 Data

The primary data used in this paper are sounding observations from June 16 to July 30, 2010 at Wuhan Station. The observation times are 0100, 0400, 0700, 1000, 1300, 1600, 1900, and 2200 BJT with a temporal resolution of 3h. The data includes wind speed and wind direction with a vertical resolution of 30m. The wind speed observation profile is shown in the black solid line in Figure 1 (observed at Wuhan

Station at 04:00 BJT on July 2, 2010).

Considering the influence of the environment and the surface (e.g. trees) on the observation data, the lowest altitude of the vertical range in this paper is chosen to be 30m. In conjunction with previous studies on LLJs, the lowest altitude is chosen to be below 600hPa [*Chen et al., 2005；Chen 1979; Chen and Yu 1988; Chen et al., 1994; Zhu Qiangen, 2010*]. The highest vertical range in this paper is selected as 4000m altitudesimilarly. Subsequently, validity tests on the observations in this range are performed [see *Wei et al., 2014*] and the missing measurements are estimated using linear interpolation.

2.2 Methods

The observations from Wuhan Station are used to analyze the characteristics of the BLJ in the middle reaches of the Yangtze River during the Meiyu season. Wuhan Station (30.6°N, 114.05°E) is located in the Jianghan Plain, a flat terrain between Dabie and Jiuling Mountains at a terrain height of about 24m. The location of Wuhan Station and its surrounding terrain are shown in Figure 2.When studying BLJ and SLLJ during the Meiyu season in the middle reaches of the Yangtze River, selected local standards suitable for the Meiyu season in the middle reaches of the Yangtze River can more accurately reveal the characteristics of jets in this region, and the response of jets to boundary layer processes and the synoptic scale system.

The BLJ and SLLJ have in common a "nose-like" feature in the wind speed profile (a wind speed maximum existing at a certain height). However, Blacadar

[1957] indicated that there is a nose-like profile of low wind speed with a cause different from the LLJ in the actual atmosphere. Therefore, it is necessary to screen out a nasal profile with a certain strength as the basis for the study of jet. In this paper, the Jet-like profile is chosen in reference to the method of Blacadar [1957]. Unlike that of Blackadar, effort has been made to find the wind speed extremes within 4000m above the ground in this paper. Due to the presence of several isotach layers in the original data, it is not convenient to extract information on the feature points for nose-like profile. Therefore, it is necessary to eliminate the influence of the isotach layers: the isotach layers (multiple layers) are extracted as a single layer, and the height of the isotach layers is expressed as its average height. The processed wind speed profile is shown by the solid cyan line in Figure 1. The red circle in Figure 2 is the nose-like feature point of the Jet-like profile.

In order to make the results more representative, the profiles used to study the LLJ in the middle reaches of the Yangtze River selected in Section 3.2 are based on the height-frequency distribution of the Jet-like profile nose-like points and the frequency distribution of the wind speed (described in Section 3). After a statistical analysis of the height and wind speed thresholds for LLJs during the Meiyu season in the middle reaches of the Yangtze River, the low-level jet observed profiles were selected. The BLJ or SLLJ height is represented by the height of the corresponding feature point while the wind speed intensity is represented by the wind speed and direction at the corresponding feature points.

3. Selection of Jet Observation Profiles in the Middle Yangtze River

3.1 Wind field characteristics during observation period

The vertical distribution of the wind field in coastal areas is different from that in inland and previous studies on LLJ mainly focused on coastal areas, which led to a limited understanding of the LLJ in the middle reaches of the Yangtze River. In addition, most of the previous studies on the wind speed of LLJs are a continuation of Bonner's [1968] study. Bonner refers to a profile with a wind speed maximum greater than or equal to 12 m/s and a falloff greater than or equal to 6 m/s as one jet observation. However, Bonner's results are based on the jet characteristics of the U.S. Great Plains. The topographic and climatic characteristics in China are quite different from those of the United States, therefore so are the jet characteristics. Some scholars also constrain the wind direction of the jets, considering them to be southerly or westerly winds that meet certain criteria [*Chen et al., 2005; Chen 1979; Chen and Yu, 1988; Chen et al., 1994*].

As seen in the vertical distribution of the wind field in the middle reaches of the Yangtze River from June 16 to July 30, 2010 (Figure 3), it is found that nose-like jet structures in the lower troposphere can also be observed in Wuhan, but the wind speed is slightly lower than the previous standard for LLJ. It is therefore necessary to choose an appropriate wind speed standard to study the jet characteristics in the middle reaches of the Yangtze River. In addition, underintensive observation during the rainy season, a nose-shaped profile for northeasterly winds was observed in June in Wuhan, which indicates the possibility of a northeasterly LLJ in this region, leading to an improved understanding of the LLJ. Based on the above analysis, it is of great significance to carry out statistics on the characteristics of local wind speed in the middle reaches of the Yangtze River.

3.2 Selection of jet observation profile

Jet-like profile nose-shaped feature points in Wuhan are widely distributed in wind speeds below 1500m, between 4 and 18 m/s, while they relatively concentrated above 1500m, ranging from 8 to 12 m/s (Fig. 4a). From Figure 4b, it can be seen that Jet-like profile nose-shaped feature points occur most frequently at the height of 400-600m, up to 41 times. In general, the nose-shaped feature points in Wuhan are mainly concentrated below the height of 1400-1600m, with a sharp decrease in frequency above this height. Bonner [1968] suggested that the upper limit of the jet should be set as the high-frequency height of the nose-shaped feature points of the Jet-like profile (a sharp decrease in frequency in higher-levels). By referring to Bonner's method, the BLJ can be tentatively distinguished from LLJ in the range of 1400-1600m. Blacadar [1957], Sun Jisong [2005], and Hao Weifeng [2001] defined the height of BLJ as that below 1500m, which is consistent with the range in this study. Therefore, the boundary height of the BLJ and SLLJ in Wuhan is finally defined as 1500m in this paper, i.e., LLJs occurring below 1500m are called BLJs, and those occurring between 1500m and 4000m are called SLLJs.

It can also be seen from Figure 4b that the wind speed of Jet-like profile nose-shaped feature points below 1500m height in Wuhan is comparable to that above

1500m height, and the distribution of nose-shaped feature points is mainly positively skewed distribution(mean value greater than the median).

After determining the height boundaries, the next step is: how can wind speed thresholds be selected that will allow for sufficient samples for jet studies to be statistically significant and representative of the jets? In order to select a reasonable and objective profile for the study of LLJs in the middle reaches of the Yangtze River, based on Bonner's method for determining the upper limit of jet height, the high-frequency wind speed values for the frequency of jets are determined as the lower limit of the jet wind speed. The statistics on the wind speed frequency of Jet-like profile nose-shaped feature points in the vertical research range are carried out. Jet-like profile nose-shaped feature points in Wuhan show a single-peak distribution of wind speed frequencies, with a maximum frequency interval of 8-10 m/s, reaching 70 times (Fig. 4c). Therefore, the wind speed threshold for LLJ in Wuhan is defined to be 8 m/s.

Next, the profiles with wind velocities of nose-shaped feature points greater than or equal to 8 m/s at nasal below 4000 m altitude in Wuhan are chosen for the low-level jet (LLJ) study, and BLJ and SLLJ are sorted based on the 1500 m height threshold. When both a BLJ and a SLLJ are present at the same time, it is called a double low-level jet (DLJ) observation. Based on the above conditions, there were 184 LLJ observations in the Wuhan area at a detection rate of 55.25%, which is basically consistent with and slightly higher than that (about 47%) of Oklahoma by Whiteman et al. [1997]. The factors that cause the higher detection rate are as follows:

(1) In this paper, the study period is concentrated in midsummer (June-July), when the southwest monsoon is strong in the middle reaches of the Yangtze River and the increased wind speed increases the frequency of jets. Du et al. [2012] analyzed the occurrence frequency of jet streams before, during, and after the Meiyu season, discovering that the frequency of SLLJs increased significantly during the Meiyu season and decreased again after. In addition, when Du [2019] studied the seasonal variation of jets in South China, he also found that the frequency of jets is highest in June, which is about twice that in other months of the warm season. Therefore, the specificity of the study period in this paper contributes to the high detection results to some extent.

(2) The vertical range of this study (4000m) is higher than Whiteman's (3000m), and therefore also includes the frequency of jets at altitudes of 3000-4000m.

(3) Most of the previous studies focused on single jet by eliminating the profiles with multiple jet-like feature points. In this paper, however, the profiles with multiple jet-like feature points are kept, with a focus on double jets (BLJ and LLJ simultaneously exist), which results in more frequent detection of jets than before.

4. Analysis of the characteristics of the jet stream in the middle reaches of the Yangtze

4.1 Vertical structure characteristics

Next, the frequency distribution of all LLJs at different heights is counted, as shown in Figure 5a. It can be found that LLJs occur more frequently between

300-1200m in the Wuhan area, with the most frequent (30 times) at 900-1200m. The frequency above 1200m starts to decrease sharply. SLLJs mainly occur at altitudes of 1800-3300m, with a maximum of 20 times. BLJs occur more frequently, and the height of BLJs are more concentrated.

Figure 5b agrees with Figure 5a that the LLJs during the Meiyu season in the middle reaches of the Yangtze River are mainly BLJs with an average height of about 1200m and an average intensity of more than 8.5m/s. Comparing the jet composite wind speed profiles with the non-jet , there are two significant differences: (1) Below 4000m, the non-jet composite wind speed is significantly lower than that of the jet composite, and the non-jet composite wind speed profile does not exceed 4.5m/s in the lower levels. However, it is interesting that the observed non-jet profile in Wuhan area also has obvious nose-like features in the lower levels. (2) The most significant difference between the jet and non-jet composite profiles lies within the boundary layer, where the jet composite profiles have stronger and deeper vertical shear.

It can be seen from Figure 6b that the difference in frequency between BLJs and SLLJs is small. However, the nose-like features of the BLJs in the composite wind speed profile in the Wuhan area are obvious, while those of LLJs are very weak. This is because the BLJs in Wuhan are relatively concentrated at a certain height, while the LLJs are relatively scattered. This is confirmed by the standard deviation of the height of the jet stream in Table 1, where that of the SLLJ occurrence height is larger than that of the BLJ.

4.2 Diurnal variation in the frequency of jets

Since the number of observations at 01:00 in Wuhan is significantly less than that at other hours (about 42 at other hours, but only 32 at 01:00), the standard frequency is selected to analyze the daily variation of jets for comparison purposes (R_t=$NJET_t$/N_t*100, where R_t represents the frequency of jets at hour t, $NJET_t$ represents the occurring frequency of jet at hour t, and N_t represents the total number of observations at hour t).

In conjunction with the LLJ diurnal variation characteristics (Fig. 6a), the Jet-like profile and the Jet occurrence frequency in Wuhan show a double-peak structure during the Meiyu season. The difference between the primary and secondary peaks in the frequency of jets is small, which are at 07:00 during the day and 22:00 at night (BJT), respectively. The main frequency peak of the Jet-like profile is recorded at 10:00 during the day, 3 hours later than that of the jets. It shows that the nose-like features of the vertical wind profile are usually more pronounced at 10:00BJT during the Meiyu season in the middle reaches of the Yangtze River, i.e., the vertical shear of the wind speed in the lower troposphere is large. In Whiteman's [1997] study of the Oklahoma LLJ, the primary and secondary peaks of LLJ frequency in warm-season were 23:00 (CST) and 05:00 (CST), respectively. The time points of two peaks in the middle reaches of the Yangtze River are roughly consistent with Whiteman's results, indicating that the development patterns of LLJs in Oklahoma and Wuhan are similar, and their formation and development mechanisms are essentially the same. However, the primary and secondary peaks of the LLJ frequency in the two regions are diurnally opposite, with the greatest frequency occurring during the day in the middle reaches of the Yangtze River (secondary peaks at night) and at night in Oklahoma (secondary peaks during the day). This reveals the influence of local factors on the LLJ in different regions, and the differences between the two regions in the primary and secondary peaks may be due to the particular weather systems of the middle reaches of the Yangtze River during the Meiyu season, i.e., the Meiyu front. The Meiyu front in the middle reaches of the Yangtze River is usually of the strongest development in the early morning, and the mesoscale circulation caused by the condensation of the latent heat of the Meiyu front has an effect on the wind speed of the LLJ [*Qian et al., 2004*], resulting in the unique diurnal variability of LLJ in the middle reaches of the Yangtze River.

From Figure 5 it can be seen that the vertical structure of jets in the Wuhan area is mainly characterized by BLJs, the frequency of which should be higher consequently. However, SLLJs occur even more frequently than BLJ as seen in Figure 6b. This is because the vertical retrieval range of the SLLJ, which is larger than that of the BLJ, stands at 2500m (i.e., within 1500m to 4000m height), while the BLJ has only 1500m (within 30m to 1500m height).

From Figure 6b, it can be seen that BLJs mainly occur at night. The frequency of BLJs shows a double-peak structure, with the maximum at 22:00 and the second peak at 07:00 at night. The frequency of BLJ decreases significantly after 07:00. The diurnal variation of SLLJs is opposite to that of BLJ, occurring mainly during the day and most frequently at 07:00. It is the peak frequencies of BLJ and SLLJ at 07:00 that make LLJ most frequent at 07BJT in Figure 6a.

An interesting phenomenon in Wuhan is that the frequency of BLJ decreases rapidly after 07:00, reaches a minimum at 16:00, but increases again at night. It may be because after 07:00, the mixed layer starts to develop during the day, the turbulent mixing in the boundary layer intensifies, the frictional drag of turbulence increases, and the vertical distribution of wind speed in the boundary layer tends to be uniform, leading to the weakening or even disappearance of the jets. The frequency of BLJs begins to increase again at 19:00 due to the development of a stable nocturnal boundary layer at this hour. The stable nocturnal boundary layer is primarily influenced by surface radiative cooling, with atmospheric temperatures dropping more rapidly near the surface, resulting in a shallow inversion layer in the lower troposphere. Turbulent mixing is weak at night and turbulent friction is decoupled when wind speed in the boundary layer is mainly influenced by surface friction drag. As a result, wind speeds are lower in the lower levels and stronger in the upper levels, leading to the formation of jet [*Blackadar, 1957*].

It was found (Table 1) that the frequency rate of BLJs in Wuhan is slightly higher at night than that during the day, but their average height is higher during the day (941.2 m) than at night (875.9 m). The diurnal variation in mean height of SLLJs is opposite to that of BLJ, with a higher frequency rate during the day, but with a higher mean height at night (2676.3m) than during the day (2474.3m). The mean values of the occurrence heights of BLJ and SLLJ in Wuhan are both larger than the corresponding medians, showing a positively skewed distribution. The standard deviation of the height of SLLJs is about twice that of BLJs, indicating a high degree of relative dispersion in SLLJs.

4.3 Directional characteristics of jets

The BLJ in the Wuhan area is generally southwesterly, with wind speeds up to 20 m/s. The frequencies of BLJs in the directions of SSW and WSW are 37 and 36, respectively, accounting for 76.84% of the total (95). The frequency of BLJs in the other three quadrants decreases sharply, and the northeast direction is a subhigh frequency region with a significant decrease in wind speed (Figure 7a). The maximum frequency of SLLJ wind direction is still dominated by southwesterly, with wind speeds up to 23 m/s. However, relative to BLJs, the wind direction of SLLJs is more westerly and the frequency of the northeasterly direction increased significantly (Figure 7b). The wind direction with the highest frequency in SLLJs is WSW, followed by the west wind, and the NNE direction is second only to the west.

When Vanderwende, et al [2015] studied jets below 2 km in the Iowa region of the United States, they found that the Iowa jets wind direction was almost non-existent in the first quadrant. In contrast, for jets in the middle reaches of the Yangtze River the first quadrant has a moderate occurrence frequency, indicating that the jets in the middle reaches of the Yangtze River are somewhat different from those in the United States. This also confirms the necessity of this study to some extent.

4.4 Jet stream intensity

The low-level wind speed in Wuhan shows significant diurnal variation, and the diurnal variation of the composite jet wind speed profile is opposite to that of the composite non-jet wind speed profile. When jets are observed, the wind speed is greater during the day than at night above 1000m. Below 1000 m, the diurnal variation of wind speed is relatively complex, but in general, the intensity of nighttime jets is slightly greater than that of daytime. The composite non-jet profiles show slightly higher wind speeds at night than during the day, a phenomenon that is most pronounced below 600 m.

Previous studies have found that the diurnal variation of BLJs becomes insignificant when mid-altitude jets exist above them [*Zhang et al., 2007*]. Therefore, in order to reveal more clearly the diurnal variation of the vertical structure of BLJs, only the pure BLJ and pure SLLJ conditions are studied in this section. The diurnal variation of the pure BLJ vertical structure is opposite to that of the pure SLLJ, where the speed of BLJ is stronger at night and the SLLJ is stronger during the day. The BLJ has the highest wind speed at 01:00 at night, and the composite wind speed can exceed 14 m/s. It begins to diminish after 01:00. The BLJ nose varies in altitude from 600-1200 m. The SLLJ is strongest at 10:00 BJT, has the lowest wind speed at 16:00 BJT, and then develops again.

The double LLJs are more pronounced at night, with stronger BLJ and SLLJ wind speeds at night and greater vertical shear. BLJs in the double low-level jet cases are significantly stronger than the SLLJs (Figure 10a). From the evolutionary features of the double jets at different hours (10b), it can be seen that the DLJ is strongest at 01:00 at night, when the BLJ and SLLJ wind speeds reach their maximum. BLJs are less variable in height, so the nose-like features are always evident. The SLLJ, on the other hand, has a large variation in height, making the nose-like features of the composite profiles correspondingly weak and highly variable.

In previous studies, it has been found that the temperature inversion layer is strongly associated with BLJs, with the development of BLJs being subject to its height and intensity [*Vanderwende et al., 2015; He et al., 2018*]. A similar phenomenon is also found in this study. At 22:00 on July 3, a temperature inversion layer was formed near a height of 400m. In the next observation, a BLJ was recorded near the height of the temperature inversion layer (about 600m), with wind speed up to 11m/s. During the next few observations, turbulence development is suppressed due to the maintenance of the temperature inversion, and the wind speed in the boundary layer is mainly influenced by surface frictional drag at this hour. As a result, the lower-level wind speed was lower, while the upper-level winds were stronger and the BLJ was maintained and developed [*Blackadar, 1957*]. By 10:00 on the 4th, the wind speed of the jet reached 13 m/s.

5. Examples of Heavy Rainfall in the Yangtze River Basin with BLJ

5.1 Spatial distribution of heavy precipitation and jets

In this section, four regional heavy precipitation events that are representative in the middle and lower reaches of the Yangtze River from 2010 to 2020 are selected:

July 16, 2010; July 1, 2016; May 25, 2019; and July 16, 2020. The 2019 heavy precipitation event occurred before the start of the Meiyu season, and the remaining three occurred during the Meiyu season. In the 2016 and 2020 cases, the heavy rainfall and the extremely heavy rainfall were concentrated in the eastern Hubei and southern Anhui along the Yangtze River, respectively. The 2019 case recorded the heaviest precipitation. On May 25 most areas of the middle reaches of the Yangtze River received an extremely heavy rainfall of more than 100mm with some sites along the River receiving more than 200mm. In the 2010 case, the precipitation areas were more northerly, mainly in the northeastern part of Hubei and the neighboring southern Henan.

All four processes were accompanied by significant SLLJs (reflected in mean wind field of 850hPa-700hPa layer) and BLJs (reflected in the wind field of 925hPa layer). Closely related to the spatial distribution of precipitation, the LLJs in 2016 and 2020 were almost identical, with southwest SLLJs exceeding 14 m/s covering most of the area south of the Yangtze River, centered in Hunan and north-central Jiangxi. Compared to 2016 and 2020, the intensity of precipitation on the northern side of Dongting Lake is greater in 2019, and the corresponding overall extent of the sLLJ is more westerly, with the southwestern SLLJ exceeding 12 m/s covering Hunan and northern Jiangxi. Corresponding to the precipitation that occurred in the northeast of Hubei in 2010, the location of SLLJ is more northerly, mainly in east-central Hubei and south-central Anhui, and is dominated by westerly winds. Unlike SLLJ, BLJs are more stable. Significant BLJs were observed in the lake areas of Dongting and

Poyang and in regions to their south prior to the four heavy precipitation events. The relative strength of the two heavy precipitation centers in the northern parts of the two lakes (the eastern Hubei precipitation center in the west and the southern Anhui precipitation center in the east) and the north-south position of the centers are closely related to the relative strength of the BLJ and the extent to which the jets extended northward.

5.2 The evolution of jets

As for the diurnal variation of SLLJs and BLJs, the panel on the right shows the evolution of the vertical distribution of the horizontal wind field from 20:00 two days before precipitation to 20:00 p.m. on the day of precipitation. In all cases, jets appeared below the 3.5 km (650 hPa) layer at night two days before the precipitation began, and again at night and early morning before the precipitation began, with significantly stronger intensity. Moreover, there were large centers below 1.5 km (or 850 hPa) in all cases. Overall, the SLLJs were dominated by southwesterly winds and the BLJs had more southerly components. In 2019, the analysis of the height-time evolution of the horizontal wind field on the south side of Dongting Lake shows that the LLJ was generated near the 900 hPa layer around 21:00-22:00, and intensified significantly from 00:00, reaching its maximum around 04:00. Then the jet rapidly stretched upward from 08:00, with its center located in the lower troposphere (near the 825 hPa layer) after 12:00. In 2016, the center of heavy precipitation was relatively stronger in the south Anhui area. The analysis of the wind field in the

Poyang Lake area revealed that its evolution was basically the same as that in 2019, with the BLJ being stronger from 22:00 to 10:00 and LLJ being the strongest from 12:00 to 16:00. Compared with 2016, the precipitation center in 2020 is also stronger in southern Anhui, but with a slightly northern rain band. The wind profile data from Xianning station along the south side of the rain band is analyzed in this paper, but the sounding data from Wuhan station along the south side of the rain band is chosen to be analyzed due to the more northern precipitation location in 2010. Both wind profile and sounding data before precipitation show that the horizontal wind speed at or below the 1.5 km level began to strengthen after 22:00, with large values occurring from 05:00-12:00; after 00:00, the wind speed at or below the 2 km level began to strengthen, with large values occurring after 06:00.

The four representative cases selected in this section clearly show the existence of LLJs before the onset of heavy precipitation in the middle reaches of the Yangtze River from the point of view of observation and analysis, and also corroborate the results of the statistical analysis. The evolution of the reanalysis wind fields in Poyang and Dongting Lakes shows a distinctive feature of jets beginning at night in the boundary layer and moving toward the lower troposphere in the morning. The wind profile and sounding data in the eastern Hubei region are also found near 1.5km in altitude. The strong southwesterly wind develops rapidly at night and peaks in the morning before precipitation onset, and the BLJ also appears earlier than the SLLJ. Although the jets over the two lakes are more southerly than the jets in the eastern

Hubei region as a whole, SLLJs are dominated by southwest winds with BLJs having a more southerly component.

6 Conclusion and discussion

Given the vast area and complex terrain of China, current upper-air sounding stations are relatively sparse and cannot reflect the local characteristics of LLJ. In China, there are few specific studies on LLJs in the middle reaches of the Yangtze River during the Meiyu season, while there are more indirect studies. Intensive LLJ observation in some areas, generally using meteorological towers, tethered balloons, radar, etc., has achieved relatively good results. In this paper a fusion of intensive sounding observations and precipitation data from Wuhan Station during the Meiyu season in 2010 are used to analyze the characteristics of the LLJ in the middle reaches of the Yangtze River. The results show that:

(1) The vertical structure of the LLJ in the middle reaches of the Yangtze River is characterized by the predominance of a Boundary-layer Jet (BLJ), with an occurrence height concentrated in the 900-1200 m. The difference between the jet composite profile and the non-jet composite profile is most pronounced in the boundary layer, with the difference being that the vertical shear of the composite jet profile is stronger and deeper in the boundary layer.

(2) The LLJ in the middle reaches of the Yangtze River has a unique diurnal variation, with the maximum frequency occurring at 07:00 during the day and the second highest at 22:00 at night. The difference in frequency between the two hours is

small, a special diurnal variation that may be attributable to the Meiyu front in the middle reaches of the Yangtze River. BLJs occur most frequently at 22:00 at night, but most strongly at 01:00 at night, with resultant wind velocities exceeding 14 m/s. Synoptic-system-related Low-Level Jets (SLLJ) occur most frequently at 07:00 during the day, but most strongly at 10:00, with resultant wind velocities exceeding 12 m/s.

(3) Regardless of BLJ or SLLJ, the wind direction is characterized by southwesterly winds. However, the wind direction of SLLJs is more westerly compared to BLJs, and the northeasterly direction of SLLJs occurs significantly more frequently.

In addition to the statistical study, the analysis of typical cases in this study shows the existence of a LLJ in the middle reaches of the Yangtze River before the onset of heavy precipitation from reanalysis data, wind profiles, and sounding observations. It is also found that the BLJ develops earlier than the SLLJ, with SLLJ dominated by southwesterly winds, and BLJ having more southerly wind components.

The existence of a LLJ, especially a BLJ, before the onset of heavy precipitation in the middle reaches of the Yangtze River is found in both the observational and reanalysis from both statistical and individual case perspectives. The mechanisms of BLJ generation together with its effect on precipitation, which is not yet well understood, is an item that has been put on the agenda as our further initiative.

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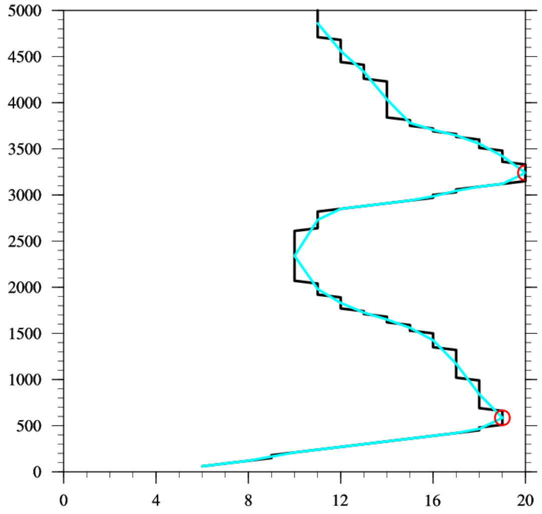

Figure 1. Wind speed profile observed at 04:00 on July 2, 2010 (BJT) at Wuhan station. The black line represents wind speed profile with the original data. The cyan line represents wind speed profile drawn by the data after removing the equal wind speed layer, and the red circles represent noses of the jet-like profile.

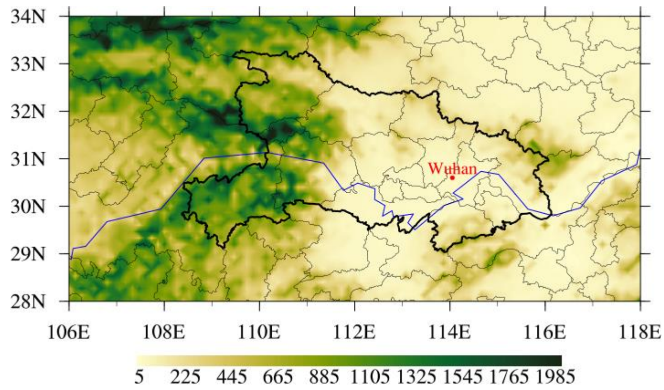

Figure 2. Location of Wuhan Sounding Station and its Surrounding Terrain（units: m）

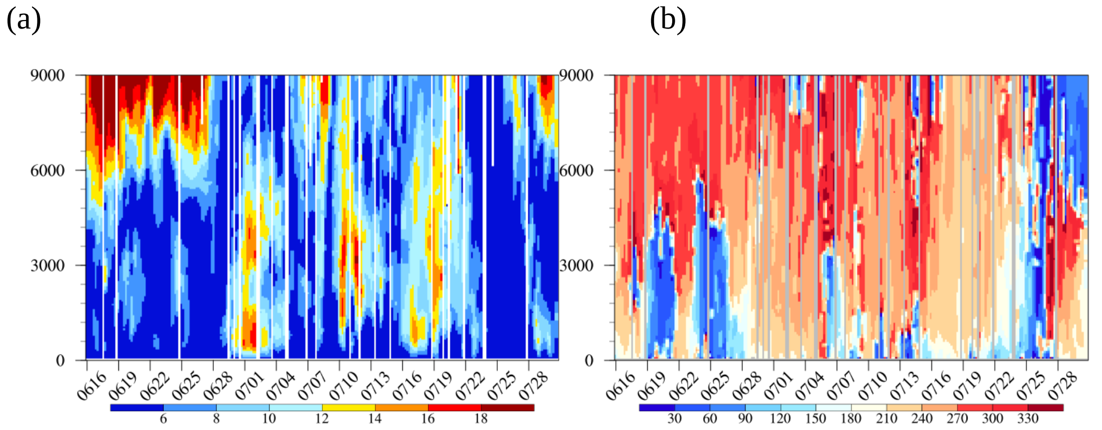

Figure 3. The evolving vertical distribution of wind speed (a) and wind direction (b) over time in Wuhan from June 16, 2010 to July 30, 2010

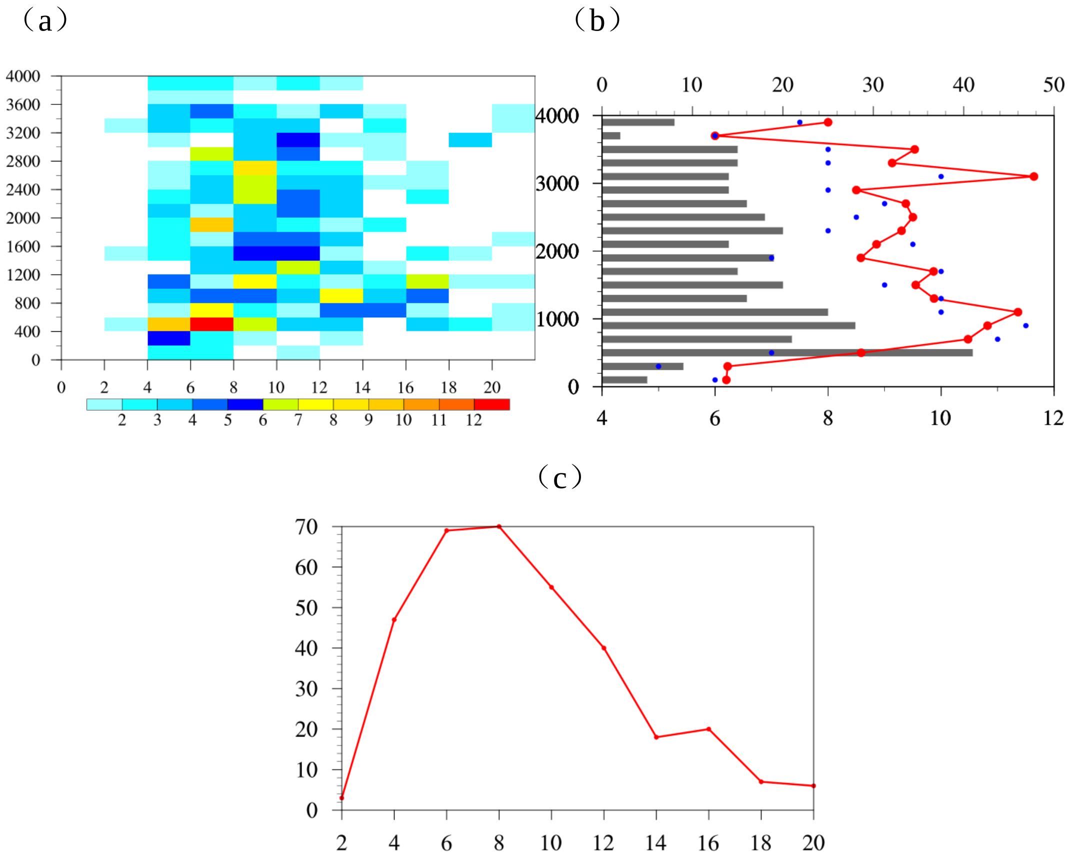

Figure 4: (a) The frequency distribution of different wind speeds at different heights for Jet-like profile of nose-shaped feature points in Wuhan (horizontal coordinates indicate wind speed, shading indicates frequency), (b) the frequency distribution (black bars) and wind speed distribution at different heights (red dots are means, blue dots are medians), (c) the total frequency distribution for different wind speeds.

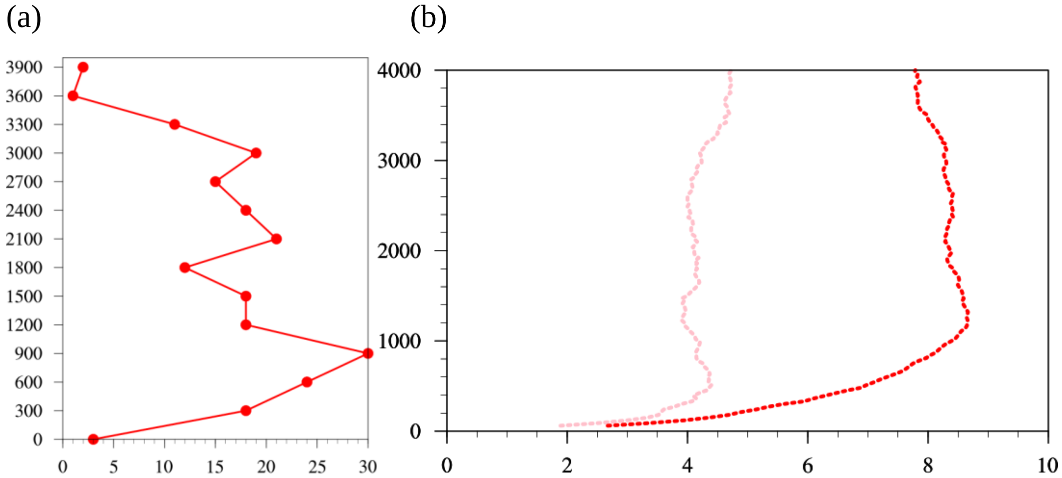

Figure 5: (a) frequency of LLJ at different altitudes; (b) resultant wind velocity for jets observation profile (red) and non-jets observation profile (pink)

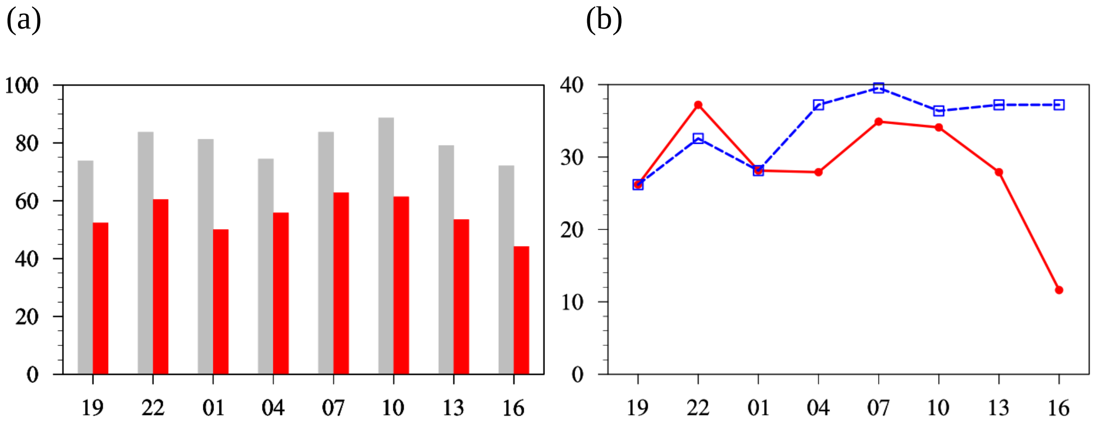

Figure 6: (a) occurrence frequencies of Jet-like profile (gray) and Jet profile (red, including BLJ and LLJ) in Wuhan at different times; (b) daily variation of BLJ and SLLJ frequencies in Wuhan (BLJ in red, LLJ in blue). 1900-0400 hours represent nighttime and 0700-1600 hours represent daytime.

Table 1 Height of BLJs and LLJs at Wuhan

category	BLJ		LLJ	
	day	night	day	night
Frequency rate	27.17%	30%	37.57%	31.25%
mean	941.2	875.9	2474.3	2676.3
median	915.0	870.0	2370.0	2670.0
Std dev	322.6	312.6	618.8	557.3
minimum	180	180	1515	1575
maximum	1500	1500	3960	3825

(a)BLJ (b) SLLJ

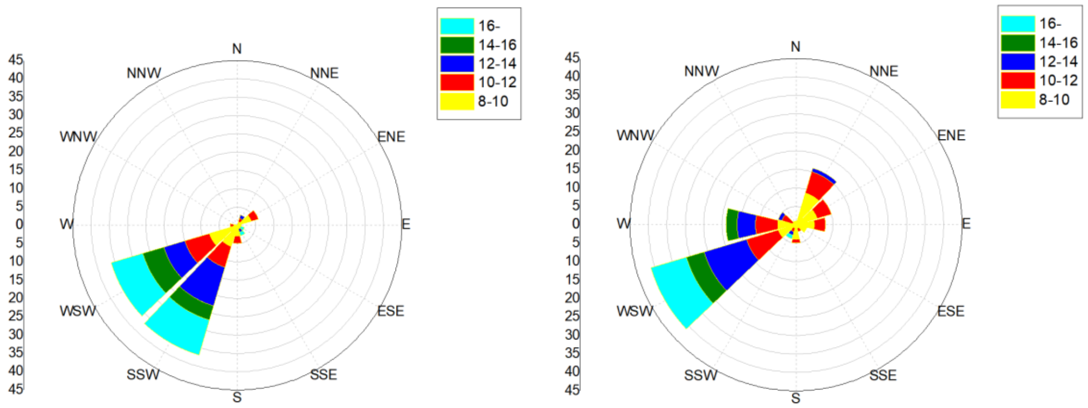

Figure 7：Wind roses summarizing all wind speeds (m s^{-1}) and directions of (a) BLJ and (b) LLJ observed by radiosonde located in Wuhan.

(a) (b)

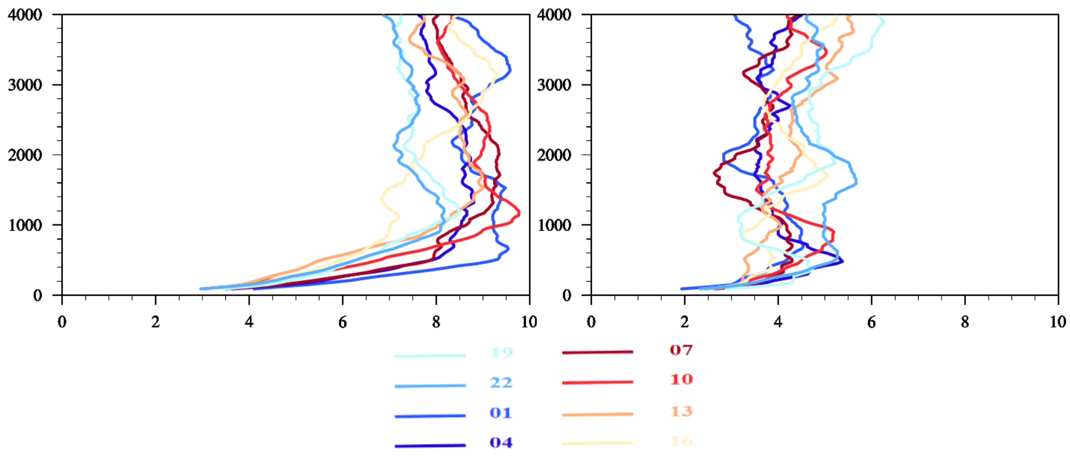

Figure 8: Diurnal variation of the composite observation profile in Wuhan at (a) jet observation hour and (b) non-jet observation hour

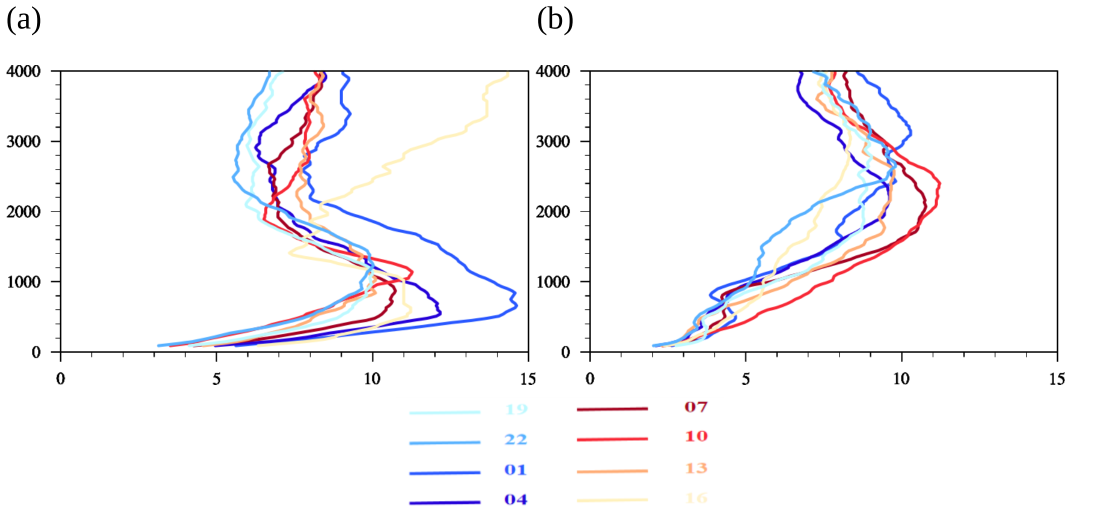

Figure 9: Diurnal variation of composite wind speed profiles for (a) pure BLJ observations and (b) pure SLLJ observations in Wuhan.

(a) (b)

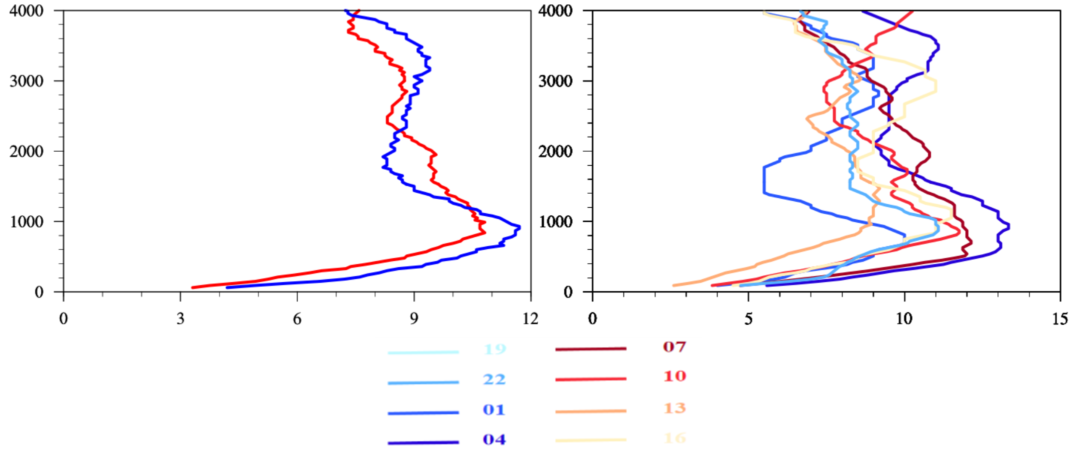

Figure10: (a) diurnal (red for daytime; blue for nighttime) variation of double LLJ, (b) variation of double LLJ at different hours in Wuhan.

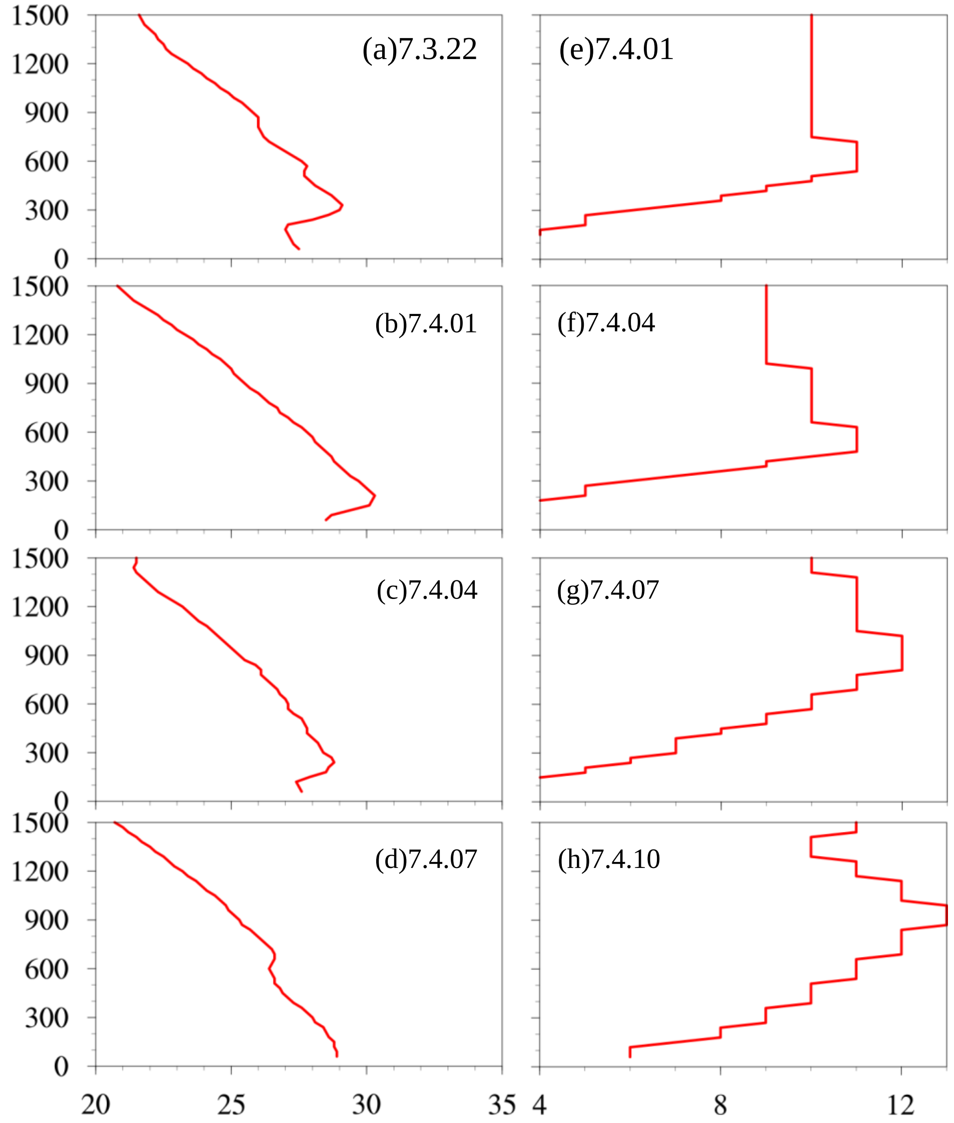

Figure 11: (a-d) Temperature profile from 22:00 on July 3 to 07:00 on July 4, 2010, (e-h) Wind speed profile from 01:00 to 10:00 on July 4, 2010

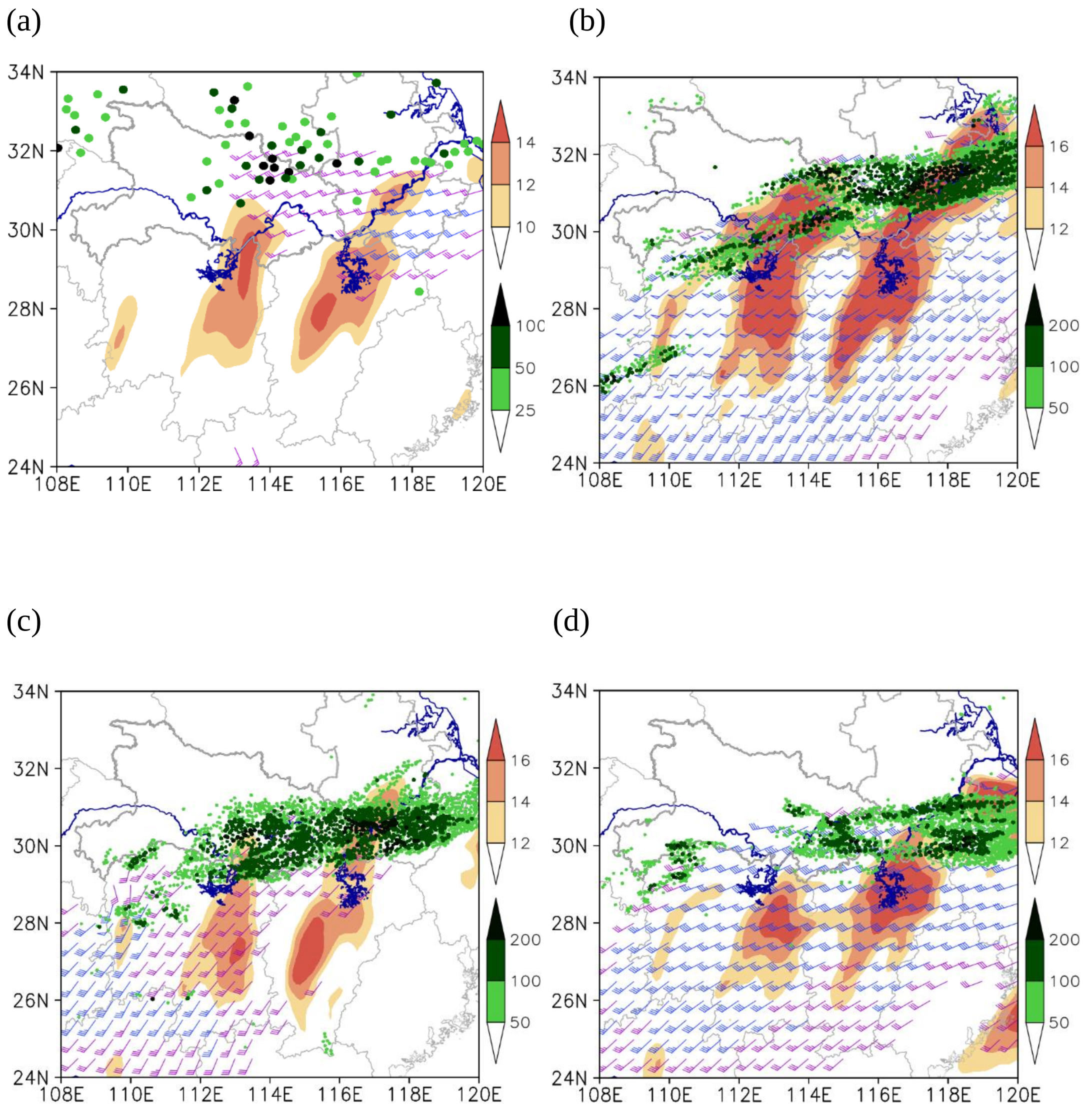

Figure 12: (a) 2010071608 wind field and 1608-1708 precipitation (b) 2016070108 wind field and 0108-0208 precipitation (c) 2019052508 wind field and 2508-2608 precipitation (d) 2020070608 wind field and 0608-0708 precipitation, where the shadows are 925hPa upper jet, the wind barbs are the mean jets between 700-850hPa, and the green dots are the 24-hour cumulative precipitation at the site.

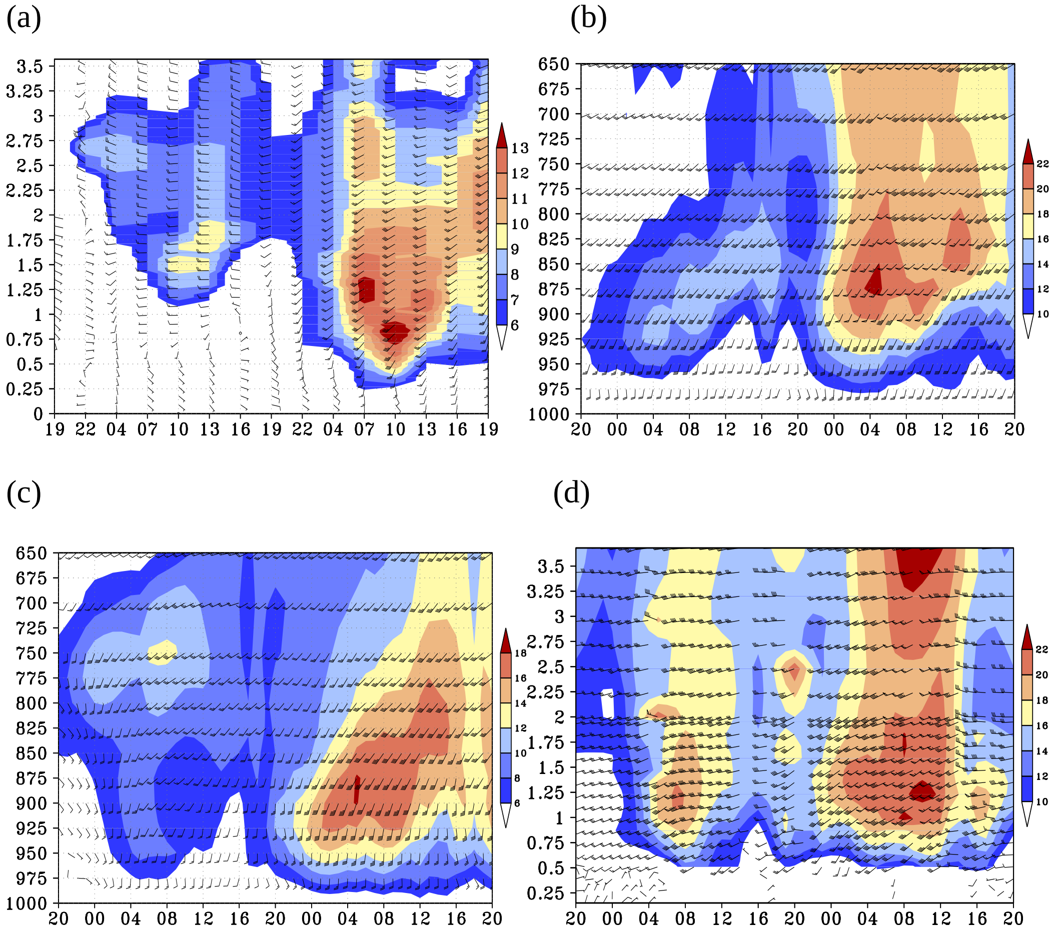

Figure 13: (a) Soundings at Wuhan Station (2010071420-071620) (b) Temporal evolution of the vertical wind field at Poyang Lake (2016062920-070120) (c) Temporal evolution of the vertical wind field at Dongting Lake (2019052320-052520) (d) Wind profile at Xianning Station (2020070420-070620)