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STATISTICAL ANALYSIS OF LOW-LEVEL JET STREAMS IN NANJING AREA BASED ON WIND PROFILER DATA

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Abstract: In order to understand the activity characteristics of low-level jets in the Nanjing area, statistical analysis and comparative study are carried out on their monthly and diurnal variations, characteristics of their cores and accompanying weather conditions using wind profile data in 2005-2008 collected by two wind profilers. The results show that low-level jets have significant monthly and diurnal variations. They occur more frequently in spring and summer than in autumn and winter and are more active in early morning and at night, with the maximum wind speed usually occurring at midnight. The central part of the low-level jet occurs mainly at the height of less than 1400 meters, and the enhancement of central speed is beneficial to the appearance of precipitation. Meanwhile, when the low-level jet appears in summer, it helps cause heavy rain. The statistical results of the boundary wind profiler are well consistent with those of the tropospheric wind profiler. Two kinds of wind profilers also have the capability of continuously detecting the development of low-level jets.

Key words: tropospheric wind profiler; boundary wind profiler; horizontal wind profile; low-level jet; statistics
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1 INTRODUCTION

A low-level jet stream (LLJS) usually refers an airstream that is both intense and narrow below the level of 600 hPa (Zhu et al.[1]), which is closely related to torrential rain, squalls, tornadoes, thunderstorms (Chen et al.[2]; Yan et al.[3]; Hou et al.[4]; Ding et al.[5]). Scientists abroad are pioneers in working on the activity pattern of the LLJS. In 1961, Walter and Hoecker[6] used the intensive measurements of balloons to study the variations of LLJSs in the Great Plain in United States. In a 1968 climatological study on LLJSs, Bonner [7] established their complete methodological structure and evolutional patterns for North America. In their 1973 research, Browning and Pardoe [8] worked on LLJSs with wintertime cold fronts or occluded warm fronts. Manabe et al. were successful in simulating cross-equatorial jet streams that were active in July over the Indian Ocean and the west coast of the Pacific Ocean[9].

Previously, research on LLJSs was mainly dependent on conventionally detected data whose low spatio-temporal resolution made it impossible to observe their continuous variation. Wind profilers, characteristic of high spatio-temporal resolution, excel in what the conventional means struggle to meet people's needs and illustrate graphically the duration, altitude, wind velocity and intensity of LLJSs. In 1996, Zhong et al. [10] used networked profiles to conduct case studies on the LLJSs of the Great Plains and were able to show their complete pictures typical of the summer due to the high resolution of the data. With wind profilers, Jashi et al.[11] studied the LLJS for the monsoon season of 2003 and discovered that July was the month with high occurrence of LLJSs, which differ much between day and night. With data from wind profilers as well as those from a 200-m tower mounted with detecting equipment at Texas Industrial University, Giammanco and Peterson[12] worked on the evolution of three typical nighttime LLJSs in southern USA. In China, related research has also been done and some important conclusions have been concluded. Wind profiles for a scientific experiment on torrential rain in south China and South China Sea monsoon were used to study the relationships between the LLJS and heavy rain, with the finding that the fluctuation of the LLJS was somewhat indicative of severe weather and intense rain(Liu et al.[13]). A study with wind profiles showed that the intensity and altitude of LLJSs are directly related with the intensity of associated severe rain (Jin et al. [14]). The relationships between single torrential rains and upper- and lower-level LLJSs were analyzed using products of wind profilers to determine that the latter and their

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downward fluctuation are closely related with the enhancement of precipita tion; precipitation can be intensified much more than it is with the downward fluctuation and enhancement of just upper-level jet streams, and heavy rain occurs mainly due to the downward propagation and intensification of LLJSs (Zhang et al.[15]).

It is known from the existing domestic and overseas research that the wind profiler-based wind field information is good at capturing the variation pattern of LLJSs. In China, most of the research focuses on case study while spending little effort in systematic analysis of multi-year statistics based on data from wind profilers. In order to contribute to the effort of LLJSs study in China, this work uses the wind data gather by two Nanjing profilers from 2005 to 2008 to statistically study the LLJSs in the region and to reveal their annual and diurnal variations.

2 DEFINITION OF LLJS FOR WIND PROFILERS

In China, a band of strong wind is defined to be a LLJS if it occurs in a particular area of the lower level of the atmosphere (e.g. 700 hPa, 850 hPa or 925 hPa) with velocity equal to or greater than a specific value (currently, 12 m/s or 16 m/s), according to Ding [16]. Most of the LLJSs in China are southwesterly, usually between 150 and 3 000 m in mid- and lower-levels of the atmosphere, with the average length between 1 000 and 2 000 m and the width around a few hundred meters. They often occur during the annually first rain season of south China and the Meiyu season in the Yangtze-Huaihe River basin. In addition to it, there is another LLJS in China, which is a southeasterly and usually happens after mid-July. Around this time of the year, a subtropical high advances northward to the Sea of Japan and tropical cyclones usually land on the coast of China, forming an intense southeasterly LLJS between the storm and the subtropical high, an important factor for the generation of torrential rain. It is therefore why the LLJSs studied in this work include both the southwesterly and southeasterly.

During the discussion of LLJSs in North America, Bonner [7] set the following criteria for their occurrence at single stations: there should be a layer of maximum wind velocity within 1.5 km above the ground, the maximum wind velocity has to be equal to or greater than 12 m/s and 6 m/s larger than the minimum wind velocity at the layer above. Based on it and with reference to various definitions at home and characteristics of wind profilers, this work defines the LLJS as follows: (1) It has to be at heights less than 2 000 m, with the wind velocity ≥ 12 m/s and the duration more than 4 h; (2) The wind velocity must first increase and then decrease, or shows a nose-shaped pattern that reaches the maximum wind velocity at a layer of particular heights; (3) Such a "nose" should have consistent wind directions for all layers of heights.

In this work, the wind field data collected from the two profilers are used to study the pattern in which the LLJSs vary. Some of their performance specifications are presented in Table 1. With a phase-controlling array of antenna, the wind profiler for the boundary layer (referred to as $profiler_{BL}$) detects heights between 50 and 3 450 m and acquires data from 40 layers of heights. For heights between 50 and 300 m, a low-level model is used to obtain data from six layers with resolution at 50 m. For heights between 400 and 3 450 m, a high-level model is used to obtain data from 34 layers with resolution at 100 m. Using a phase-controlling array of antenna with cross-polarization and half-wave dipole, the wind profiler for the troposphere (referred to as $profiler_{T}$) detects heights from 150 to 16 650 m in three modes of high, middle and low levels. The data detected by the low-level model is used to analyze the LLJS in a range of 150 through 3 825 m and at resolution of 75 m.

Table 1. Technical parameters for the two wind profilers.

Wind profiler	Antenna size	Operating frequency	Detected heights/m	Detecting mode	Distance resolution/m
Boundary layer	1.67 m×1.67 m	L band	50~3 450	Low-level High-level	50~300:50 300~3 450:100
Troposphere	9.6 m×9.6 m	UHF band	150~16 650	Low-level Middle level High level	150~3 825:75 2 100~7 955:150 4 950~16 650:300

3 STATISTICAL ANALYSIS OF LLJS

3.1 *Monthly variation*

To ensure the representation and efficiency of the data used in the statistical analysis, the wind profiles for monthly variation statistics follow the definition below. If the LLJS maintains continuously for ≥4 h in a day, the day is counted as a LLJS day; if the LLJS occurs intermittently for no less than 4 h in accumulation, the day is counted as a LLJS day; if the LLJS appears for 4 h but over two days, the day is counted as a jet stream (JS) day.

As it started to operate from February 26, 2005, the $profiler_{BL}$ does not have data for January and February and it produced no data in March to May as the operating room was being overhauled and related cords were not connected properly. Because the machine broke down for 10 days in May 2007, data for this time were invalid. In the time other than the spans of time above, the $profiler_{BL}$ was working normally and had reliable data. Since its official start on January 1, 2006, the $profiler_T$ was in generally normal condition except in March and June to October 2007 when the data was invalid due to break-down of hardware caused by power stoppage. As the two profilers were less than 100 m from each other, the wind field data determined by them can be considered consistent. Next, the data, 26 groups in all, from the two profilers in the four years are compared and analyzed by the month for the statistics of LLJSs (Fig. 1). The correlation coefficient for the two sets of data was found to be 0.966, which shows that they are consistent in recognizing the LLJS. Because of it, this work takes the maximum as the data included in the statistics if the two sets of data are inconsistent, efficiently making up for the loss by one of the profilers in some months.

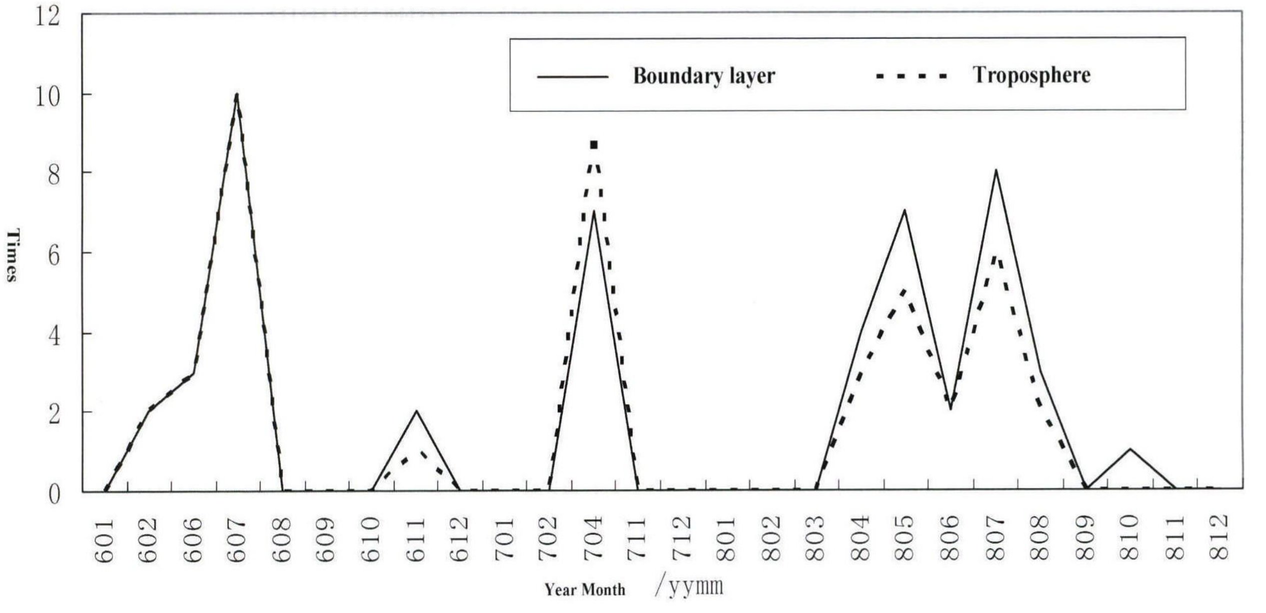

Figure 1. Comparisons of the statistics of the two profilers. The abscissa indicates the year and month (e.g. 601 means January 2006) and the ordinate indicates the total occurrences of the LLJS in a month.

Figure 2 gives the statistical result of monthly LLJSs variation with the two profilers. Their composite data can well detect the LLJSs in 2005—2008 except for January and February in 2005. It is known from the statistics that the LLJS always happened in April—July of these years while there were no LLJSs at all in January, September and December. For the other months, the LLJS happened irregularly. It is known from the curve of the mean results of these years that April and July are the two months with the most

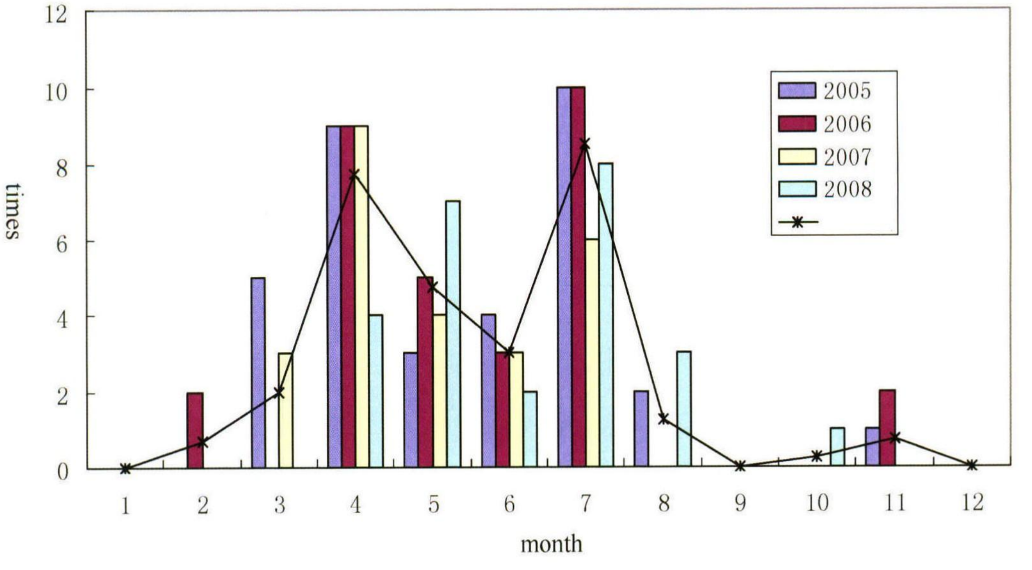

Figure 2. Monthly variations of the LLJS by the profilers in 2005 to 2008. The curve with the asterisk is for the mean.

occurrences of LLJSs, about 8 times per year, followed by March, May, June and August, 2 to 5 times per year. February, October and November are the months with the least occurrences of LLJSs, less than 2 times per month. It is apparent that the JJJS is active April—July but not active in September—December and January—February, showing significant seasonality. The LLJS has much higher frequency in spring and summer than in autumn and winter.

3.2 *Diurnal variation*

When running the statistical study of diurnal LLJS variation, as the velocity of the LLJS core and the height at which the LLJS begins to transport its momentum downward are two indicators of the intensity, the time at which the height of maximum velocity is lower (lowest) is taken as that of the maximum core velocity if it is the same for two or more moments of time. For the two profilers in question, statistical study is carried out addressing both the probability of occurrence of the LLJS and that of the maximum LLJS core velocity (Fig.3). It is shown that the LLJS can appear at any time of the day. More exactly, the LLJS has two peaks, at 06:00 and 21:00 (Beijing Time, same below), and a valley, at 15:00, according to the profiler$_{BL}$ statistics, and it reaches the highest point at 21:00—24:00 and gets to the bottom at 16:00 according to the profiler$_{T}$ statistics. It is thus known from the statistics of the two profilers that the LLJS shows significant diurnal variation, most vigorously in early morning and during the night, and is relatively inactive in the time from midday to the evening.

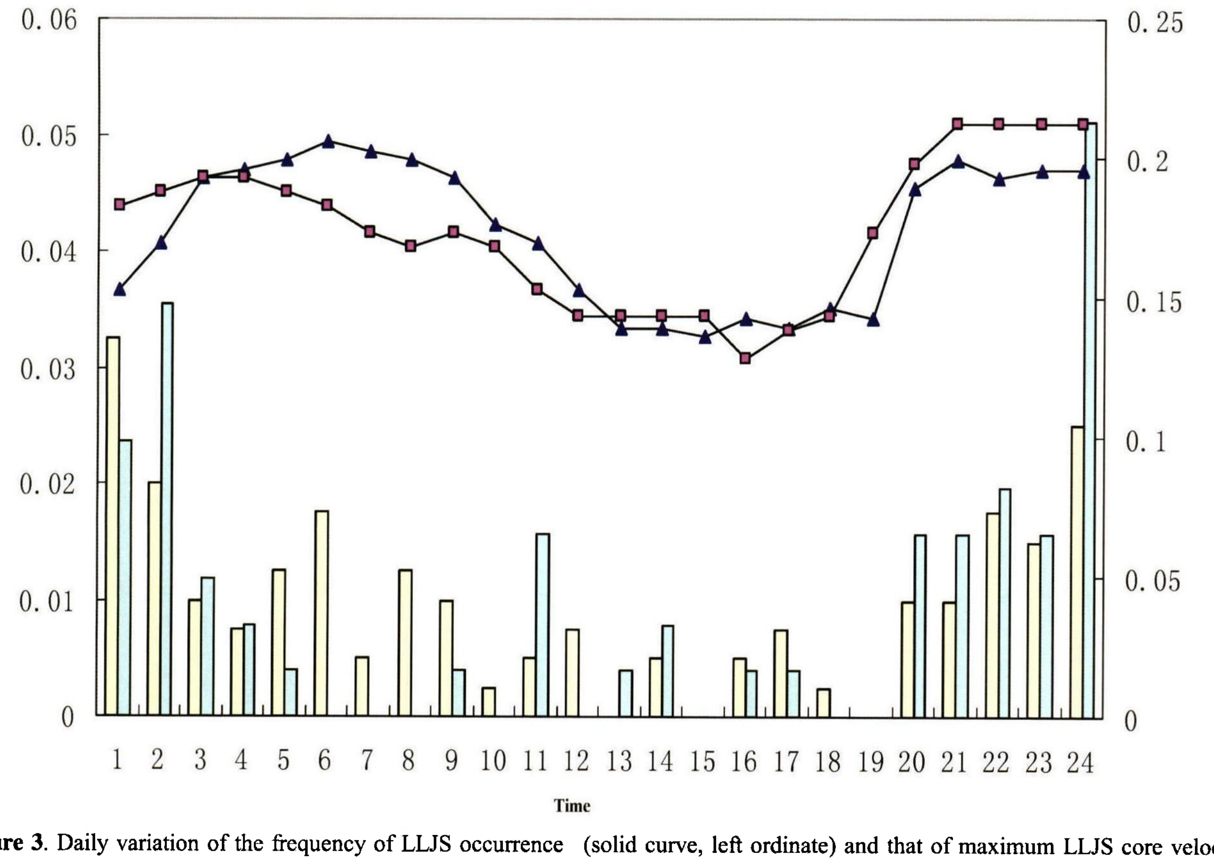

Figure 3. Daily variation of the frequency of LLJS occurrence (solid curve, left ordinate) and that of maximum LLJS core velocity (column, right ordinate) as measured by the profiler$_{BL}$ (triangle) and the profiler$_{T}$ (square).

It is shown by the yellow column that the maximum of LLJS core velocity has the largest probability of occurrence at 01:00 but is zero at 13:00, 15:00 and 19:00. It is known from the blue column that the maximum is more concentrated, at 01:00, but drops to zero at 06:00—08:00, 10:00, 12:00, 15:00, 18:00 and 19:00. It is then concluded from the statistics of the two profilers that the maximum of LLJS core velocity also has significant diurnal variation: the probability for it to appear is much larger 20:00—02:00 than at other time of the day, and 24:00 and 01:00—02:00 are the two periods of time when the maximum is most seen, which is generally consistent with Chen et al.[2].

Analyzing the correlation between the two sets of statistics (about the probability of LLJS and its maximum core velocity), we found that the coefficient is 0.779 and 0.706 respectively, suggesting that they are significantly correlated and vary consistently with time. As compared with their monthly statistics, the correlation is much smaller, mainly due to the fact that the monthly statistics is the result from comparing data for the same moment of time while the comparison here covers all data from the two profilers. No data was recorded in March, April and May of 2006 for Profiler$_{BL}$ but in March and June—October of 2007 for Profiler$_T$, causing inconsistent data size for the two profilers. Besides, the diurnal variation of the LLJS is subject to multiple factors such as the occurrence time of the inversion layer and whether or not it is raining. The two profilers are then affected by missing data for different months and resultant statistics give inconsistent timing of peaks and valleys of the LLJS occurrence. Despite it, generally consistent diurnal tendencies of the LLJS can be still identified.

3.3 *LLJS core*

The characteristics of the LLJS core include the velocity and the altitude at which it appears. As the two profilers have inconsistent resolution, differences may occur in these characteristics even for the same process of a LLJS. It is necessary to compare the velocity to choose a larger value as the statistical result; when the velocity is the same but the altitude is not, the value for the lower altitude will be included in the statistics. In this work, monthly variations of these characteristics for 2005—2008 are statistically summarized (Fig.4). It is known from Fig.4 that the LLJS core velocity varies between 14 and 34 m/s with the average at 20.48 m/s, about 82% of the core velocity is less than 25 m/s and more than half the velocity varies between 20 and 25 m/s, and only two values of the velocity are more than 30 m/s, taking up only about 1.7% of the total. Fig.4 also shows the altitude where the LLJS is active is between 100 and 1 800 m, with most below the 1 400 m (approximately equivalent of the altitude of 850 hPa) while just 16.2% above it, and moreover, the core appears more frequently below 700 m (about the altitude of 925 hPa) than between 700 and 1 400 m, taking up about 51.3% of the total.

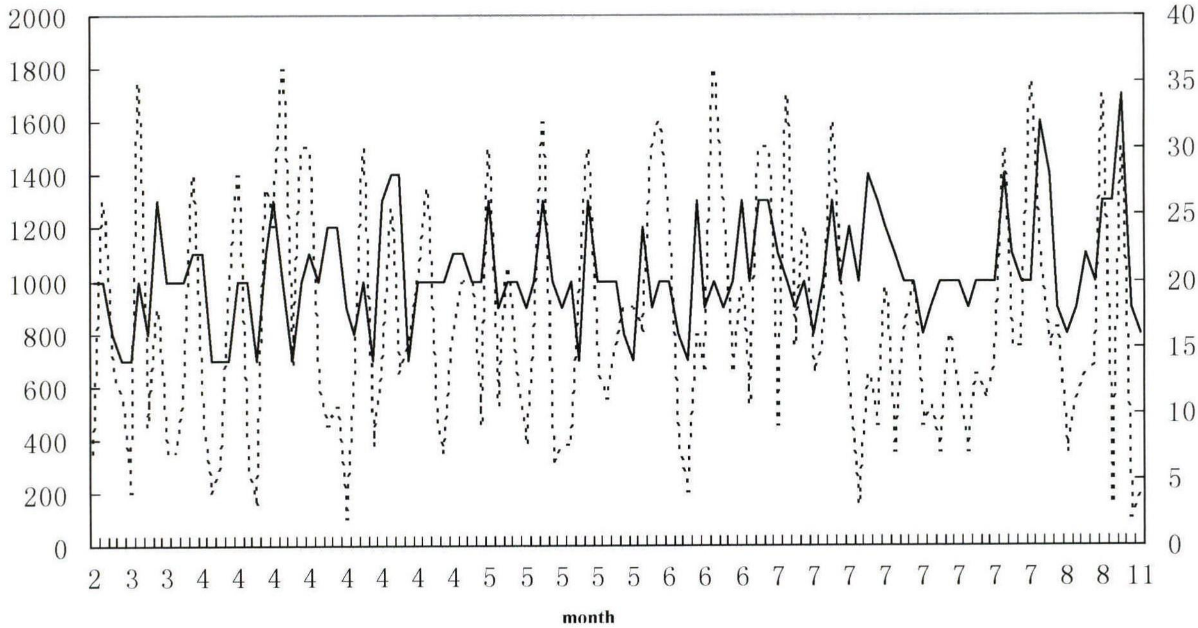

Figure 4. Monthly variation of the LLJS core velocity (solid curve, for the right ordinate) and its altitude (dashed curve, for the left ordinate) in 2005-2008. The solid curve indicates the LLJS core velocity and dashed curve indicates the altitude of the LLJS core.

3.4 *LLJS and precipitation*

A total of 116 LLJS days were detected using the two profilers in 2005—2008 and they were used as statistical samples. The data of precipitation was from an observation station closest to both the profilers, about 2 km away. The sample of LLJS for the four years was classified according to whether it rains or not (Fig.5). It is known from Fig.5 that the LLJS is mainly seen in March to August, taking up 95.7% of the total, and April and July are the months with the most frequent LLJS, amounting to 56.9% of the total. It is known from the case with precipitation (blue column) that April has relatively low probability of having both the LLJS with precipitation, only 9.4%, but July has much greater probability of having both of them, as much as 73.5%. It is then clear that the LLJS is closely related to precipitation in summer but it is not necessarily associated with precipitation in other months.

With further analysis, we discovered that there are 51 LLJS days in April and May and 43 days without precipitation (red column), 84.3%. The LLJS takes place in 38 of these rain-free days and only confines to two periods of time: 00:00 to 10:00 and 19:00 to 24:00. Having compared the temperature profiles, we found that there is temperature inversion on these days and corresponding in time to the occurrence of the LLJS. It is clear that the LLJS on rain-free days may be related to the inversion.

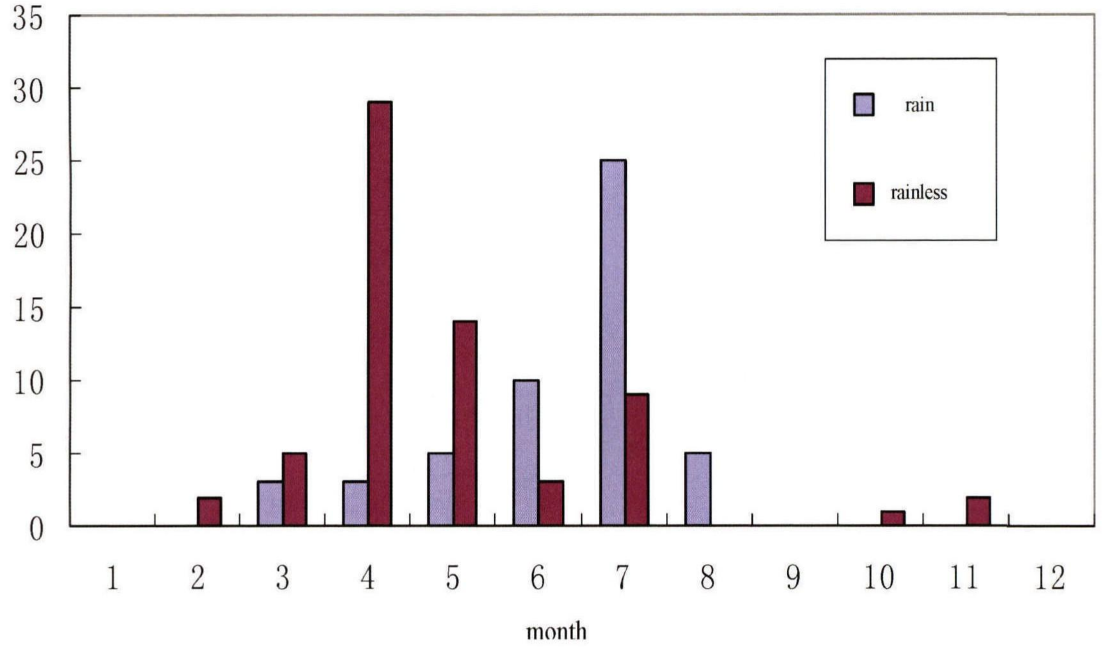

Figure 5. Comparisons of the LLJS for 2005-2008 classified by whether or not there is rain. The blue column indicates the LLJSs occurring with precipitation and the red column indicates those without precipitation. The ordinate is for the times of occurrence.

Next is the result of a comparison between the days of torrential rain in June to August and the LLJS. For the 24 hard rain days, there are 21 LLJSs, taking up 88% of the total rain processes. It is then clear that the occurrence of the summertime LLJS is well correlated with torrential rain. Besides, by looking into the statistics presented in Section 3.3, we also found that the velocity of the LLJS core velocity is 21.52 m/s on average for a rain day but drops to 19.89 m/s for a rainless day, suggesting that an increased LLJS core velocity is favorable for the generation of precipitation.

4 CONCLUSIONS

In this work, wind field data from two profilers in Nanjing from 2005 to 2008 are used to study the characteristics of the LLJSs statistically in terms of the monthly and diurnal variation as well as whether or not it rains.

(1) The LLJS is highly seasonal, which takes place much more frequently in spring and summer than in au tumn and winter.

(2) In spring, the occurrence of the LLJS is closely related with the existence of inversion; it develops vigorously at night but weakens or even disappears during daytime.

(3) The appearance of the upper-level jet stream in summer is closely related with precipitation, especially torrential rain.

(4) As shown in our study, the LLJS core velocity is mainly less than 25 m/s and at altitudes less than 1 400 m. Besides, its intensification is favorable for the generation of rain, which makes better basis for monitoring the LLJS.

REFERENCES:

[1] ZHU Qian-gen, LIN Jin-rui, SHOU Shao-wen, et al. The Principles and Methods of Synoptics [M]. Beijing: China Meteorological Press, 1992: 193 (in Chinese).

[2] CHEN Zhong-ming, HE Guang-bi, CUI Chun-guang, et al. The coupling reaction among convective cloud cluster and moisture frontal zone and low level jet [J]. J Trop Meteorol, 2007, 23(3): 246-254 (in Chinese).

[3] YAN Shu-lian, ZHOU Shu-ling, LI Hong-jiang. Diagnostic analysis of rainstorm in Shangdong Peninsula influenced by a far-away tropical depression [J]. J Trop Meteorol, 2008, 14(1): 73-76.

[4] HOU Jian-zhong, LI Ming-juan, ZHAO Bing-ke, et al. Analysis of the circulation evolution and water vapor transport of a rare torrential rain in early spring, Shanxi [J]. J Trop Meteorol, 2009, 25(2): 251-256 (in Chinese).

[5] DING Zhi-ying, LIU Cai-hong, SHEN Xin-yong. Statistical analysis of the relationship among warm sector heavy rainfall, upper and lower tropospheric jet stream and south Asia high in May and June from 2005 to 2008 [J]. J Trop Meteorol, 2011, 27(3): 307-316 (in Chinese).

[6] WALTER H, HOECKER J R. Three southerly low-level jet systems delineated by the Weather Bureau special pibal network of 1961 [J]. Mon Wea Rev, 1963, 91 (10-12): 573-582.

[7] BONNER W D. Climatology of the low level jet [J]. Mon Wea Rev, 1968, 96(12): 833-850.

[8] BROWNING K A, PARDOE C W. Structure of low-level jet streams ahead of mid-latitude cold fronts [J]. Quart J Roy Meteorol Soc, 1973, 99(422): 619-638.

[9] MANABE S, HAHN D G, HOLLOWAY J L. The seasonal variation of the tropical circulation as simulated by a global model of the atmosphere [J]. J Atmos Sci, 1974, 31(1): 43-83.

[10] ZHONG S Y, FAST J D, BIAN X D. A case study of the

Great Plains Low-Level jet using wind profiler network data and a high -resolution mesoscale model [J]. Mon Wea Rev, 1996, 124(5): 785-806.

[11] JOSHI R R, NARENDRA S, DESHPANDE S M, et al. UHF wind profiler observations of monsoon low level jet over Pune [J]. Indian J Radio & Space Phys, 2006, 35: 349-359.

[12] GIAMMANCO I M, PETERSON R E. 44th AIAA Aerospace Science Meeting [C]. 2006.

[13] LIU Shu-yuan, ZHENG Yong-guang, TAO Zu-yu. The analysis of the relationship between pulse of LLJ and heavy rain using wind profiler data [J]. J Trop Meteorol, 2003, 9(2): 185-163.

[14] JIN Wei, QU Yan, YAO Xiu-ping, et al. Mesoscale structure and evolution of low-level jet and its relationship with the heavy rainfall during a torrential rain process [J]. Meteorol Mon, 2007, 33(12): 31-38 (in Chinese).

[15] ZHANG Jing-ying, QI Liang-bo, WANG Qing-hua. Analysis of relationship between heavy rain and jet stream with radar VWP product [J]. Meteorol Mon, 2005, 31(12): 41-44 (in Chinese).

[16] DING Yi-hui. Advanced Synoptics [M]. Beijing: China Meteorological Press, 1991: 443-452 (in Chinese).

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