Study on the Characteristics of Low-level Jets in Short-term Heavy Rainfall under the Influence of Northeast Cold Vortex in Shenyang Based on Wind Profile Radar

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Abstract: To enhance the understanding of the mechanisms behind heavy rainstorms influenced by the northeast cold vortex in Shenyang, we analyzed the intensity, height, and index of low-level jets during short-term heavy rainfall events from May to September between 2017 and 2021. The findings are as follows: (1) The maximum wind speed below 2 km generally follows a normal distribution, with low-level jets already present prior to approximately 30% of the heavy rainfall events. The maximum wind speed at corresponding percentiles shows a slight increase as the rainstorm approaches. However, the frequency of low-level jets decreases, and wind speeds significantly drop during the rainstorm. (2) The height distribution of low-level jets increases with altitude, reaching its lowest point 2 to 3 hours before the onset of heavy rainfall. At this time, low-level jets exhibit their strongest and most vigorous development. Combined with the warm, moist air from the southwest providing moisture and thermal energy, these conditions can trigger the onset of heavy rainstorms. (3) The hourly distribution of the low-level jet index (I) remains relatively consistent leading up to a rainstorm. As the rainstorm nears, wind speeds decrease, and the minimum height of low-level jets rises, resulting in a decrease in the low-level jet index (I).

Keywords: Northeast Cold Vortex; Wind Profile Radar; Short-term Heavy Rainfall; Threshold Selection; Low-level Jet

1. Introduction

The Northeast Cold Vortex is a significant weather system responsible for causing low-temperature damage, prolonged rainfall and flooding, hail, and severe convective weather such as thunderstorms and strong winds in Northeast China. It greatly influences the region's weather and climate. Research indicates that during the summer, the cold vortex accounts for 30% of short-term heavy rainfall events in Liaoning Province, with peak precipitation intensities reaching 105 mm•h^{-1}, which can easily trigger natural disasters[1-4]. The relationship between the Northeast Cold Vortex and short-term heavy rainfall is strong, with prolonged durations of the cold vortex leading to more frequent short-term heavy rainfall events. To understand the causes of these phenomena, meteorologists have conducted extensive research. With advancements in observational data and deeper research insights, the focus of studies on heavy rain in Northeast China has shifted from large-scale environmental field analysis to detailed examinations of mesoscale and microscale systems. Research increasingly shows that heavy rainfall results from the interaction of multiscale weather systems, with the development and evolution of mesoscale systems having significant impacts within favorable large-scale circulation patterns. Notably, the relationship between low-level jets, vertical wind shear, and heavy rainfall is particularly significant[5-7].

Currently, the high-altitude observational data obtained through conventional methods have relatively low spatial and temporal resolution. High-altitude wind field observations are limited to twice-daily measurements from radiosonde stations, resulting in limited early research on mesoscale systems during heavy rain events. In recent years, the gradual application of new detection data has made it possible to obtain high-resolution high-altitude observational data, facilitating more in-depth research on mesoscale systems in heavy rain events. Wind profiler radar is an excellent instrument for detecting high-altitude wind fields. It offers continuous, unattended, all-weather atmospheric wind field monitoring. Unlike balloon-based wind measurements, wind profilers can provide continuous detection with time intervals of 5-6 minutes and spatial resolutions of tens of meters, ensuring high precision and operational reliability. Its high spatial and temporal resolution makes it particularly advantageous for detecting mesoscale systems, thus enabling research on the relationship between mesoscale wind field structures, their changes, and heavy rainfall[8-11].

However, previous studies have predominantly focused on the analysis of individual events, lacking comprehensive analysis of the mesoscale system characteristics of widespread heavy rainfall. Particularly, there has been insufficient research on the changes in low-altitude wind field characteristics near the onset of heavy rainfall, with few case studies and limited statistical significance. This paper utilizes wind profiler radar data to analyze the changes in low-altitude wind field characteristics near the occurrence of short-term heavy rainfall in the Shenyang area, aiming to enhance the understanding of the mechanisms behind heavy rainfall formation in Shenyang and improve the accuracy of heavy rainfall forecasting and warnings in the region.

2. Data and Methods

Short-term heavy rainfall cases at the Shenyang Meteorological Observatory were analyzed, utilizing wind profiler radar data from May to September between 2017 and 2021. A case was defined as a short-term heavy rainfall event when the hourly precipitation was equal to or greater than 20 mm per hour at the Shenyang Meteorological Observatory. The data used in this study were obtained from the wind profiler radar located at the Shenyang Meteorological Observatory (123.31°E, 41.44°N), which has a temporal resolution of 6 min and a spatial resolution of 120 m. Precipitation data were sourced from the hourly records at the Hunhe National Observation Station, where the wind profiler radar is situated.

Following the case selection criteria, 11 short-term heavy rainfall cases (hereinafter referred to as “rainstorms”) occurring at the wind profiler radar site were identified. To better understand the mechanisms of short-term heavy rainfall formation, the study focused on analyzing the characteristics of low-level jet wind speed, height, and low-level jet index in the three hours preceding the rainstorm. To minimize the impact of precipitation on data quality, cases with no precipitation or very light precipitation (hourly precipitation less than or equal to 10 mm) in the three hours before the rainstorm were selected. Due to data limitations, 6 out of the 11 cases were chosen for detailed analysis.

3. Results Analysis

3.1 Analysis of Low-Level Jet Wind Speed Characteristics

To better analyze the evolution characteristics of the low-level jet before the occurrence of rainstorms, this study defined strong southwest, south, and southeast winds exceeding 12 m/s below 2 km in altitude as low-level jets, focusing on these for detailed research. The maximum wind speed was categorized into intensity intervals with a 1 m/s increment, and the wind speed variations within different intensity intervals were studied. From Figures. 1a to 1d, it can be observed that the maximum wind speeds in the lower layers generally follow a normal distribution, with the highest percentage of wind speeds ranging between 6 to 18 m/s, accounting for over 65% of the total, while the proportions at both ends gradually decrease as wind speed increases or decreases.

The horizontal axis in a-d represents wind speed in m/s, and the vertical axis represents the percentage. The solid line is the fitted curve.

- (a). 3 hours before the rainstorm
- (b). 2 hours before the rainstorm
- (c). 1 hour before the rainstorm
- (d). At the time of the rainstorm
- (e). Box plot of hourly wind speeds (vertical axis unit: m/s)

The distribution of wind speeds also indicates a correlation between the occurrence of rainstorms and the presence of low-level jets. The proportions of low-level jets appearing 3 hours, 2 hours, and 1 hour before, and at the time of the rainstorm, are 34.9%, 31.7%,29.1%, and 23.4% respectively. Figure 1 shows that approximately 30% of low-level jets were already present 3 hours before the rainstorm, with the highest proportion occurring at this time. As the rainstorm approached, the proportion of low-level jets gradually decreased, further weakening at the time of the rainstorm.

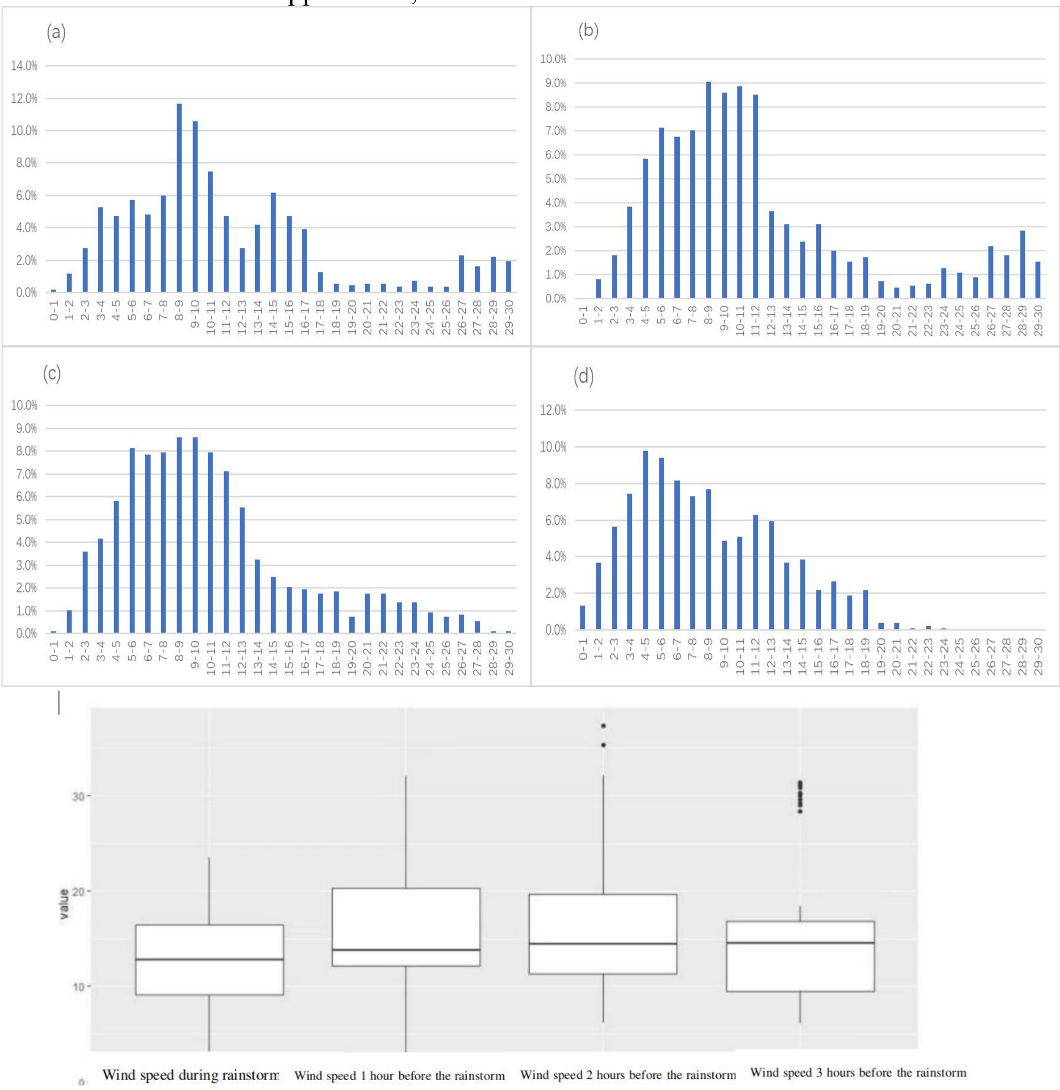

Figure 1. Percentage Distribution of Maximum wind Speeds below 2 km.

The proportions of wind speeds exceeding 20 m/s 3 hours, 2 hours, and 1 hour before, and at the time of the rainstorm, were 11%, 13.4%, 9.5%, and 0.8% respectively. Thus, the highest proportion and wind speeds of low-level jets were observed 3 and 2 hours before the rainstorm, gradually decreasing as the precipitation approached.

Figure 1e presents the box plot of maximum wind speeds below 2 km for each hour as the rainstorm approaches. There is a slight increasing trend in the maximum wind speeds at the same percentile as the rainstorm approaches but a rapid decrease after the rainstorm occurs, indicating some predictive significance for short-term heavy rainfall. The 75% of maximum wind speeds 3 hours, 2 hours, and 1 hour before the rainstorm reached 9.4 m/s, 11.3 m/s, and 12.1 m/s respectively. Based on previous research, the median (50th percentile) of maximum wind speed distribution is considered the threshold before the rainstorm, with values of 14.5 m/s, 14.4 m/s, and 13.8 m/s for 3 hours, 2 hours, and 1 hour before the rainstorm respectively. About 50% of rainstorm events were preceded by the presence of a low-level jet with wind speeds around 14 m/s, which similarly showed a weakening trend after the onset of precipitation.

3.2 Analysis of Low-Level Jet Altitude Characteristics

The lowest height at which wind speeds exceed 12 m/s is considered the minimum altitude reached by the jet. Figure 2 depicts the percentage distribution of the minimum altitude reached by the low-level jet as the rainstorm approaches (with a height interval of 100 m) and a box plot, analyzing the altitude variation characteristics of the low-level jet within different height intervals. The figure shows that the distribution height of the low-level jet increases with altitude, with approximately 60% distributed below 1.5 km. The proportions of ultra-low-level jets appearing 3 hours, 2 hours, and 1 hour before, and at the time of the rainstorm, are 27.5%, 25.5%, 21.1%, and 26.7% respectively, indicating a certain significance for rainstorm forecasting.

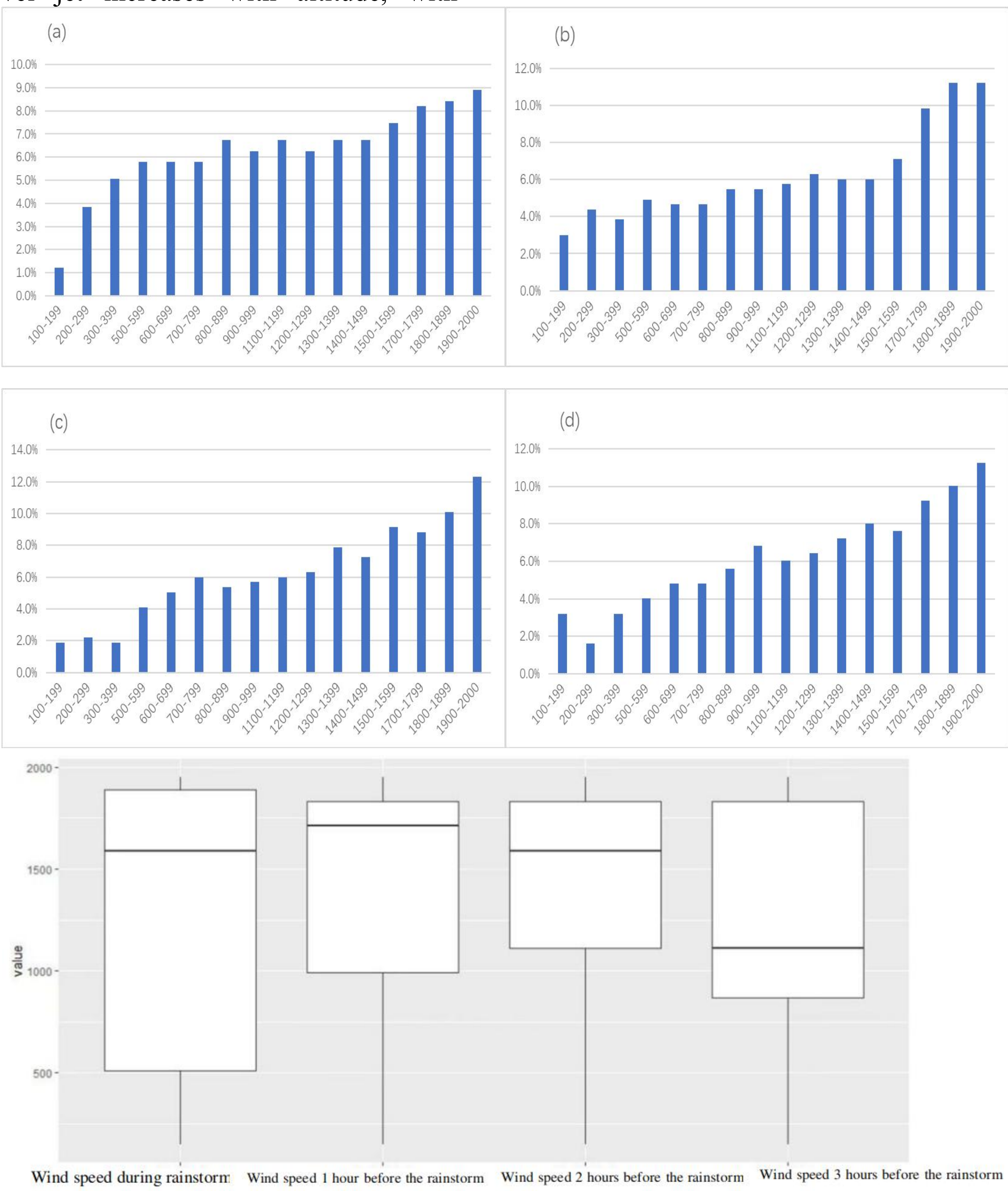

Figure 2. Percentage distribution of minimum altitudes of low-level jets.

The horizontal axis in a-d represents altitude in km, and the vertical axis represents the percentage. The solid line is the fitted curve.

- (a). 3 hours before the rainstorm
- (b). 2 hours before the rainstorm
- (c). 1 hour before the rainstorm
- (d). At the time of the rainstorm
- (e). Box plot of hourly altitudes (vertical axis unit: km)

Three hours before the rainstorm, except for the maximum and minimum values, the altitude at the same percentile tends to rise as the rainstorm approaches, with a slight decrease after the onset of heavy precipitation. The minimum altitudes are reached 3 and 2 hours before the rainstorm, combining with the wind speed characteristics of the low-level jet, indicating that the low-level jet reaches its lowest and strongest levels 3 and 2 hours before the rainstorm, with the most vigorous development. This, combined with the warm and humid airflows from the southwest providing moisture and thermal conditions, can trigger the occurrence of rainstorms.

Selecting the 50th percentile of the minimum altitude distribution as the threshold, the thresholds for 3 hours, 2 hours, and 1 hour before the rainstorm are 0.4 km, 0.6 km, and 0.9 km respectively.

3.3 Analysis of Low-Level Jet Index Characteristics

To further investigate the relationship between rainstorm intensity and low-level jets, the low-level circulation index I (where I=V/D) is introduced. Here, V represents the maximum wind speed at the low-level jet center below 2 km, and D denotes the minimum altitude at which wind speeds reach 12 m/s during that time.

Figures 3a to 3d illustrate the distribution of the low-level jet index I in different intensity intervals, with an interval of 2*10-3s-1. The hourly distribution characteristics of the low-level jet index I remain relatively consistent as the rainstorm approaches, primarily concentrated in the range of 0~12*10-3 s-1, accounting for over 80%.

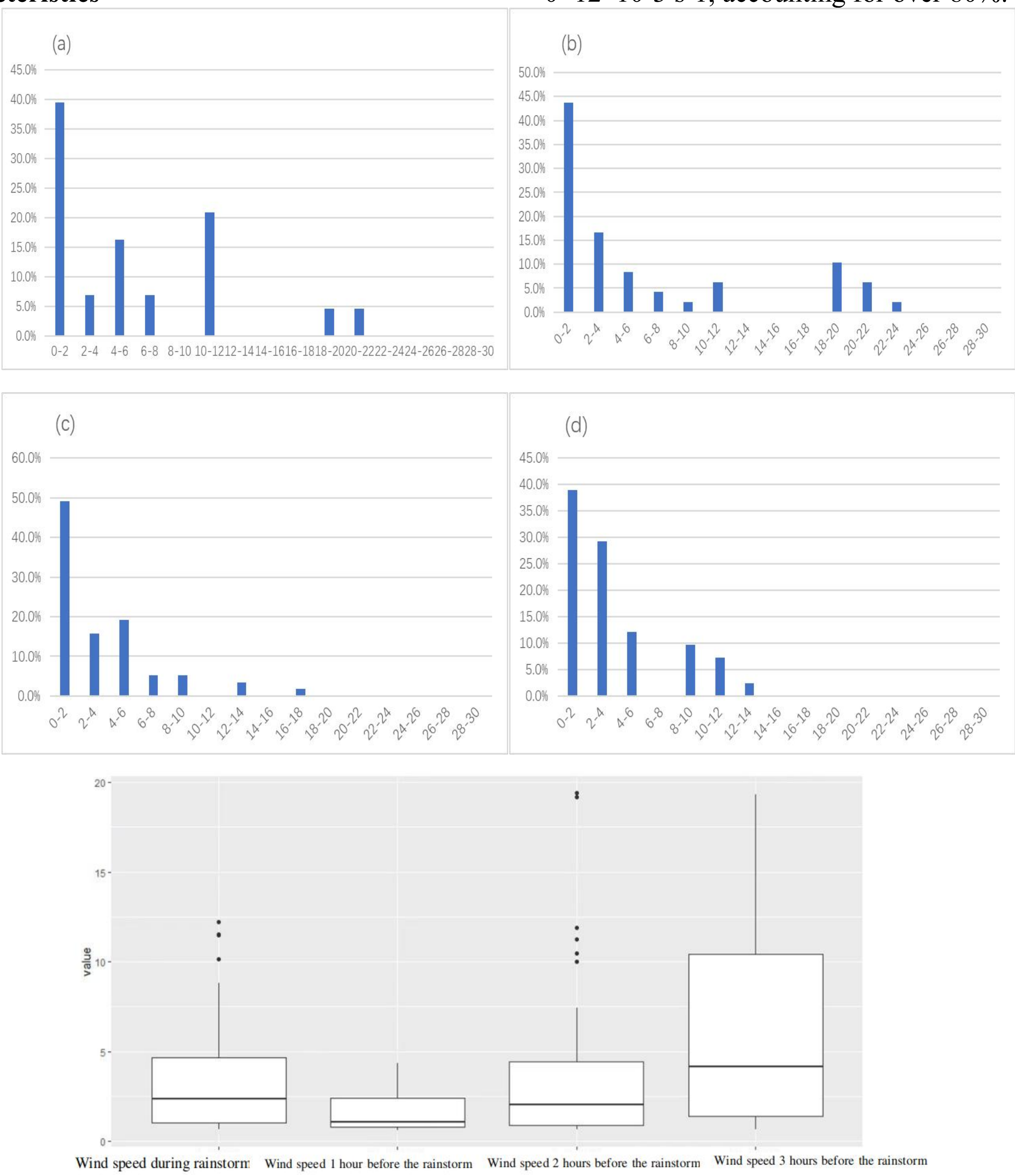

Figure 3. Percentage Distribution of Low-Level Jet Index I.

The horizontal axis in a-d represents wind speed in 10-3 s-1, and the vertical axis represents the percentage. The solid line is the fitted curve.

(a). 3 hours before the rainstorm
- (b). 2 hours before the rainstorm
- (c). 1 hour before the rainstorm
- (d). At the time of the rainstorm
- (e). Box plot of hourly indices (vertical axis unit: 10-3 s-1)

Figure 3e presents the box plot of hourly I values. It is observed that the values of the low-level jet index at the same percentile are almost consistent 3 and 2 hours before the rainstorm, with the 50th percentile values being 4.1*10-3 s-1 and 3.1*10-3 s-1, respectively. As the rainstorm approaches, the I value shows a decreasing trend, with the 50th percentile value dropping to 2.3 2.3*10-3 s-1. Combining the analyses from sections 2.1 and 2.2, it is evident that the decrease in low-level jet wind speed and the increase in minimum altitude as the rainstorm approaches lead to the reduction in the low-level jet index I.

4. Conclusion and Discussion

This study selected short-duration rainstorm events recorded by the Shenyang wind profiler radar at the Shenyang Observatory from May to September between 2017 and 2021. By analyzing the wind profiler radar data, we examined the intensity, altitude, and index of low-level jets three hours before and during the onset of rainstorms, yielding the following conclusions:

(1) The maximum wind speed below 2 km generally follows a normal distribution, with wind speeds between 6 and 18 m/s accounting for the highest percentage, over 65% of the total. Approximately 30% of low-level jets are present before the rainstorm, with the highest occurrence three hours prior. Both the proportion and wind speed of low-level jets peak three and two hours before the rainstorm, then gradually decline as the rainstorm approaches, with a further weakening and a sharp decrease in high wind speeds at the time of the rainstorm.

(2) There is a correlation between the occurrence of rainstorms and the presence of low-level jets. The maximum wind speed at the same percentile shows a slight increasing trend as the rainstorm approaches, but rapidly decreases after the rainstorm begins, indicating its significance for short-term rainstorm forecasting. The 75th percentile maximum wind speeds three hours, two hours, and one hour before the rainstorm reach 9.4 m/s, 11.3 m/s, and 12.1 m/s, respectively.

(3)The distribution height ratio of low-level jets increases with altitude, with approximately 60% distributed below 1.5 km. Ultra-low-level jets appear 27.5%, 25.5%, 21.1%, and 26.7% of the time three hours, two hours, one hour before, and during the rainstorm, respectively, providing indicative significance for rainstorm forecasting. The lowest altitudes are reached three and two hours before the rainstorm. Considering the wind speed characteristics of low-level jets, the jets are at their lowest, strongest, and most vigorous three and two hours before the rainstorm. Coupled with the warm and moist airflow from the southwest providing moisture and thermal conditions, this can trigger rainstorm occurrences.

(4) The hourly distribution characteristics of the low-level jet index I remain consistent as the rainstorm approaches, primarily concentrated in the range of 0 - 12*10-3 s-1, accounting for over 80%. The reduction in low-level jet wind speed and increase in minimum altitude as the rainstorm approaches lead to a decrease in the low-level jet index I.

(5) Using the median values of various physical quantities before the rainstorm as thresholds, the maximum wind speed thresholds three hours, two hours, and one hour before the rainstorm are 14.5 m/s, 14.4 m/s, and 13.8 m/s, respectively. The minimum altitude thresholds are 0.4 km, 0.6 km, and 0.9 km, respectively.

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