On the Nationwide Variability of Low-Level Jets Prior to Warm-season Nocturnal Rainfall in China Revealed by Radar Wind Profilers

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Abstract

Nocturnal rainfall initiation is closely linked to low-level jets (LLJs), but national-scale LLJ features over China—especially their evolution preceding warm-seasonal nocturnal rainfall—remain unknown due to scarce high-resolution vertical wind observations. Here, we reveal the fine vertical structure of LLJs and their rapid evolution within 2 hours preceding the onset of nocturnal heavy rain (HR) and non-HR across four phases of rainy seasons in China during the warm season (April–October) of 2023–2024, utilizing data from a nationwide network of radar wind profilers (RWPs) in combination with surface observations and reanalysis data. Results show that nocturnal rainfall accounted for over 50% of warm-season rainfall, with 56% preceded by LLJs within 2 hours leading up to their onset. In monsoon regions, approximately 45% of nocturnal HR were LLJ-associated (LLJ_HR) and produced heavier rainfall than non-LLJ_HR events. Critically, LLJ_HR events underwent a minute-scale 'rapid reorganization' of LLJs structure, characterized by oscillatory evolution in jet height, frequency and strength. This creates favorable environment for the 'final-stage intensification' of dynamic field during the last ~30 min, where the widespread intensification of jet—coupled with significant thermodynamic instability—serves as a decisive triggering mechanism for HR. In stark contrast, LLJ_non-HR events exhibit quasi-steady or weakening dynamical trends, accompanied by an inadequate thermodynamic response that lacks such synergistic coupling. These findings demonstrate that minute-scale dynamic adjustments driven by swift evolution of the LLJ is essential for nocturnal HR, thereby providing observational constraints for regional model parameterizations and nowcasting accuracy.

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Short Summary

Nighttime rainfall often links to low-level jets (LLJs), but we lack clarity on nationwide LLJ features. We here used a nationwide radar wind profiler network to study LLJ changes 2 hours before rainfall, covering China's 2023–2024 rainy seasons. 56% nighttime rainfall had LLJs. The LLJs-associated heavy rain needed a rapid adjustment of LLJs' vertical structure, especially a significant intensification within 30 minutes preceding rain. This shows the importance of LLJ in nowcasting rainfall.

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1. Introduction

Forecasting nocturnal heavy rainfall (HR) and associated severe convective weather remains a major challenge in hazardous weather prediction (Davis et al., 2003; Trier et al., 2006), owing to the complexity of triggering mechanisms, the scarcity of continuous high-resolution observations, and inaccuracies in model parameterizations (Carbone and Tuttle, 2008; Reif and Bluestein, 2017; Weckwerth et al., 2019; Zhao et al., 2025). Crucially, the low-level jet (LLJ) that exhibit a diurnal cycle with a maximum at night is widely recognized as a key contributor to nocturnal HR (Bonner 1968; Mitchell et al., 1995; Tuttle and Davis, 2006), as documented in regions or countries such as the Great Plains of the United States (Maddox, 1983; Higgins et al., 1997), Argentina (Marengo et al., 2004), India (Monaghan et al., 2010), North China Plain (Li et al., 2024).

The LLJs primarily originate from the inertial oscillations (IO) following the sudden decay of turbulence after sunset (Blackadar, 1957) and thermal imbalances induced baroclinicity over sloping terrain (Holton, 1967). Functioning as concentrated corridors for heat, moisture, and momentum transport, LLJs can modulate the diurnal oscillation in water vapor by IO (Rasmusson, 1967; Zhang et al., 2019) and enhance convective instability, particularly when elevated high-θ_e air encounters frontal boundaries (Trier et al., 2017). Also, strong low-level vertical wind shear (VWS) associated with LLJs necessarily benefits deep lifting (Maddox et al., 1979; Stensrud, 1996; Rasmussen and Houze, 2016). These mechanisms collectively provide essential thermodynamic and dynamic support for the initiation and organization of nocturnal convection, especially where LLJs force low-level ascent at jet termini or via positive vorticity advection left of the jet axis (Chen et al., 2017; Du and Chen, 2019; Xia and Zhao, 2009).

Furthermore, LLJs interact synergistically with other key factors to trigger HR that is associated with mesoscale convective systems (Chen et al. 2010; Chen et al., 2017; Chen et al., 2024), including terrain effects (Anthes et al., 1982; Pan and Chen, 2019; Huang et al., 2020), gravity waves (Weckwerth & Wakimoto, 1992), among others.

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These interactions are highly sensitive to the prevailing synoptic and subsynoptic-scale environmental conditions (e.g., Hodges and Pu, 2019) and fine-scale structural of LLJs, including LLJ frequency, spatial redistribution, and particularly localized wind profile accelerations (Pitchford and London, 1962; Walters and Winkler, 2008; Du and Chen, 2019; Li et al., 2024). Understanding these intricate evolution features of LLJs is critical for improving the forecasting of nocturnal HR.

Despite advances facilitated by regional reanalysis (e.g., Doubler et al., 2015; Li et al., 2021), numerical modeling (e.g., Zhang and Meng, 2019), radiosonde observations (e.g., Whiteman et al., 1997; Yan et al., 2020), and emerging artificial intelligence techniques (e.g., Subrahmanyam et al., 2024) in understanding the climatology and physical mechanisms of LLJs and their role in HR forecasting, significant knowledge gaps remain. A critical shortcoming lies in the inability to capture minute-scale evolution of LLJs during the nocturnal pre-storm period. Conventional observing systems lack the spatiotemporal resolution required to resolve rapid changes in pre-storm environments (Weisman et al., 2015; Cao et at., 2025; Roots et al., 2025), thereby hindering systematic analysis of fine-scale structure of LLJs and their evolution within the critical 2-hour window preceding rainfall.

Moreover, the mechanisms and impacts of LLJs exhibit considerable variation across monsoon phases and geographic regions. As a classic monsoon climate region, China exhibits particularly prominent nocturnal rainfall contributions across major climate-sensitive areas (Yu et al., 2014), where LLJs play a crucial role in modulating primary rainfall belts (Sun, 1986; Chen et al., 2010; Wang et al., 2013; Horinouchi et al., 2019), such as those in Eastern China (Chen et al., 2017; Xue et al., 2018) and South China (Du et al., 2020; Bai et al., 2021; Fu et al., 2021). However, nationwide comparative studies examining LLJ precursor signals across different monsoon phases in China are still lacking.

Radar wind profilers (RWPs) can offer transformative potential by capturing minute-resolution wind profiles to reveal pre-rainfall dynamic precursors (Zamora et al., 1987; Du et al., 2012; Molod et al., 2019; Guo et al., 2023). For example, Gebauer

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et al. (2018) demonstrated the capability of RWPs to elucidate how heterogeneous structures of LLJ trigger nocturnal convection in Great Plains; Based on a linear net of RWPs deployed across the North China Plain, our previous study (Li et al., 2024) observed rapid intensification of moisture flux convergence (MFC) driven by a surge in LLJs profile within 30 min preceding nocturnal rainfall onset, highlighting the sensitivity of RWP to minute-scale perturbations of LLJs profiles. However, it remains an open question whether this minute-scale precursor is universally applicable across diverse monsoon phases throughout mainland China. Furthermore, the systematic differences in the fine-scale LLJ evolution that distinguish HR from non-HR have yet to be fully elucidated.

Therefore, this study utilizes a nationwide network of RWPs to address the following two questions: 1) How do the vertical structure of LLJs and their minute-scale evolution within 0–2 hours preceding nocturnal rainfall vary across different rainy season phases? and 2) What are the systematic differences in LLJ dynamic-thermodynamic mechanisms between LLJ-influenced HR and non-HR events? The remainder of this paper is structured as follows: Section 2 details data and methodology, Section 3 presents comparative analyses of characteristics of rainfall and LLJs evolution, and Section 4 synthesizes key conclusions.

2. Data and Methodology

2.1 Radar wind profiler measurements

The RWP observations collected from 31 stations across China (Fig.1) from April to October in 2023–2024 were analyzed in this study, which can provide wind speed and direction with a vertical resolution of 120 m and an interval of 6 minutes (Liu et al., 2019). To reduce the potential influence of poor data quality, RWP data underwent strict quality control following procedures proposed by Wei et al. (2014) and Miao et al. (2018). Firstly, to minimize contamination from precipitation particles, which can introduce significant errors in Doppler-based wind retrieval, all observations during

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rainfall periods were removed. Secondly, within each profile below 3 km above ground level (AGL), missing values and significant outliers that defined as values exceeding 2.5 standard deviations from the mean were removed. Next, for each profile, if more than 40% of the data points below 3 km AGL were outliers or missing, that entire profile was discarded. Finally, discontinuous, or missing data points were estimated using linear interpolation. Following this quality control process, 109,400 wind profiles were discarded and a total of 2,606,042 profiles across China were available for analysis during the study period.

2.2 Multi-source meteorological data

In addition, 1-min rainfall measurements were directly acquired from the rain gauge measurements at 2160 national weather stations across China to identify rainfall events. Rainfall amounts were accumulated over 6-min intervals to ensure temporal alignment with the RWP measurements. Ground-based meteorological variables are measured at 1-min intervals from national weather stations, including 2-m air temperature, relative humidity, and surface pressure. All ground-based data have undergone rigorous quality control (China Meteorological Administration, 2020; Zhao et al., 2024) and are publicly accessible at the National Meteorological Information Center of China Meteorological Administration (CMA).

Furthermore, to diagnose large-scale circulation patterns and environmental conditions preceding nocturnal rainfall influenced by LLJs, this study utilized meteorological variables derived from the fifth generation of the European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) of the global climate (Hersbach et al., 2020). The ERA5 data features a horizontal resolution of 0.25°×0.25° across 37 vertical pressure levels and hourly temporal resolution. Unless otherwise specified, all datasets cover the study period of April to October in 2023–2024.

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2.3 Identification of nocturnal rainfall events

Firstly, days with typhoon activity were excluded. To minimize the impact of rainfall on RWP measurements, a minimum dry interval of 2 hours was required between consecutive rainfall events. Following the methodology of Li et al. (2024), a rainfall occurrence was defined when the total accumulated rainfall which was measured by all rain gauges within a 25-km radius of each RWP station exceeded 0.1 mm. Accounting for rainfall intermittency, a valid rainfall event required at least two subsequent occurrences within 30 min following initial detection. Any isolated initial occurrence not meeting this criterion was discarded. Notably, this 25-km radius serves as a rigorous spatial constraint to not only mitigates the limitations of single-gauge measurements but also ensures the onset of rainfall at this scale are temporally coherent with that of the rain gauge co-located with RWP (as confirmed by sensitivity tests in Fig. S1). This guarantees direct physical coupling between local rainfall and the RWP-observed wind profiles.

Nocturnal rainfall events were defined as those occurring between 2000 and 0800 Local Standard Time (LST). Based on operational classifications from the National Water Resources Bureau and CMA, the rainy season was categorized into four consecutive phases: (1) the South China Pre-summer Rainy Season (April 1 to June 8, 2023 and April 1 to June 9, 2024), (2) the Meiyu Season (June 9 to July 14, 2023 and June 10 to July 21, 2024), (3) the North China Rainy Season (July 15 to August 31, 2023 and July 22 to August 31, 2024), and (4) the West China Autumn Rainy Season (September 1 to October 31 for both 2023 and 2024). These phases are subsequently designated as Phase 1 to Phase 4 throughout this study. Four regions of interest (ROIs) were subsequently selected for detailed analysis (see Table 1).

Further screening identified locally nocturnal HR events, where the mean 6-min rainfall intensity exceeded the 75th percentile of all recorded rainfall events at each station. This threshold can effectively distinguish significant HR from weak rainfall while ensuring a sufficient sample size for robust statistical analysis of minute-scale LLJ dynamics (Table S1). Furthermore, a sensitivity test by varying the thresholds to

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85th and 95th percentile to ensure that the main conclusion regarding the precursory signals of LLJs is robust within a reasonable threshold range (see Figs. S2–S5),.

Statistical analysis revealed 3,155 nocturnal rainfall events during the 2023–2024 warm seasons (within the 31 red circles shown in Fig.1). Event counts per rainy season phase were 1,109, 689, 652, and 705 respectively, with 841 events classified as nocturnal HR events.

2.4 Identification of LLJs and associated rainfall event

To ensure identified LLJs exhibit significant vertical wind shear characteristic of jet-like profiles, the following criteria are adopted: (1) a maximum horizontal wind speed exceeding 10 m s^{-1} in the lowest 3 km AGL, and (2) a wind speed reduction of at least 3 m s^{-1} from the maximum to minimum below 3 km AGL, or to 3 km AGL if no minimum exists. These deliberately conservative wind speed thresholds maximize LLJ sample size for enhanced statistical robustness. This definition standard has been widely adopted in previous studies (Bonner, 1968; Whiteman et al., 1997; Du et al., 2014; Yan et al., 2020). The strength of LLJ or jet nose is defined as the maximum wind speed along the entire profile. The LLJ core height is defined as the altitude of the wind speed maximum during LLJ occurrences. Correspondingly, the LLJ direction is determined by the wind direction at the height of the LLJ.

We define rainfall events where LLJ occurs at least twice within 2 hours before rainfall as an LLJ event (Li et al., 2024). The HR events influenced by LLJs (LLJ_HR events), HR events without LLJ influence (non-LLJ_HR events), and non-HR events affected by LLJ (LLJ_non-HR events) are further distinguished.

3. Results and discussion

3.1 General characteristics of nocturnal rainfall and LLJs

Firstly, we characterized the spatiotemporal patterns of rainfall and LLJs observed nationwide during the 2023-2024 warm season. Nationally, nocturnal rainfall accounted for 50.9% of total warm-season rainfall, with pronounced concentrations

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over North, Northeast and Southwest China (Figs. 2d and 2g). In contrast, the pronounced daytime rainfall dominance in South China (Fig. 2a) may arise from the interaction between enhanced onshore monsoonal flows and terrain (Bai et al., 2020), sea breeze fronts and cold pool (Chen et al., 2016). In terms of frequency, nocturnal rainfall occurred more frequent, constituting 52.5% of the total rainfall frequency versus 47.5% for the daytime, with the highest nocturnal proportions found in southwestern and eastern regions (Figs. 2e and 2h). Although the national mean rainfall intensity was generally lower at night (1.2 mm/h) than during the day (1.2 mm/h; Figs. 2c and 2f), the probability of nocturnal HR occurrence was was significant (51.3%), particularly across western China, North China, and northeastern China (Fig. 2i).

Figure 3 displays the key attributes of LLJs detected at all 31 RWPs across China using the criteria defined in Section 2. Nocturnal LLJs activities occurred more frequently, with an overall occurrence frequency increase of nearly 18% (Figs. 3a and 3e). Spatially, the regions exhibiting pronounced jet activity and high absolute wind speeds were collocated with those experiencing intense nocturnal rainfall, particularly over northern and eastern regions. Vertically, these jets manifest as intensified LLJ core concentrated below 1 km AGL (Figs. 3f and 3g). This vertical restructuring likely responds to nocturnal surface cooling and IO. The dominant wind direction shifted to westerly, southerly or southwesterly flows at night across most regions, potentially driven by thermal contrasts within the monsoon circulation pattern and topographic forcing.

Statistical analysis revealed substantial linkage between LLJs and nocturnal rainfall. Specifically, 56% of nocturnal rainfall events across China were preceded by the presence of LLJs within 2 hours, establishing nocturnal rainfall influenced by LLJs as a major component of warm-season rainfall in China. This relationship was modulated by the seasonal migration of the western Pacific subtropical high (WPSH), which drove corresponding shifts in HR belts that closely synchronized with the spatiotemporal evolution of LLJ activity. The proportion of nocturnal rainfall events associated with LLJs during the four rainy season phases reached 60.4%, 56.3%, 49.4%,

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and 54.9%, respectively (Fig. 4a). Among 841 identified nocturnal HR events, the percentages classified as LLJ_HR events ranged from 33.9% to 47.2% across the four phases. These results indicated that the mere presence of LLJs, while a frequent precursor to general nocturnal rainfall, is necessary but insufficient for HR.

However, spatial analysis of site-averaged rainfall intensity revealed that LLJ_HR events consistently produced heavier rainfall than non-LLJ_HR events, particularly within the four ROIs identified in each phase (red boxes in Fig. 5). The non-LLJ_HR events exhibited spatially heterogeneous intensity distributions, where localized maxima may occur in areas outside the primary rain belts. For instance, during Phase 2 in ROI-3 (Fig. 5f), sporadic high-intensity events driven by deep cold trough system resulted in high site-averaged intensities even without LLJs, whereas in ROI-2, the absence of LLJs typically corresponded to weaker frontal precipitation (Fig. S6). This reflected the dominant role of LLJ coupling in primary rain belts region. Furthermore, a total of 71, 49, 33, and 34 nocturnal HR events were identified in these ROIs during from Phase 1 to Phase 4 (Fig. 4b). From the LLJs perspective, nearly 31.1% of LLJ events were classified as HR events across phases relative to LLJ_non-HR events, which unexpectedly suggests the presences of LLJs do not invariably result in HR. From the HR perspective, nearly 45.0% of HR events were associated with LLJs within 2 hours before onset relative to non-LLJ_HR events. In general, these findings imply an association between HR and LLJ in ROIs during specific phases, but certain HR instances can still materialize during non-LLJ events due to other influencing factors (e.g., land-sea breezes, topographic lifting, or mesoscale convective systems).

Furthermore, at the national scale, probability distributions of rainfall intensity (Fig. 6) indicated that LLJ_HR events exhibited a distinct probability advantage in the high-intensity tail (≥ 2 mm/6 min) compared to non-LLJ_HR events during Phases 1 and 3. During Phases 2 and 4, however, the distributions of the two event types were similar, and LLJ_HR events even exhibited somewhat weaker rainfall. Regionally, rainfall intensities within the key ROIs generally exceeded the national average, particularly for LLJ_HR events. Specifically, LLJ_HR events in ROI-1 and ROI-2

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demonstrated significantly higher probabilities of heavier rainfall (≥ 2 mm/6 min), while those in ROI-4 during Phase 4 favored intensities near 0.5 and 2.8 mm/6 min. Notably, despite the relatively high frequency of LLJ_HR events in ROI-3 during Phase 3 (see the pie charts in Fig. 6), their probability of producing extreme rainfall intensities was lower than that of non-LLJ_HR events. This suggests that LLJs may not represent the dominant mechanism for extreme rainfall in this particular region and season.

In summary, although LLJ_HR events generally exhibit higher rainfall intensities, the relatively high proportion of LLJ_non-HR events suggests that the mere presences of LLJs does not invariably lead to HR. Therefore, further investigating the fine-scale vertical structures of LLJs preceding rainfall is crucial to distinguish the specific dynamical characteristics of LLJs that lead to HR.

3.2 Minute-scale evolution of LLJs preceding nocturnal heavy and non-heavy rainfall

To elucidate the contrasting precursor characteristics of LLJs that lead to nocturnal rainfall of differing intensities, this section examines fine-scale vertical structure and continuous evolution of LLJs within 2 hours preceding both LLJ_HR and LLJ_non-HR events during four phases in their respective ROIs. The results revealed the distinct spatiotemporal variations in vertical structure and evolutionary patterns of LLJs occurred across seasonal phases.

During Phase1 in ROI-1, LLJ_HR events exhibited a significant increase in frequency starting 108 min before rainfall onset, reaching secondary peaks at –84 min and –60 min, culminating in maximum frequency immediately preceding HR (Fig. 7a). Meanwhile, the average wind profiles showed a rapid intensify trend from 48 min before HR onset, with the jet core reaching its peak wind speed (about 12.2 m s^{-1}) and its height distinctly decreased (Fig. 8a), although there is the transient weakening of jet strength within 60–48 min preceding HR. These LLJs featured a bimodal vertical distribution with frequent occurrence layers at 0.5–1 km and 1.5–2 km AGL. This structure was characteristic of double low-level jets (DLLJs), where the coexistence of the boundary layer jets (BLJs) and synoptic-system-related low-level lets (SLLJs)

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generates a deep layer of forced ascent via BLJ-exit convergence and SLLJ-entrance divergence. This dynamical coupling significantly favors organized deep convection in ROI-1 (Uccellini and Johnson, 1979; Du and Chen, 2018; Du and Chen, 2019; Liu et al., 2020). Note that the composite wind profile (Fig. 8a) does not show a distinct bimodal vertical distribution due to smoothing from averaging. Detailed examination of wind profiles revealed that approximately 40% of LLJ_HR events exhibited DLLJs, while only 20% of LLJ_non-HR events showed such a structure. Therefore, LLJ_non-HR events lacked this dynamic coupling, with jets predominantly confined to the single 0.5–1 km layer. Although LLJ_non-HR events showed a gradual increase in frequency from –48 min, along with strengthening winds prior to rainfall (Figs. 7e and 8e), these changes were rather limited compared to the pronounced evolution seen in LLJ_HR events under a background of overall lower frequency and weaker intensity. This steady and weak dynamical structure failed to provide sufficient dynamic lifting to efficiently initiate strong convection.

Both event types exhibited notably high frequencies and intensities of LLJs over ROI-2 during Phase 2, yet their evolutionary dynamics diverged sharply. For LLJ_HR events, a coherent oscillatory vertical reorganization of LLJs is evident (Figs. 7b and 8b). At the first stage, both LLJ frequency and wind speed maximum peaked (exceeding 12 m s^{-1}) at –120 min, with the core situated 1.5–2 km AGL. Subsequently, a rapid descent of frequently occurring height of LLJs to below 1 km AGL occurred, accompanied by a concurrent decline in frequency and profile intensity to a minimum around 84–72 min preceding HR. Analysis of wind kinetic energy and its vertical transport (see Eqs. 1 and 2 in supporting material) confirmed that the 'sudden drop' likely results from the downward momentum transfer (Fig. S7a and c), which can efficiently enhance low-level disturbances and dynamic forcing and serve as an effective indicator of HR 1–2 hours later (Liu et al. 2003; Fu et al., 2020). Following this descent, a distinct recovery phase ensued from –60 min, where the frequency increased reaching a secondary peak at –48 min and jet core re-ascended to 1–2 km AGL. The LLJ profile strength re-intensified to about 11.4 m s^{-1}. This rise of the jet core and secondary enhancement are likely tied to cold pool-LLJ interactions and

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intensified upward motion or latent heat release in convective clouds (further discussed in Section 3.3). In conclusion, this pattern suggests an intense internal dynamical adjustment process. In comparison, LLJ_non-HR events lacked such low-level momentum transfer signals (Fig. S7b and d) and maintained a quasi-steady state, with consistent LLJs strength (near 11.8 m s^{-1}) and a preferred height range of 1–2 km AGL (Fig. 8f). The LLJs frequency exhibited gradual changes, peaking weakly at 36 min preceding rainfall before a subsequent rapid decrease (Fig. 7f). This pattern indicates an absence of the rapid dynamical redistribution observed in LLJ_non-HR events.

During Phase 3 in ROI-3, LLJ_HR events exhibited a bimodal temporal distribution in LLJ frequency, with proent peaks at –96 min and –48 min (Fig. 7c). The dominant LLJ height was centered between 1–1.5 km AGL. The wind profiles showed a corresponding evolution where the maximum wind speed increased from approximately 8 m s^{-1} at –120 min to a first peak about 9.5 m s^{-1} by –84 min. It then reached a secondary peak near –48 min and displayed a characteristic transient weakening (–48 to –24 min), after which a rapid intensification resumed until HR occurred (Fig. 8c). Conversely, LLJ_non-HR events were characterized by substantially lower LLJs frequency (around 20%) and more diffuse structure (Fig. 7g), with wind profiles showing weaker intensification preceding rainfall (Fig. 8g). Thus, the pronounced, rapid change and final intensification in LLJs likely reflect a key dynamical mechanism conducive to HR initiation. However, the overall weaker wind profiles potentially explained the lower probability of heavier rainfall in LLJ_HR events over ROI-3 during Phase 3 relative to other region and phases.

During Phase 4 in ROI-4, LLJ_HR events exhibited a distinctive two-stage intensification process. The wind profiles initially strengthened rapidly starting from -120 min, reaching a primary peak of approximately 12.8 m s^{-1} at -72 min (Fig. 8d), coinciding with a secondary peak in LLJ frequency. Following a brief weakening (–60 to –48 min), a renewed and explosive intensification occurred from –48 min onwards, continuing until rainfall onset. Throughout this period, the LLJ cores remained concentrated between 0.5–1.5 km AGL (Fig. 7d). In sharp contrast, LLJ_non-HR events displayed a pattern of premature peaking followed by decay. Both frequency and

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intensity peaked earlier at –84 min, followed by general attenuation (Fig. 7h). By –48 min, weakened wind profiles stabilized into a double-core structure maintaining around 10 m s^{-1}, with distinct jet cores near 0.8 km and 1.7 km AGL (Fig. 8h). Crucially, in the LLJ_non-HR event, this premature peak and the subsequent continuous attenuation of the low-level wind field resulted in a lack of sustained dynamic forcing during the critical pre-rainstorm stage, failing to trigger HR.

Synthesizing the evolution across all phases, although a distinct transient weakening of jet profiles was consistently observed, the wind profiles of LLJs consistently showed a rapid increasing and height of core decreased in around the final 30 min before HR. We propose that this minute-scale oscillatory behavior—characterized by a 'weakening-then-strengthening' or 'descent-then-ascent' pattern—represents a physically consistent signature of the dynamic environment adjustment essential for HR. Physically, this phenomenon is likely attributable to the momentum consumption by developing convection or the flow blocking effect due to strong convergence (Markowski & Richardson, 2010). Consequently, this rapid reorganization and final-stage intensification of the low-level dynamical field constitutes a decisive triggering mechanism for HR, standing in sharp contrast to the weaker, quasi-steady evolution observed in LLJ_non-HR events.

Furthermore, probability distributions of LLJ strength and height within 2 hours preceding rainfall were compared across key regions (Fig. 9). During Phase 1 in ROI-1, the strength of LLJs in LLJ_HR events was notably stronger by 2–3 m s^{-1} than that in LLJ_non-HR events (Fig. 9a). Height distributions showed distinct bimodal peaks near 0.9 km and 1.75 km AGL (Fig. 9e). The average LLJs height was generally higher in LLJ_HR events, which is usually affected by the coupling of the upper-level jet stream or the sea-land breeze. During Phase 2 in ROI-2, LLJ_HR events showed higher probabilities of strong LLJs (17–28 m s^{-1}) compared to the dominant 13 m s^{-1} intensity in LLJ_non-HR events (Fig. 9b). Influenced by large-scale circulation patterns, both event types featured LLJs centered near 1.5 km AGL (Fig. 9f), though LLJ_HR events developed a secondary maximum near 0.8 km AGL due to pre-rainfall descent of the jet core (Fig. 7b). Contrastingly, Figure 9c shows that LLJ_HR events were associated

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with weaker jet strengths (around 11 m s^{-1}) compared to LLJ_non-HR events (14–23 m s^{-1}) in ROI-3 during Phase 3, suggesting that strong LLJs don't necessarily induce HR here. The height of LLJ in LLJ_HR events mainly concentrated near 1.2 km AGL, whereas in LLJ_non-HR events, it was more uniformly distributed between 0–3 km AGL with a higher probability nearly 1.5 km (Fig. 9g). For Phase 4 in ROI-4, LLJs strength peaked near 15 m s^{-1} in both event types, but LLJ_HR events featured stronger jets reaching 25–30 m s^{-1} (Fig. 9d). The LLJs height in both events peaked predominantly at 0.8 km AGL, with secondary peaks at 1.5 km for LLJ_HR and 2.0 km AGL for LLJ_non-HR events (Fig. 9h).

In summary, although different internal dynamic adjustments, including frequency, occurrence height, and wind profile intensity of LLJs, preceding LLJ_HR events were observed due to the different dominant mechanisms influencing rainfall in each phase, our findings highlight the role of fine-scale LLJ structures and their rapid vertical reorganization in modulating nocturnal rainfall intensity, offering valuable insights for improving regional nocturnal HR forecasting.

3.3 Thermodynamic evolution associated with LLJs preceding nocturnal heavy and non-heavy Rainfall

The section 3.2 has clarified that the fine-scale dynamic characteristics of LLJs—including their temporal evolution, vertical structure, and intensity variations—play a pivotal role in modulating nocturnal rainfall intensity during rainy season phases. However, the influence of LLJs on rainfall generation and intensification rarely operates in isolation; instead, it depends strongly on the accompanying large-scale thermodynamic environment, which provides the necessary moisture supply and convective instability to sustain or amplify heavy rainfall. Thus, to fully unravel the mechanisms underlying the distinction between LLJ_HR and LLJ_non-HR events, it is essential to complement the dynamic analysis with an in-depth examination of the thermodynamic conditions associated with LLJs within the immediate pre-convective environment (at 1 hour prior to nocturnal rainfall onset).

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Further analysis of large-scale thermodynamic conditions at 1 hour prior to nocturnal rainfall onset (Figs. 10 and 11) reveals consistently stronger thermal instability for LLJ_HR versus LLJ_non-HR events, accompanied by stronger MFC within key regions during each rainy season.

During Phase 1 in ROI-1, thermodynamic conditions were comparable between event types. Southwesterly LLJs transported warm-moist air masses from the South China Sea and Bay of Bengal, forming a pronounced warm-humid tongue (Fig. 10a and 10e). Coupled with MFC centers developing north of the jet axis (Fig. 11a and 11e), this configuration facilitated nocturnal rainfall development. During Phase 2 in ROI-2, LLJ_HR events exhibited a significantly stronger warm-moisture tongue with core θ_e reaching 358 K—approximately 2 K higher than in non-HR events (Figs. 10b and 10f). Dynamically, the stronger LLJ core (>1.2 m s^{-1} difference) drove a sharper, continuous band of MFC along the left flank of the jet axis (Fig. 11b), creating a robust triggering mechanism for HR (Fig. 11b). During Phase 3 in ROI-3, intensified southwesterly LLJs in HR events drove substantial northward transport of abundant moisture and higher θ_e air (>2 K difference) northward into a low θ_e environment (Fig. 10c), enhancing convective instability. The synergistic interaction of this moist, high-energy advection with orographic forcing from the Taihang Mountains generated intense MFC, with peak values south of Beijing approximately 30×10^{-5} km m^{-2} s^{-1} (Fig. 11c) than those in LLJ_non-HR events, thereby driving nocturnal HR. Thermodynamic contrasts were most pronounced during Phase 4 in ROI-4. Thermodynamic contrasts were most pronounced during Phase 4 in ROI-4. LLJ_HR events featured a deep high-θ_e region (>356 K) over the southeastern Tibetan Plateau (Fig. 10d), contrasting with the cold highs and lower θ_e prevalent in LLJ_non-HR events (Fig. 10h). Concurrently, accelerated easterly-southeasterly LLJs drove warm, moist air towards the steep eastern Plateau margin. The impingement of this flow against the sharp topographic gradient generated intense dynamic lifting and low-level convergence. This mechanically forced ascent, synergizing with the abundant moisture transport and strong MFC (Fig. 11h), played an essential role in triggering the observed nocturnal HR in this region.

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To elucidate the rapid processes leading to occurrence of rainfall, the minute-scale evolution of key thermodynamic and dynamic parameters was further analyzed (Fig. 12), including surface θ_e, LLJ index and VWS. Specifically, LLJ index is defined as the ratio of maximum wind speed below 3 km to the height where wind first exceeds 10 m s^{-1}. A rapid rise in LLJ index will reflect the extension and pulsing intensity of the LLJ, and its magnitude has been shown to be positively correlated with subsequent rainfall intensity 1–2 hour later (Liu et al., 2003). VWS is calculated as the wind speed difference between the surface and jet height divided by the jet height and is used to characterize the bulk shear from the surface to the jet layer associated with the dynamical forcing and organization of convection (Wei et al., 2014).

Figure 12a illustrates that during Phase 1 in ROI-1, despite the similarity in large-scale environments between LLJ_HR and LLJ_non-HR events, they exhibited distinct differences in the continuous evolution of LLJ-associated thermodynamic conditions preceding rainfall onset. LLJ_HR events exhibited abrupt thermodynamic enhancement from 90 min preceding the onset of rainfall driven by rapid intensification of LLJs, with surface θ_e and VWS surging approximately 1.5 K and 0.5 s^{-1} respectively. Concurrently, the LLJ index surged from approximately 0.05 to 0.08 and VWS peaked sharply at –60 min, signaling LLJs intensification and core descent (Figs. 7a, 8a). This rapid, minute-scale co-intensification of thermodynamic and dynamic processes serves as a critical precursor triggering HR. In contrast, LLJ_non-HR events showed weaker increases of θ_e and VWS and a declining LLJ index (by about 0.02) alongside rising jet cores, reducing low-level shear and convergence efficiency, thereby diminishing overall rainfall intensity.

During Phase 2 in ROI-2, the thermodynamic environment displayed a distinct 'weakening-reintensification' pattern (Fig. 12b), which aligns precisely with the intristic dynamical adjustments of the wind field presented in Fig. 8b. Initially, at –120 min, concurrent peaks in the LLJ index and VWS were observed, coupled with a high surface θ_e of 348.3 K. During the subsequent transition period, a drastic elevation in the jet core height starting from –84 min caused a precipitous drop in the LLJ index. The timing of this rapid evolution suggests a transient optimal window for nocturnal rainfall

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During Phase 2 in ROI-2, LLJ_HR events showed concurrent peaks in dynamic parameters (LLJ index, strength and VWS) coupled with high θ_e (348.3K) at -120 min (Fig. 12b). … [72]

triggering that is characteristic of LLJ_HR events in ROI-2. Following this, rapid surface cooling began 60 min prior to HR. This cooling was likely induced by the outflow of cold pool outflow associated with alternation or propagation of convective systems embedded within the Mei-Yu front cloud system (Zhang et al., 2023). The resulting dense cold air wedging beneath the strong southwesterly LLJs can lift the jet axis above the cold-pool interface, further enhancing uplift and promoted rainfall (Luo et al. 2014). This in turn facilitated the final re-intensification of the jet structure (Fig. 7b and 8b). Importantly, this configuration sharply enhances low-level vertical wind shear and horizontal convergence (Fig. 12b), further promoting HR development. For LLJ_non-HR events, weaker thermodynamic support and diminished dynamic forcing with consistently lower LLJ indices within 60 min preceding rainfall resulted in insufficient lift to sustain HR. Compared with the disordered fluctuations of the LLJ_non-HR events, these results emphasized the importance of thermal-dynamic synergy influenced by LLJs evolution in triggering HR.

During Phase 3 in ROI-3, LLJ_HR events featured prominent thermal compensation (surface $\Delta\theta_e$ > 1K, 850hPa $\Delta\theta_e$> 2K versus non-HR events), despite possessing generally weaker dynamical forcing compared to other phases (Fig. 12c). Temporally, the evolution was marked by distinct pulsations: The LLJ index exhibited a rapid rise (from ~0.03 to ~0.06) starting 84 min prior to HR onset (Fig. 12c) driven by a surge of LLJs profiles, while VWS peaked synchronously with the maximum LLJ frequency. Subsequently, a secondary peak in both the LLJ index and VWS was observed between –60 and –48 min. Although the subsequent decline in wind speed and frequency led to notable fluctuations in these parameters, a substantial intensification of VWS (increasing by ~1.5 s^{-1}) amd LLJ index occurred within the final 24 min driven by a rapid acceleration of the LLJ wind field. This co-evolution with rapid surface warming (increase of 0.25 K) released convective instability and enhanced convergence (Fig. 10). Nevertheless, the overall weaker dynamical conditions likely limited the depth and organization of convection, explaining the reduced probability of heavier rainfall compared to other phases. In contrast, during LLJ non-HR events, the LLJ index (~0.03) and θ_e vary rather gradually.

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During Phase 4 in ROI-4, under the favorably thermal environments (θ_e > 346 K), LLJ_HR events showed a two-stage dynamic intensification. Initially, the LLJ index surged, while the VWS and jet intensity reached synchronous secondary peaks at –72 min. In the second stage, VWS increased rapidly by ~0.9 (Fig. 12d), and the LLJ index maintained an overall upward trend, peaking immediately prior to onset due to the surging jet. But LLJ_non-HR events showed weakening trends in both dynamic and thermodynamic conditions during the final 30 min and exhibited weaker changes (ΔVWS < 0.45 s^{-1}, ΔLLJ index < 0.02), reflecting an absence of the coordinated intensification necessary to initiate and sustain HR.

Although the evolution paths of the thermodynamic environment vary across different phases, a universal cross-region precursor emerges: the LLJ index and VWS consistently exhibits a strengthening or stabilizing trend in the final approximately 30 min preceding HR onset, operating in concert with significant low-level warming (rising θ_e). In contrast, non-HR events generally lack this culminating dynamical intensification. Overall, these results adequately showcase the sensitivity of regional HR to the fine-scale structural evolution of LLJs and their coupling with thermodynamic environments.

4. Summary and concluding remarks

Wind profile measurements from a nationwide network of 31 RWPs during the warm seasons (April–October) of 2023–2024 were utilized to characterize the minute-scale evolution of LLJs as dynamic precursors to nocturnal rainfall across China. By systematically comparing the vertically resolved behaviors of LLJs within the 2-hour window preceding nocturnal HR and non-HR events across four distinct rainy season phases, this study elucidates the critical dynamic-thermodynamic related to LLJs distinctions governing rainfall intensity.

Statistical analysis reveals that at the national scale, nocturnal rainfall accounted for nearly half of the total warm-season precipitation, with 56% of these nocturnal events exhibiting LLJ influence within the preceding 2 hours. In the key ROIs,

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approximately 45.0% of identified HR events were associated with LLJs. Generally, these LLJ events exhibited a distinct probability advantage in producing heavier rainfall intensities compared to non-LLJ events, underscoring the strong linkage between LLJs and nocturnal HR.

Pronounced differences in LLJ evolution were consistently observed between HR and non-HR events across all phases, despite regional variations in synoptic forcing. During Phase 1 in ROI-1, a bimodal vertical distribution of LLJs and their rapid thermodynamic-dynamic co-intensification starting 84 min prior to rainfall were identified as key precursors of LLJ_HR events, in sharp contrast to the decoupled dynamics of LLJ_non-HR events. Phase 2 (ROI-2) was characterized by a distinct oscillatory process, where HR events featured a rapid descent of the LLJ core below 1 km followed by a robust rebound, distinguishing them from the quasi-steady state of LLJ_non-HR cases. In Phase 3 (ROI-3), LLJ_HR events exhibited significant thermal compensation and bimodal pulsations (peaks at -96 and -48 min), with a critical final-stage intensification serving as the decisive trigger. Similarly, Phase 4 (ROI-4) featured a distinctive two-stage intensification, where a rapid LLJ surge within 48 min of onset distinguished LLJ_HR events from the significantly attenuated dynamical structures of LLJ_non-HR events.

Although the specific dynamical pathways vary across different phases, all LLJ_HR events exhibit a "final-stage intensification" of the LLJs (LLJs strength, VWS and LLJ index) specifically within the 30 min preceding rainfall in synergy with thermodynamic instability (rising θ_e). This result can confirm the universality of the final-stage low-level dynamic intensification observed in our previous analysis (Li et al., 2024) as a robust trigger for nocturnal HR across diverse monsoon regions. Crucially, however, the current work identifies a novel "preparatory adjustment" phase (30–120 minutes prior) for LLJs structure (LLJs frequency, strength and height) that was not fully resolved in the regional study. This national-scale analysis reveals that the final dynamic trigger is contingent upon this earlier synergistic coupling of minute-scale jet evolution and thermodynamic destabilization. This coupled "rapid reorganization" process constitutes the essential, nationally valid precondition for HR

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generation, contrasting with the quasi-steady evolution observed in LLJ_non-HR events. This underscores that the occurrence and intensity of nocturnal rainfall are ultimately regulated by regionally specific thermo-dynamic interactions modulated by the evolution of fine vertical structure of the LLJ.

This study establishes distinct dynamic-rainfall linkages associated with LLJs across different warm-season rainy periods in China. Future research should: (1) expand multi-source observations to establish dynamic thresholds for early forecasting systems of nocturnal rainfall, and (2) develop quantitative frameworks relating LLJ structural evolution to rainfall intensity, offering theoretical support for optimizing physical processes in LLJ parameterization schemes within high-resolution numerical models. Additionally, the physical mechanisms governing evolution of LLJs height or strength immediately preceding rainfall onset require further investigation.

Data Availability

The LLJs retrieved from the RWP network can be acquired from https://doi.org/10.5281/zenodo.17176759 (Li and Guo, 2025). The data from the weather station are obtained from the China Meteorological Data Service Centre at https://data.cma.cn/en, and the original ERA5 reanalysis data used here are available from the ECMWF in Hersbach et al. (2020).

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Author Contributions

The study was completed with close cooperation between all authors. JG designed the research framework; NL performed the analysis and drafted the original manuscript

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~~Crucially, A key finding is that nocturnal LLJ_HR events universally require rapid, coupled minute-scale dynamical intensification occurring 30-120 min preceding rainfall onset, acting in synergy with thermodynamic instability. LLJ_non-HR events consistently displayed insufficient dynamic-thermodynamic coupling, reflected in stable or declining LLJ parameters.~~ …

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with contribution from JG; JG, XG, ZZ, YZ. JG, NT, YW, and YZ helped revise the manuscript.

Completing interests

The authors declare that they have no conflict of interest.

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Table 1. Table of Representative Radar Wind Profiler Stations in Mainland China

Region	Station		Longitude (°)	Latitude (°)	Altitude (m)
ROI-1	58839	MQ	118.86	26.22	160.70
	59046	LZ	109.46	24.36	314.40
	59137	JJ	118.54	24.81	124.80
	59287	GZ	113.48	23.21	65.00
	59758	HK	110.25	19.99	69.00
ROI-2	57461	YC	111.36	30.74	253.80
	57687	CS	112.79	28.11	119.00
	57793	YCN	114.36	27.79	132.00
	58238	BJ	118.90	31.93	40.60
	58321	HF	117.03	31.57	50.00
	58367	LH	121.47	31.18	5.00
	58459	XS	120.29	30.18	48.80
ROI-3	53463	HHHT	111.68	40.82	1152.10
	53772	TY	112.58	37.62	785.00
	54511	BJ	116.47	39.81	31.50
	54534	TS	118.10	39.65	23.20
	54602	BD	115.48	38.73	16.80
ROI-4	57816	GY	106.73	26.59	1197.60
	56290	XD	104.18	30.77	514.00
	56651	LJ	100.22	26.85	2382.40
Other stations	50936	BC	122.47	45.36	156.00
	51463	WLMQ	87.65	43.79	935.00
	51628	AKS	80.38	41.12	1107.10
	52754	GC	100.08	37.2	3301.50
	52889	LZ	103.89	36.06	1519.20
	57516	CQ	106.46	29.57	260.00
	53845	YA	109.45	36.58	1180.40
	54342	SY	123.51	41.73	50.00
	54857	QD	120.13	36.23	12.00
	55664	DR	87.07	28.63	4302.00
	57171	PDS	113.12	33.77	142.00

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Figures

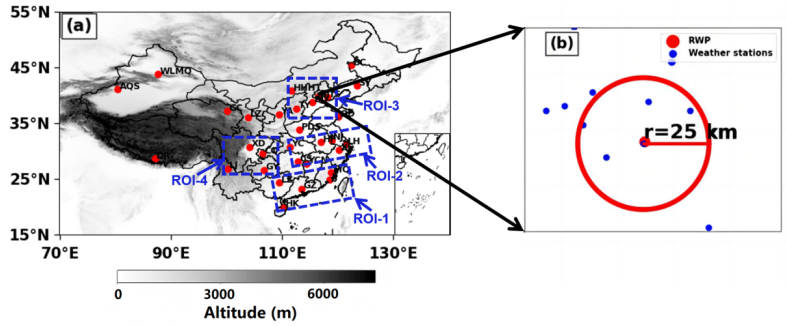

Figure.1 (a) Spatial distribution of 31 Radar Wind Profiler (RWP) stations across China, with four regions of interest (ROIs) demarcated by blue dashed boxes: ROI-1, ROI-2, ROI-3, and ROI-4. (b) Schematic of spatial co-location: Beijing Observatory's RWP (red circle) and rain gauges (black dots) within a 25-km radius

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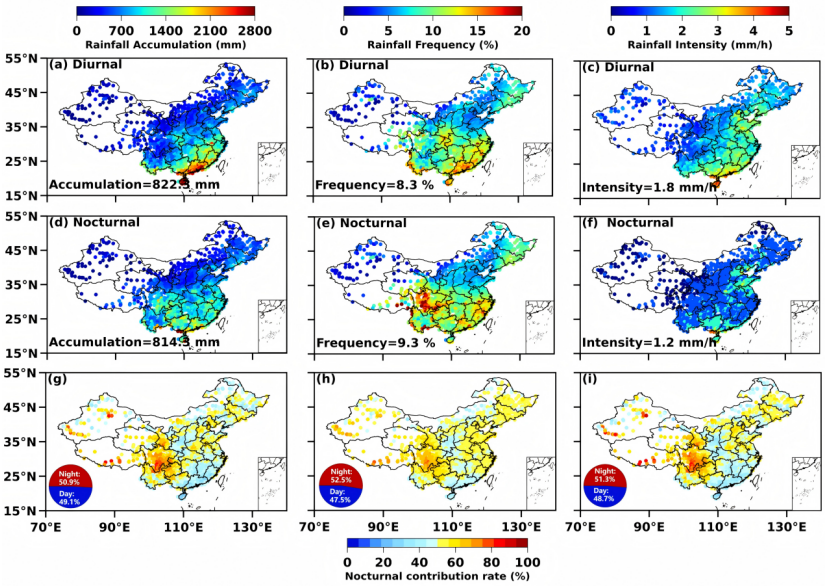

Figure 2. (a–c) Spatial distributions of accumulated rainfall (mm), rainfall frequency (%) and rainfall intensity (mm/h) in the daytime from April to October in 2023–2024. The numbers in the upper left corner represent the national average; (d–f) the same as (a–c), but in the nighttime; (g–i) Nocturnal contribution ratios of accumulated rainfall, frequency, and occurrence frequency of heavy rainfall (>75th percentile intensity). The pie charts illustrate the relative contribution rates of daytime (blue) and nighttime (red) at the national scale

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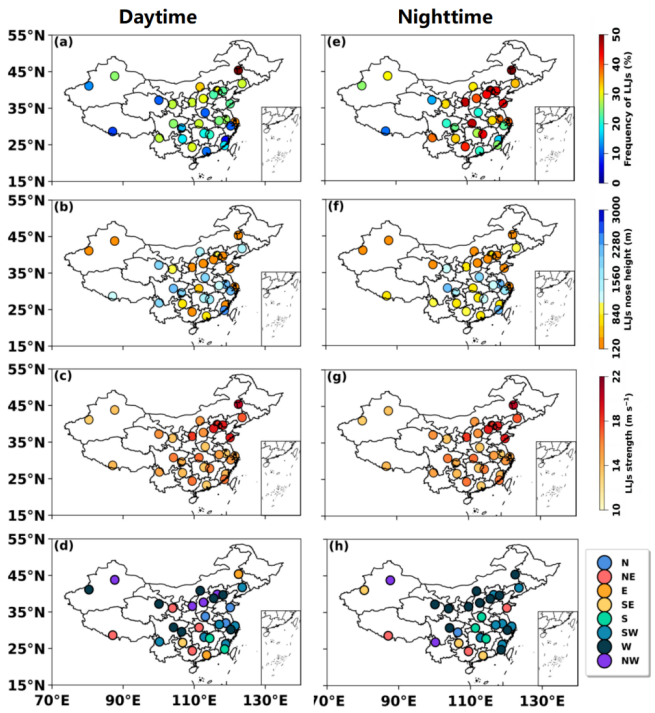
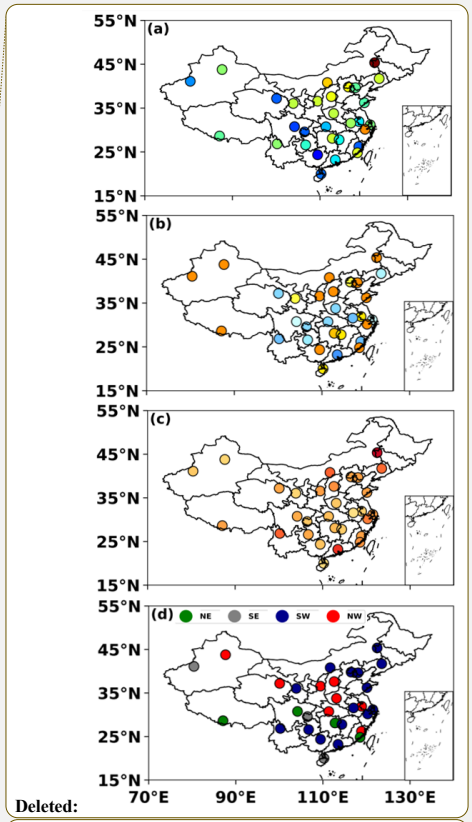


Figure 3. (a–d) Spatial distribution of occurrence frequency, height, strength, and the dominant wind direction of LLJs observed by 31 RWP stations during April–October from 2023 to 2024 in the daytime. (e–h) Same as (a–d), but in the nighttime.



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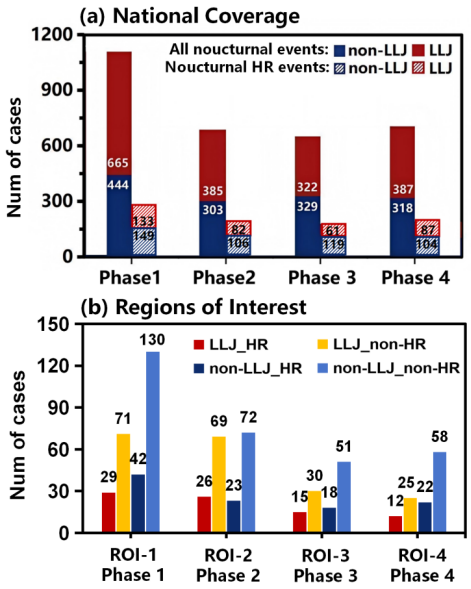
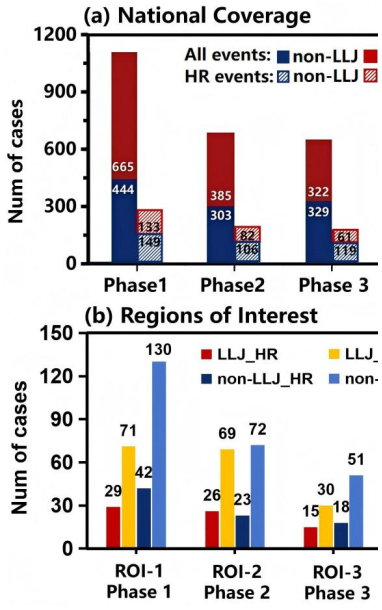


Figure 4. Statistics of all nocturnal rainfall events (solid-filled bars) and heavy rainfall (HR; diagonally striped bars) events across China during four phases, categorized into LLJ events (red) and non-LLJ events (blue). (b) Statistics of all nocturnal events within the four ROIs (ROI-1 to ROI-4) during their corresponding phases, categorized into four types: LLJ_HR (red), LLJ_non-HR (yellow), non-LLJ_HR (dark blue), and non-LLJ_non-HR (light blue) events.



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Deleted: (a) Statistic of all nocturnal rainfall events (solid-filled bars) and heavy rainfall (HR; diagonally striped bars) events selected across China during four phases, including LLJ events (red) and non-LLJ events (blue); (b) Same as panel (a), but for nocturnal HR events in from ROI-1 to ROI-4 during corresponding phase, including LLJ-HR (red), LLJ_non-HR (yellow), non-LLJ_HR (dark blue), and non-LLJ_non-HR (light blue) events.

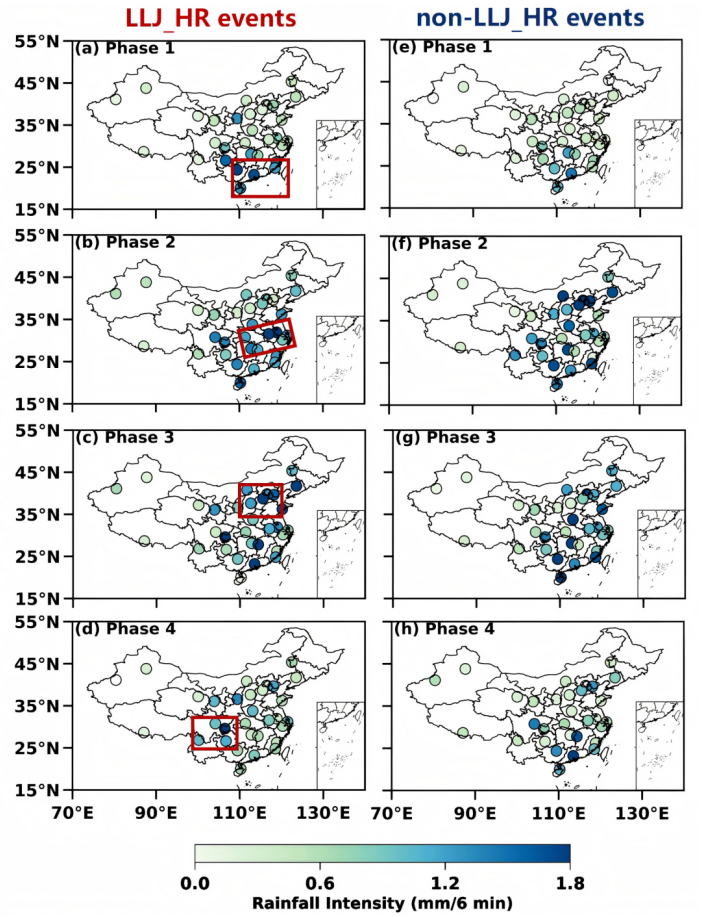

Figure 5. (a–d) Spatial distributions of average rain rate (mm/6 min) for nocturnal LLJ_HR events during the warm season from Phase 1 to Phase 4 across China; (e–h) Same as (a–d), but for non-LLJ_HR events. The red frame indicates four ROIs.

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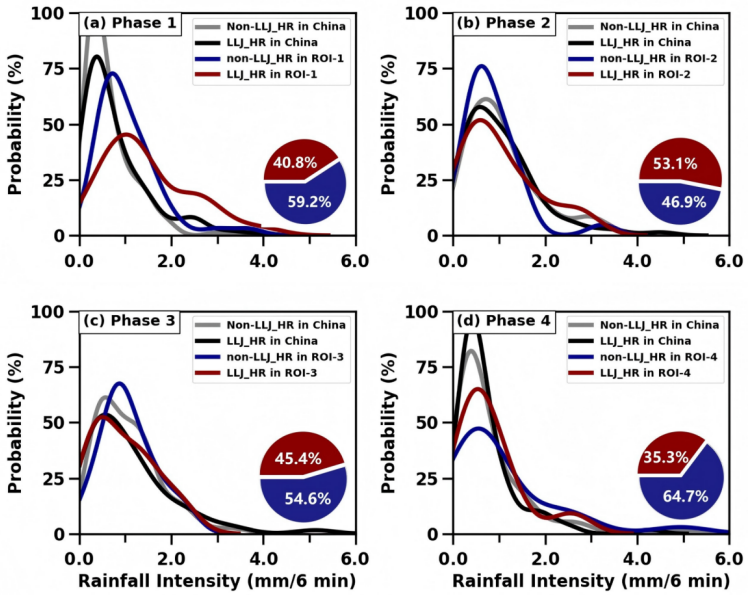

Figure 6. (a) Probability density distributions of average rain rate (mm/6 min) for LLJ_HR events (black solid lines) and non-LLJ_HR events (gray solid lines) across China during Phase 1, and specifically in ROI-1 for LLJ_HR events (red solid lines) and non-LLJ_HR events (blue solid lines). (b-d) the same as panel (a), but for comparisons between national-scale and other regional-scale events in ROI-2 during Phase 2, ROI-3 during Phase 3, and ROI-4 during Phase 4. The pie chart at the lower right shows the proportion distribution of LLJ_HR (red) and non-LLJ_HR (blue) events in these key regions during each period

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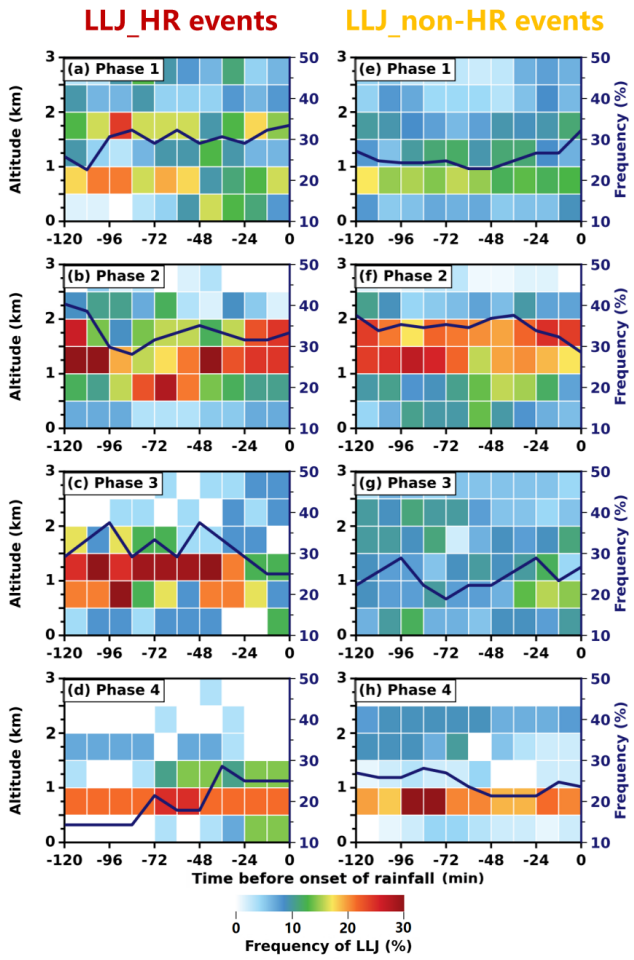

Figure 7. Time-height evolution of LLJ occurrence frequency (color shading, every 12 min, within 500 m vertical bins) detected by RWP with 2 hours preceding nocturnal rainfall in LLJ_HR events in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) in ROI-4 during Phase 4. Dark blue solid lines denote accumulated LLJ frequency over 0–3 km latitude. (e-h) Same as (a-d), but for LLJ_non-HR events.

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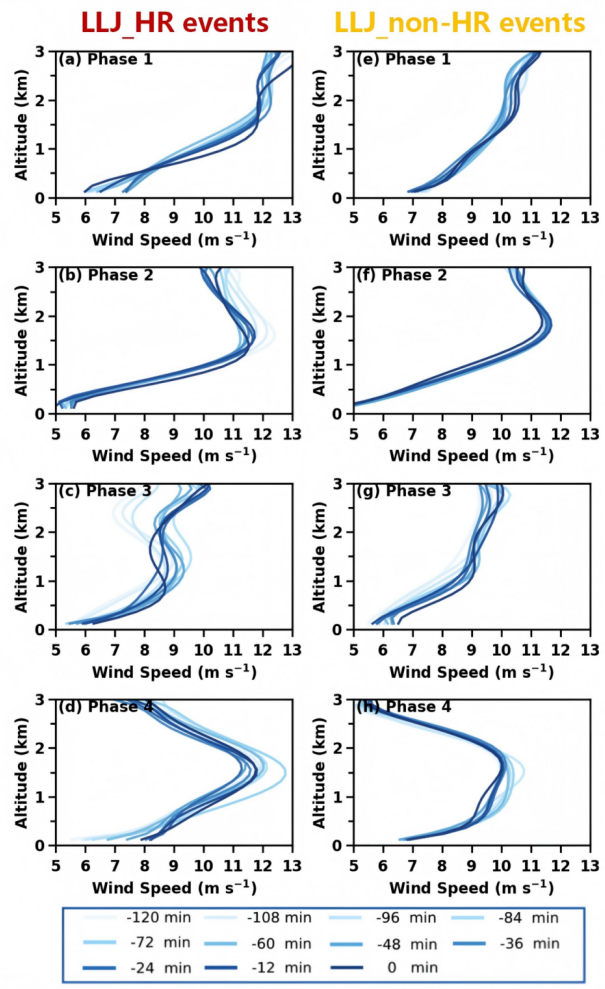

Figure 8. (a-d) Evolution of RWP-detected mean wind profiles of LLJs (blue solid lines, every 12 min) within 2 hours preceding nocturnal rainfall in LLJ_HR events in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) in ROI-4 during Phase 4. (e-h) Same as (a-d), but for LLJ_non-HR events

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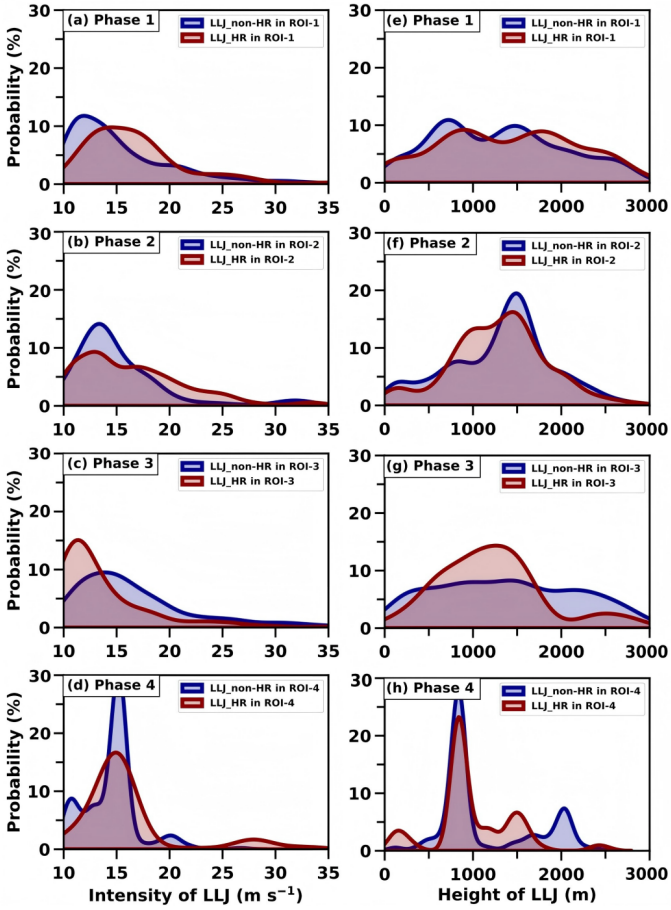

Figure 9. Probability density distributions of jet core intensity from RWP observations within 2 hours preceding nocturnal rainfall in LLJ_HR events in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) in ROI-4 during Phase 4. (e-h) Same as (a-d), but for the height of LLJs

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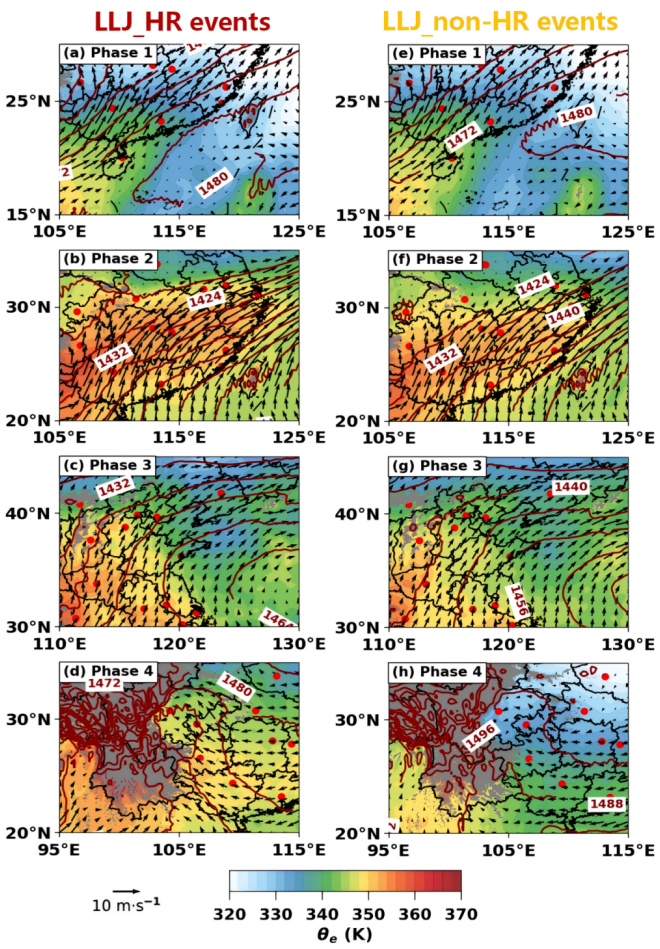

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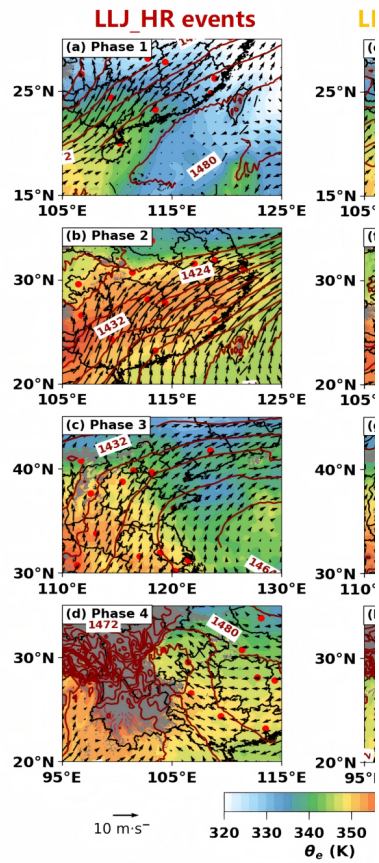

Figure 10. Distributions of equivalent potential temperature (shading, unit: K) at 850 hPa, superimposed with 850 hPa horizontal wind vectors (black arrows) and geopotential height contours (red solid lines), for LLJ_HR events within 1-hour time window preceding nocturnal rainfall onset in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) in ROI-4 during Phase 4. Gray shading denotes terrain elevation exceeding 850 hPa level. The reference vector (10 m s^{-1}) is shown at the lower-left corner. (e-h) Same as (a-d), but for LLJ_non-HR events

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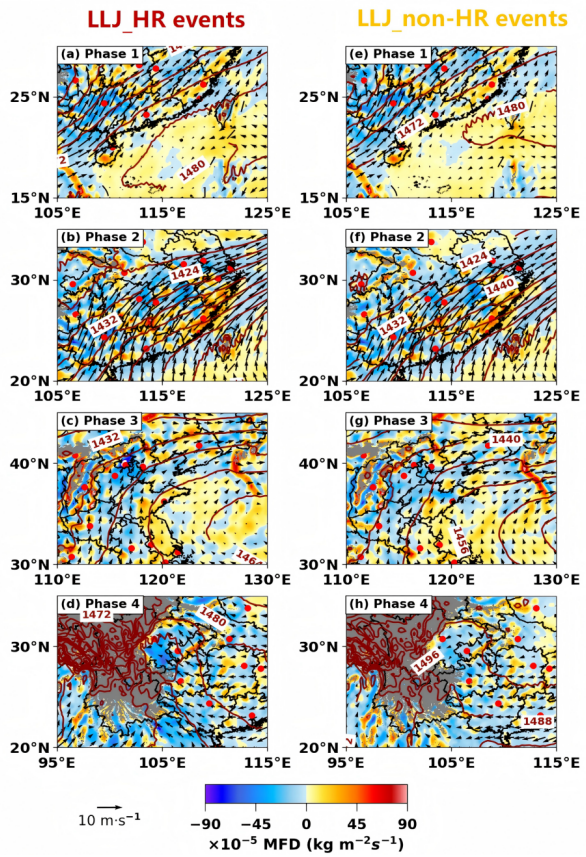

Figure 11. Same as Figure 10, but showing the integrated moisture flux divergence (shading, unit: kg m^{-2} s^{-1}) between 1000–700 hPa at 1 hour prior to nocturnal rainfall onset

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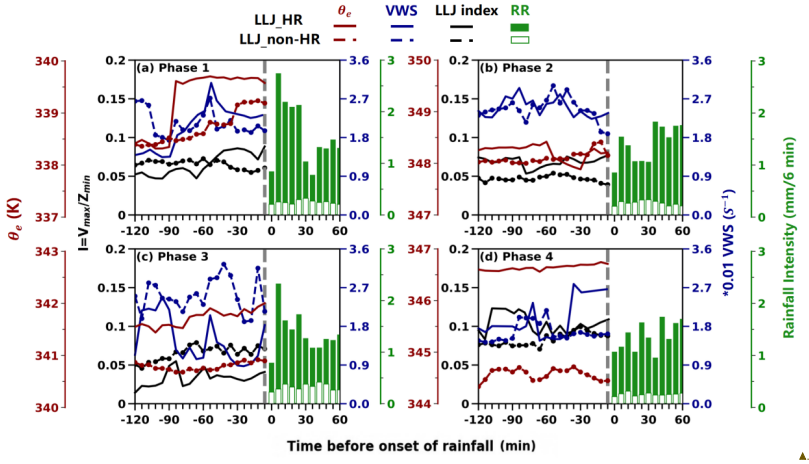

Figure 12. Temporal evolution of surface equivalent potential temperature (θ_e, red lines), vertical wind shear (VWS, blue lines), and LLJ index (I, black lines) averaged within 2 hours preceding nocturnal rainfall for LLJ_HR events (solid lines) and LLJ_non-HR events (dashed lines) in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) in ROI-4 during Phase 4. Green bars denote 6-min averaged rain rate (mm/ 6 min) after LLJ_HR (solid bars) and LLJ_non-HR (open bars) events onset

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