Response to Reviewers' Comments

Reviewer #1:

RWPs are advanced equipment capable of capturing wind profile evolution on minute scale. This equipment offers valuable information and potential precursors for nowcasting rainfall and convection occurrence. It is particularly crucial for region like China that has established nationwide RWP network. For this purpose, this work employed 31 RWP stations across China, and explored their minute-scale information before nocturnal rainfall production, with emphasis on the indication by RWP-detected LLJ traits. Unique dynamic features leading to rainfall were revealed across distinct regions and phases across China. The differences in LLJ-involved heavy rainfall and non-heavy rainfall events were further examined from both dynamic and thermodynamic viewpoints. Overall, the findings are meaningful for advancing our knowledge on the LLJ-related activities and their interaction with other factors preceding rainfall production in different regimes. The manuscript is generally well-written. In my opinion, this paper is acceptable after some minor revisions.

Response: First of all, we thank you for taking the time to review our manuscript and offering constructive and thoughtful suggestions! Per your kind comments, we have carefully revised the manuscript. For clarity purpose, here we have listed the reviewers' comments in bold font, followed by our response in blue plain font, and the modifications to the manuscript are in blue italics.

Minor comments:

1. Abstract: The "multiscale responses" is ambiguous here.

Response: We agree that intended meaning of "multiscale responses"—the synthesis of data from multiple sources (RWP data, surface automatic weather station and reanalysis data) and multi-dimensions (from large-scale circulation to fine-scale vertical structure)—was not sufficiently clear and could lead to ambiguity.

To address this, we have revised the relevant sentence in the abstract to directly and precisely describe our methodological approach, which is shown as follows:

"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."

2. Throughout the manuscript: Several sentences in the manuscript contain grammatical mistakes, such as those beginning with "While" and "And" (L217–218, L235–238, L253–255, L298–299, and elsewhere). There is also misuse of hyphen (-) and long dash (–), especially those between the months (April– October), years (2023–2024).

Response: Amended as suggested.

3. L50: Suggest to revise "The heavy rains linked to LLJs" as "The LLJs-associated heavy rain".

Response: Amended as suggested.

4. L88: Can you provide some examples for "mesoscale systems"? On the other hand, this term seems not parallel with "terrain effects" and "gravity waves" logically.

Response: This sentence has been rephrased as:

"*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.*"

5. L149: Suggest to revise "Miscellaneous" as "Multi-source".

Response: Amended as suggested.

6. L156: Can you provide some reference for the quality control procedure of ground-based data?

Response: Yes, we have added some reference for the quality control procedure of ground-based data in this revised manuscript:

"All ground-based data have undergone rigorous quality control (China Meteorological Administration, 2020; Zhao et al., 2024) and are publicly available by the China Meteorological Administration (CMA)."

References

Zhao, Y., Liao, J., Zhang, Q., Chen, J., Gong, X., Shi, Y., Shi, M., Yang, D., Fan, S., Zhou, X., Cao, L., and Hu, K.: Development of China Ground Climate Normal Value Dataset from 1991 to 2020, Chinese Journal of Atmospheric Sciences (in Chinese), 48(2), 555–571, doi:10.3878/j.issn.1006-9895.2204.22010, 2024.

China Meteorological Administration: Specification for Automatic Observation of Ground Meteorology. China Meteorological Press, 2020.

7. L182: Revise symbol: comma to period.

Response: Amended as suggested.

8. L185–190: I am not so sure about the rationality and accuracy of HR definition here, given HR has its common-used definition in routine operation.

Response: We think that utilizing the station-specific 75th percentile as the threshold is reasonable and necessary for this study, based on the following three considerations:

(1) Warm-season rainfall across China exhibits strong spatial heterogeneity. At present, in China's meteorological operations, the terms "≥ 20 mm/h" and "≥ 50 mm/day" are commonly used to define hourly heavy rainfall and rainstorm days respectively. Based on the definition method using a fixed threshold, it can reflect the absolute intensity of extreme precipitation but often miss locally significant events in arid regions and causes statistics bias of nationwide LLJ-associated rainfall events. Compared with business applications, the relative threshold method is more commonly

used to define heavy rain (Zhai et al., 2005; Zhang and Zhai, 2011; Xiao et al., 2016; Wu et al., 2019). By using a station-specific percentile threshold, we ensure the identification of locally significant rainfall events relative to the local climatology and can better compare local difference of fine-scale dynamical processes of LLJ before HR events versus non-HR events.

(2) The 75th percentile was chosen as the optimal threshold to effectively distinguish significant heavy rainfall from weak rainfall while ensuring a sufficient sample size for robust statistical analysis. As evidenced in Table S1, utilizing a stricter threshold (e.g., the 85th and 95th percentile) would drastically reduce the sample size to single digits in certain phases, rendering statistical conclusions unreliable and without statistical significance. The 75th percentile effectively retain a sufficient sample size to ensure statistical power while still effectively filtering out weak precipitation.

(3) Sensitivity analysis by varying the thresholds to 85th and 95th percentile to ensure our key conclusions are not artifacts of this specific threshold. As shown in Figure S1–S4, the results showed that although the specific lead times varied when changing the thresholds, LLJ_HR events still undergo a minute-scale "rapid reorganization" characterized by oscillations in jet height, frequency and strength, and the "final-stage intensification" of LLJs structure. LLJ_non-HR events still exhibit quasi-steady or declining dynamical response of LLJs. The main conclusion regarding the precursory signals of LLJs is robust within a reasonable threshold range.

Therefore, the 75th percentile serves as an optimal balance between maintaining statistical power and successfully distinguishing the essential difference of dynamical mechanisms prior to HR and non-HR events. Thank you for raising this important point regarding the percentile-based threshold for defining HR events, which prompted a thorough investigation. We have incorporated these justifications, and the sensitivity analysis results into Section 2.3 and the Supplementary Material of the revised manuscript.

Table S1 Statistics of the number of LLJ_HR and LLJ_non-HR events during four rainy season phases under different percentile levels of rainfall intensity

Type	Percentile	Phase 1	Phase 2	Phase 3	Phase 4
LLJ_HR	75th	29	26	15	12
	85th	20	15	10	8
	95th	9	8	5	4
LLJ_non-HR	75th	71	69	30	25
	85th	95	103	47	33
	95th	110	112	53	38

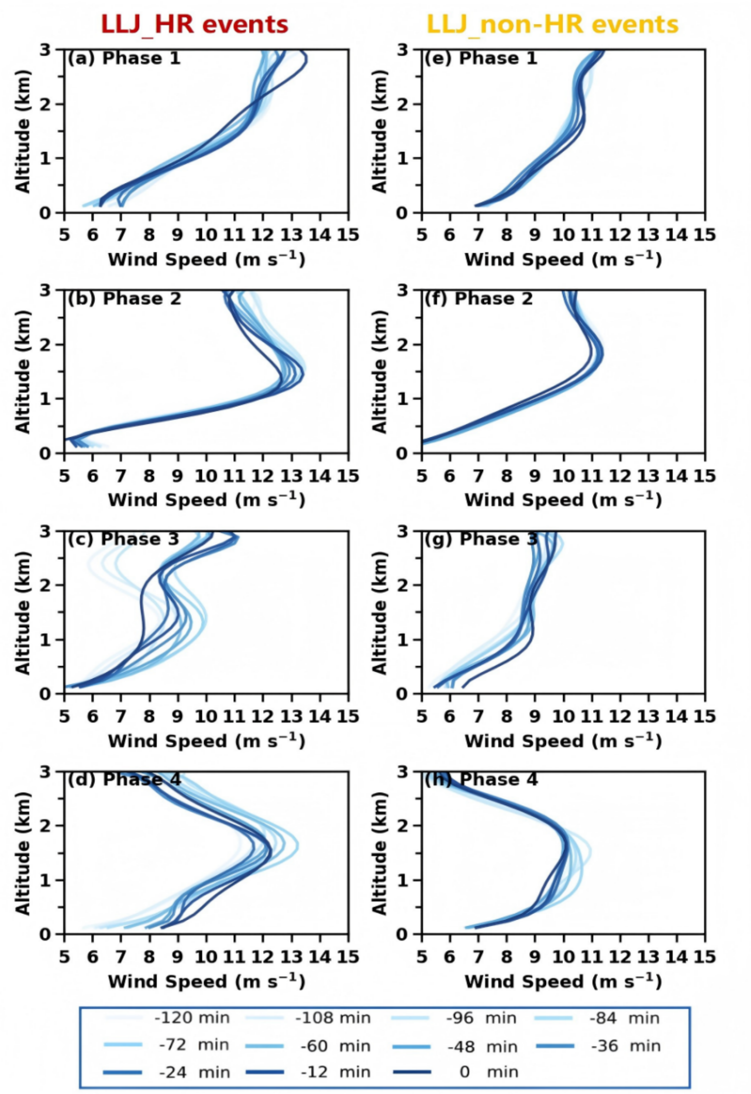

Figure S1. (a-d) Evolution of RWP-detected mean wind profiles of LLJs (blue solid lines, every 12 min) within 2 hours preceding nocturnal rainfall in LLJ-HR events (≥85th percentile) in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) in ROI-4 during Phase 4. (e-h) Same as (a-d), but for LLJ_non-HR events

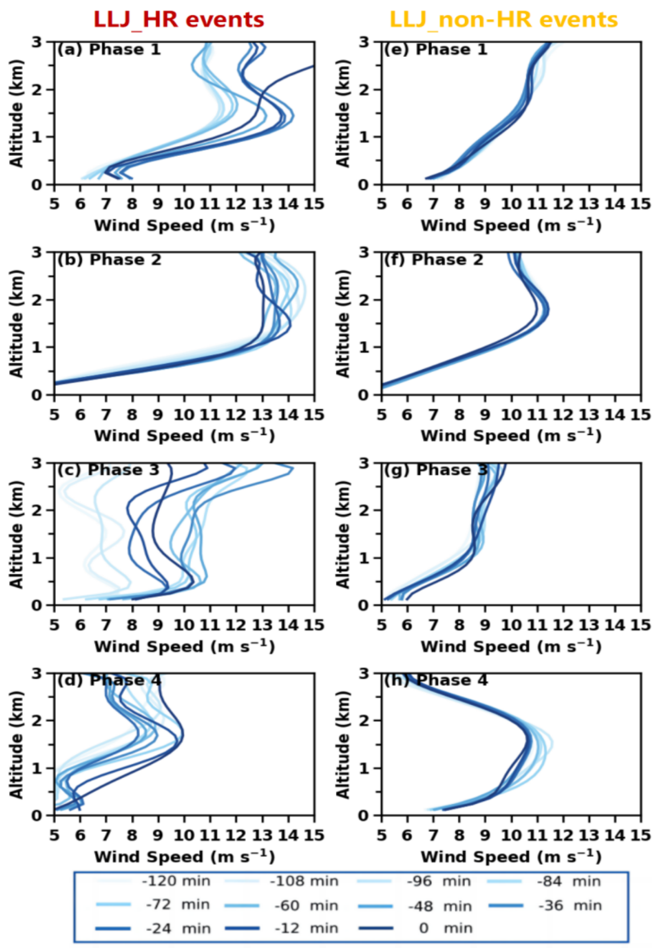

Figure S2. Same as Figure S1, but for HR events (≥95th percentile).

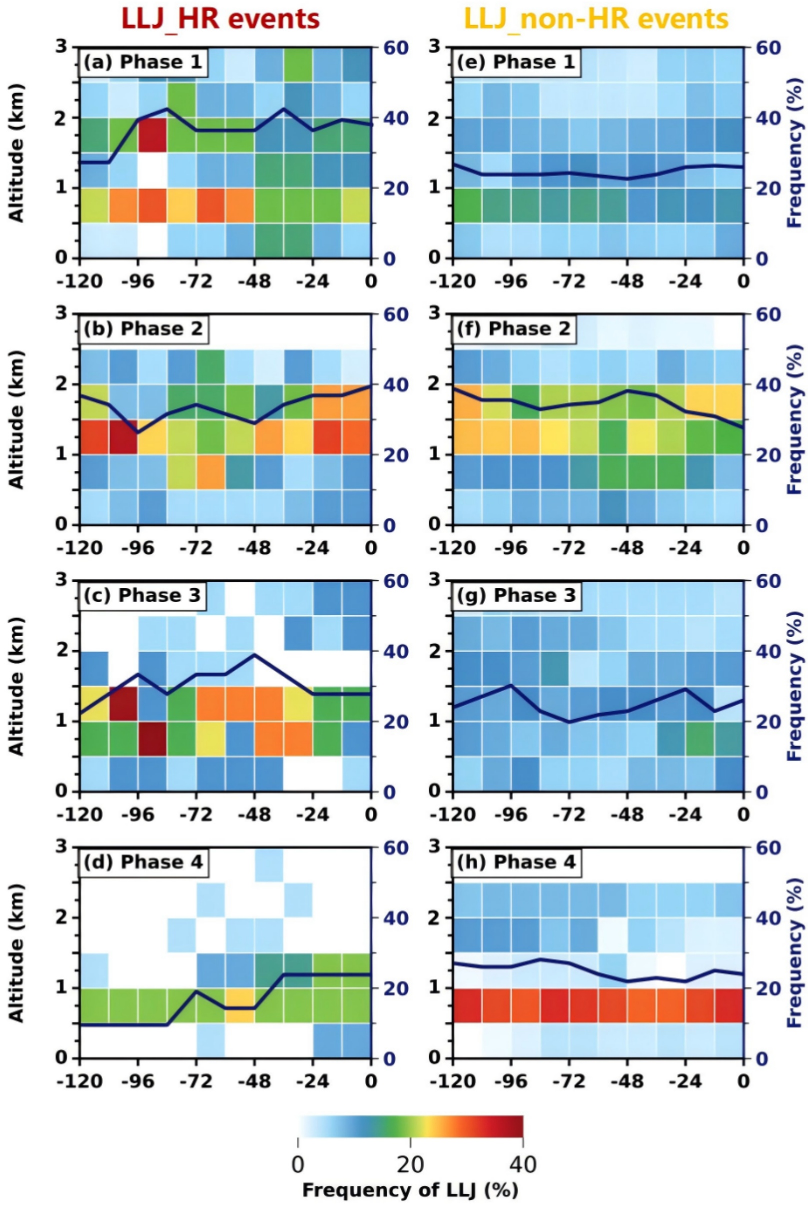

Figure S3. Time-height evolution of LLJ occurrence frequency (color shading, every 12 min, within 500 m vertical bins) detected by RWP with 2 hours preceding nocturnal rainfall in LLJ-HR (≥85th percentile) events in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) 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

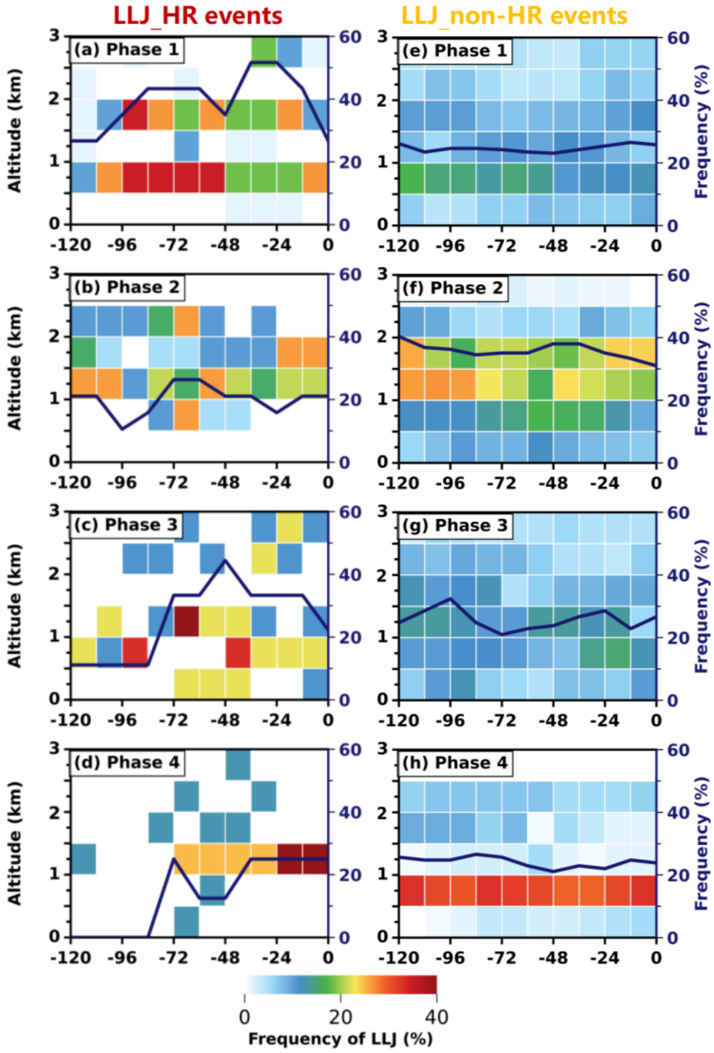

Figure S4. Same as Figure S3, but for HR events (≥95th percentile).

9. L194: Add space before 10 m s-1. The authors are encouraged to provide reference for the choice of this LLJ magnitude.

Response: Amended as suggested.

10. L203: should be "an LLJ-associated rainfall event"?

Response: Actually, in our study, the term "LLJ event" specifically denote a category of rainfall events that are associated with LLJ activity. This definition is adopted for brevity and is consistent with the convention established in prior literature in our field (e.g., Li and Du, 2021; Li et al., 2024). Therefore, this definition is clearly stated and believe it is sufficiently clear to the reader. Therefore, we have retained the original term "LLJ event" in our revised manuscript.

11. L211: The contribution rate is “50.9%” in Fig. 2g, rather than “51.6%”.

Response: Amended as suggested.

12. L212–215: Please provide literature for this speculation.

Response: Relevant literatures have been added in this revision per your kind suggestions, which is shown as follows:

“In contrast, the pronounced daytime rainfall dominance in South China 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)”

References

Bai, L., Chen, G., Huang, Y., and Meng, Z.: Convection initiation at a coastal rainfall hotspot in South China: Synoptic patterns and orographic effects, J. Geophys. Res. Atmos., 126(24), e2021JD034642, doi: 10.1029/2021JD034642, 2021.

Chen, X., F. Zhang, and K. Zhao: Diurnal Variations of the Land–Sea Breeze and Its Related Precipitation over South China. J. Atmos. Sci., 73, 4793–4815, doi:10.1175/JAS-D-16-0106.1, 2016.

13. L215–216: “52.5%” and “47.5%” is the relative contribution rate of frequency, but not the frequency of nocturnal rainfall or daytime rainfall. Please clarify the frequency at national scale that is quite confusing in current statement.

Response: We have revised the sentence to explicitly clarify that these values represent the relative proportion of occurrence frequency.

14. L222: “displayed” -> “displays”.

Response: Amended as suggested.

15. L223–226: I think the more intense nocturnal rainfall should be attributed to the absolute magnitude of nocturnal LLJs. It seems unreasonable to relate this intense rainfall with the enhancement of nocturnal LLJs relative to daytime LLJs.

Response: We fully agree with the reviewer's opinion. It is inaccurate to relate intense rainfall with the enhancement of nocturnal LLJs relative to daytime LLJs. We have revised the text to explicitly emphasize that it is the high occurrence frequency and strong absolute intensity of nocturnal LLJs that spatially correspond to the intense nocturnal rainfall, treating the diurnal difference primarily as background context:

"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)."

16. Figure 2: It seems (a)–(f) here are unnecessary to be shown since they are not cited in the text. It would be better to add relevant description for these subplots, or delete them.

Response: Per your kind suggestions, relevant descriptions for subplots of a-f have been added.

17. Figure 3d–h: Why only four directions for LLJs, but not eight directions?

Response: we have re-analyzed the data using an eight-direction classification (N, NE, E, SE, S, SW, W, NW) to better capture the subtle variations in the low-level flow. The revised figure is as follows:

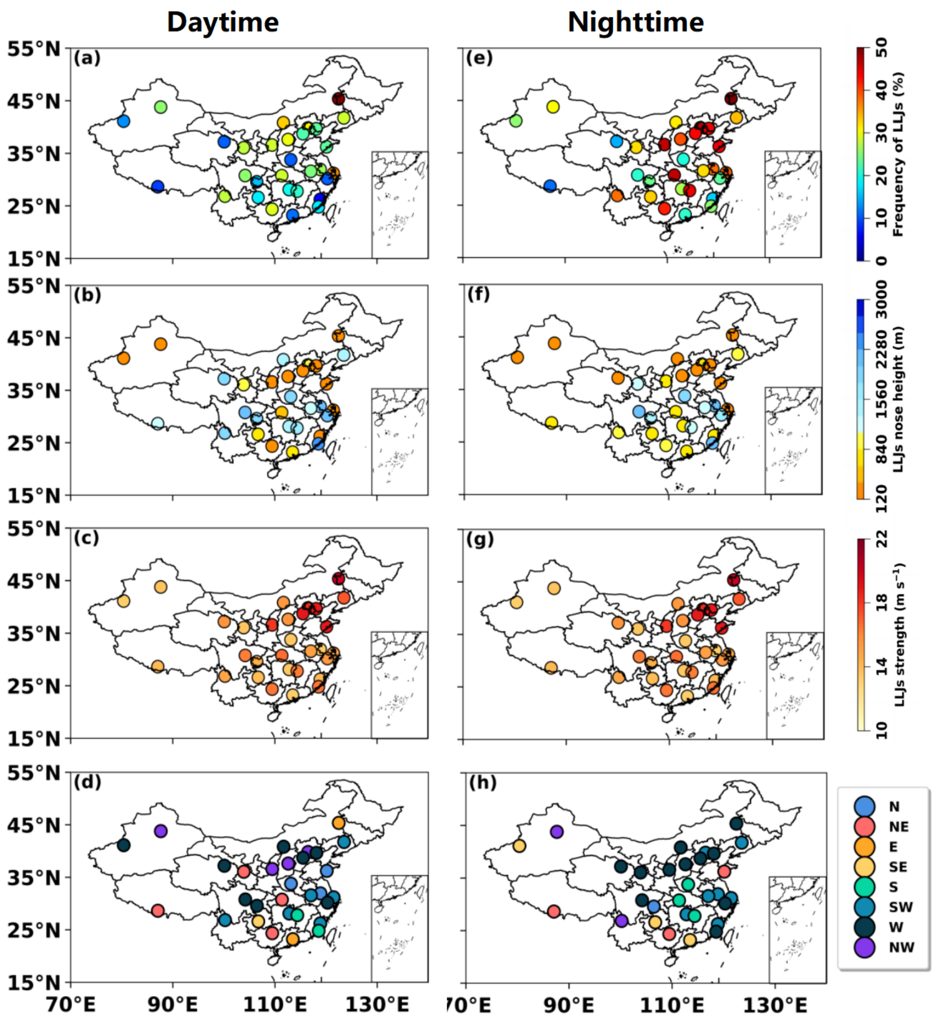

Figure 3. (a–d) Spatial distribution of occurrence frequency, height, strength, and the dominant wind direction of LLJs observed by 31 RWP stations during April–October from 2023 to 2024 in the daytime. (e–h) Same as (a–d), but in the nighttime.

18. L247: Please consider deleting "Therefore". There is no causal relationship between the two sentences.

Response: Deleted as suggested.

19. L251–253: The statement of "nearly 45.0%" cannot be well supported by the pie charts in Fig. 6.

Response: Thanks for the correction. We have removed the citation "(see the pie charts in Fig. 6)" in the revised manuscript to avoid confusion. Furthermore, we have thoroughly proofread the entire manuscript to ensure strict consistency between all textual descriptions and their corresponding figures.

20. Figure 7: Do the blue line denote the accumulated LLJ frequency over 0–3 km latitude?

Response: Yes. We have clearly stated this in the figure caption.

21. L289: Consider deleting "However".

Response: Amended as suggested.

22. Figure 8c: The maximum wind speeds are lower than 10 m/s. I wonder how they satisfy the LLJ definition in section 2.

Response: The LLJ definition (≥10 m/s) is applied to identify individual LLJ profile. However, Figure 8 presents a average result of wind profiles within 2 hours preceding to all rainfall events. Due to the variability and difference in the exact height and timing of the jet core across different events, the averaging process inevitably "smooths out" the peak intensities. Consequently, the mean maximum wind speed naturally appears lower than the threshold required for individual detection. This is an expected statistical outcome and a standard statistical characteristic of composite analysis in synoptic meteorology (e.g., Wei et al., 2013; Li et al., 2024).

23. L322–324: The double LLJs in Du and Chen (2019) are at nearly 950 hPa (BLJ) and 700 hPa (SLLJ). How the bimodal peaks here correspond to their double LLJs?

Response: The concept of "double LLJ" fundamentally refers to the coexistence of a BLJ and a SLLJ. While Du and Chen (2019) utilized specific pressure levels (e.g., 950 hPa and 700 hPa) as diagnostic proxies to represent these features in large-scale synoptic analysis, the underlying physical definitions are based on vertical height ranges rather than fixed pressure surfaces. According to the standard definition established in Du et al. (2012), BLJs are characterized by jet cores occurring below 1 km, whereas SLLJs are defined by cores within the 1–3 km layer. Therefore, the bimodal peaks observed in our study correspond precisely to these two distinct height categories, demonstrating that our vertical profile results are fully consistent with the "double LLJ" structure in South China described in previous literature.

Nonetheless, the phrasing used here to reference the literature could be misleading. Accordingly, we have amended the text.

24. L335: It should be "under 1.7 km"?

Response: We thank the reviewer for this careful check. After a thorough re-examination of the Figure 9, we have corrected the value to "nearly 1.5 km" in the revised manuscript to ensure accuracy.

25. L360: The choice of 1 hour instead of 2 hours used before should be further explained.

Response: Our choice of the 1-hour window for thermodynamic analysis was driven by two considerations:

First, large-scale thermodynamic fields (e.g., temperature, moisture) generally evolve more slowly than the fine-scale kinematic features of LLJs. We examined the conditions at 2 hours prior, 1 hour prior, and the rainfall onset time, and found that the thermodynamic patterns remained largely consistent across these intervals.

Second, the 1-hour preceding window was selected as the most representative snapshot of the "immediate pre-convective environment" that directly supports the subsequent rainfall. While Section 3.2 focused on the process of LLJ evolution (requiring a 2-hour dynamic window), Section 3.3 focuses on the background state, for which the 1-hour snapshot is sufficient and appropriate.

The above content has been supplemented and revised in the original text.

26. L363: "MFC" stands for?

Response: Apologize for the omission of full name for the acronym that appears in the first time. Actually, "MFC" stands for moisture flux convergence, which has been added in this revised manuscript.

27. L365–387: The authors are encouraged to add more specific citation of Fig. 10 and Fig. 11 for these statements, for the convenience of reader.

Response: Amended as suggested.

28. L390–391: The physical meanings of "LLJ index" and "VWS" here are unclear, especially "LLJ index". Please try to clarify these terms.

Response: Agreed. Per your kind suggestion, we have revised the manuscript to explicitly state both the calculation procedures and the reason for selecting these two variables.

The LLJ index and vertical wind shear (VWS) were used to quantify the minute-scale dynamical coupling between jet intensity and vertical structure immediately prior to rainfall onset, which provides more integrated insights than analyzing wind profiles in isolation.

For LLJ index, it is calculated as the maximum wind speed below 3 km divided by the height where the wind speed first exceeds 10 m s^{-1} (Liu et al., 2003). This index compactly links jet intensity and the vertical position where the jet becomes established. A rapid rise in LLJ index indicates a stronger jet and/or a lower occurrence height, quantitatively reflects the downward extension and pulsing intensity of the LLJ. And its magnitude has been shown to be positively correlated with subsequent precipitation intensity 1-2 hour later, providing indicative value for nowcasting.

For VWS, it is calculated as the wind-speed difference between the near-surface level and the jet level divided by the jet height (Wei et al., 2014), which measures the bulk shear from the surface to the jet layer. Enhanced VWS provides a more favorable environment for lifting and organization or intensification of convection.

The above-mentioned response and clarification have been well incorporated in this revised manuscript in the section 3.3.

29. L403: weaker increases in surface θe?

Response: Apologize for the incorrect description. We have made the revisions in our manuscript as follows:

"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."

30. L279–318, L365–447: The presentation of the results across different regimes appear to be burdensome for readers. Please consider reorganizing these texts to highlight the similarities and differences among the regimes.

Response: Amended as suggested.

Reviewer #2:

This study utilizing a nationwide network of radar wind profilers to reveal the different responses of LLJs within 2 hours preceding the onset of nocturnal HR and non-HR events during the warm season in China. Through the analysis of four Phases, the authors analyze the general characteristics, minute-scale and thermodynamic evolution between the nocturnal HR and non-HR associated with LLJs. In summary, this manuscript is well structured with detailed figures. Several statistical findings provide a comprehensive summary of the effect of LLJ in nocturnal HR and non-HR events, which offer a valuable insight and mechanism analysis for future nowcasting at the national scale. However, some critical issues remain unresolved. The manuscript would be significantly strengthened by a more in-depth analysis of the physical mechanisms underlying the distinct LLJ-rainfall relationships across different phases and regions. Furthermore, the statistical significance and physical meaning of some presented differences are not fully convincing and require further justification. The manuscript also has some typographical issues and typos, still need the authors to check carefully. I suggest major revisions before the manuscript can be accepted.

Response: We sincerely appreciate your constructive and thorough comments on our manuscript. Your insightful feedback has been invaluable in identifying critical areas for improvement, and we have carefully addressed each of your concerns through extensive revisions and supplementary analyses. We have addressed the reviewers' concern one by one to the best of our abilities. The revision has contained robust physical explanations and a cohesive methodological framework. For clarity purpose, here we have listed the reviewers' comments in bold font, followed by our response in blue plain font, and the modifications to the manuscript are in blue italics.

Major Comments:

1. This work valuably extends the authors' previous research from North China to a national scale. To contextualize this new contribution, a dedicated discussion about differences and similarities with those from your previous regional study would be highly beneficial for readers.

Response: Good point! Per your kind suggestion, more in-depth discussion for this difference and similarities with our previous regional study (i.e., Li et al., GRL 2024) has been added in this revision, which is shown as follows:

1. In the Introduction section:

"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."

2. In the Conclusion section (Section 4): To systematically synthesize the comparison, distinguishing between validated commonalities and new, broader insights specific to the national-scale analysis. The core of the comparison is as follows:

(1) Universality (Similarities):

This nationwide study confirmed the final-stage intensification and reorganization of the LLJs specifically within the last 30 min preceding rainfall, in synergy with thermodynamic instability, is a universal prerequisite for triggering nocturnal heavy rainfall. This validates the "rapid intensification of LLJs profiles within 30 min before rainfall" identified in our previous North China study as a robust signal across diverse monsoon regions.

(2) New insights (Differences & advancements):

For spatiotemporal scope: This study expands from a single region (North China) to a national scale covering four distinct climatic zones and extends the temporal analysis to four phases of rainy season.

For mechanistic depth: We identified a synergistic "preparatory reorganization" phase occurring 30–120 minutes prior to HR, which was not fully observed in the previous study.

We found that the final dynamic trigger is contingent upon this earlier period in LLJ_HR events, where rapid minute-scale LLJ evolution couples with thermodynamic destabilization (e.g., jet core descent/ascent, transient weakening followed by strengthening, θ_e surge), although the specific pathways of this reorganization exhibit significant spatial and phase heterogeneity and differences in temporal evolution across seasonal phases. This "rapid reorganization" of the coupled dynamic-thermodynamic field constitutes the essential precondition for LLJ_HR generation distinct from LLJ_non-HR events, which contrasts sharply with the weaker, quasi-steady evolution of LLJs and insufficient dynamic-thermodynamic coupling 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.

2. L141-145: The method of quality control in unclear. The authors mention that eliminated the observation during rainfall periods but don't give an explanation. I recommend explaining it to help the readers to understand. And in the second step, the authors don't clarify the standard of outliers, is it same as the standard in the third step? It is necessary to adjust the order to describe the definition of outliers

Response: Apologize for the unclear description of the quality control procedures in the original manuscript. We have revised the text to clarify the quality control step and the physical rationale for excluding rainfall data. The revised descriptions are shown as follows:

"Firstly, to minimize contamination from precipitation particles, which can introduce significant errors in Doppler-based wind retrieval, all observations during 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."

3. Is it reasonable to set the threshold of exceeding the 75th percentile of all rainfall events to define the HR events? The authors can supply that is it previous studies used this standard?

Response: Yes, we deem the use of a station-specific 75th percentile threshold—exceeding this value to define heavy rainfall (HR) events—reasonable and necessary for the present study, for the following two key considerations:

Firstly, a sufficient sample size is prerequisite for the minute-scale statistical analysis of LLJ evolution preceding rainfall. As evidenced in Table S1, utilizing a stricter threshold (e.g., the 85th and 95th percentile) would drastically reduce the sample size to single digits in certain phases, rendering statistical conclusions unreliable and without statistical significance. The 75th percentile effectively retain a sufficient sample size to ensure statistical power while still effectively filtering out weak precipitation.

Secondly, sensitivity analysis by varying the thresholds to 85th and 95th percentile to ensure our key conclusions are not artifacts of this specific threshold. As shown in Figure S1–S4, the results showed that although the specific lead times varied when changing the thresholds, LLJ_HR events still undergo a minute-scale "rapid reorganization" characterized by oscillations in jet height, frequency and strength, and the "final-stage intensification" of LLJs structure. LLJ_non-HR events still exhibit quasi-steady or declining dynamical response of LLJs. The main conclusion regarding the precursory signals of LLJs is robust within a reasonable threshold range.

Therefore, the 75th percentile serves as an optimal balance between maintaining statistical power and successfully distinguishing the essential difference of dynamical mechanisms prior to HR and non-HR events. Thank you for raising this important point regarding the percentile-based threshold for defining HR events, which prompted a thorough investigation. We have incorporated these justifications and the sensitivity analysis results into Section 2.3 and the Supplementary Material of the revised manuscript.

Table S1 Statistics of the number of LLJ_HR and LLJ_non-HR events during four rainy season phases under different percentile levels of rainfall intensity

Type	Percentile	Phase 1	Phase 2	Phase 3	Phase 4
LLJ_HR	75th	29	26	15	12
	85th	20	15	10	8
	95th	9	8	5	4
LLJ_non-HR	75th	71	69	30	25
	85th	95	103	47	33
	95th	110	112	53	38

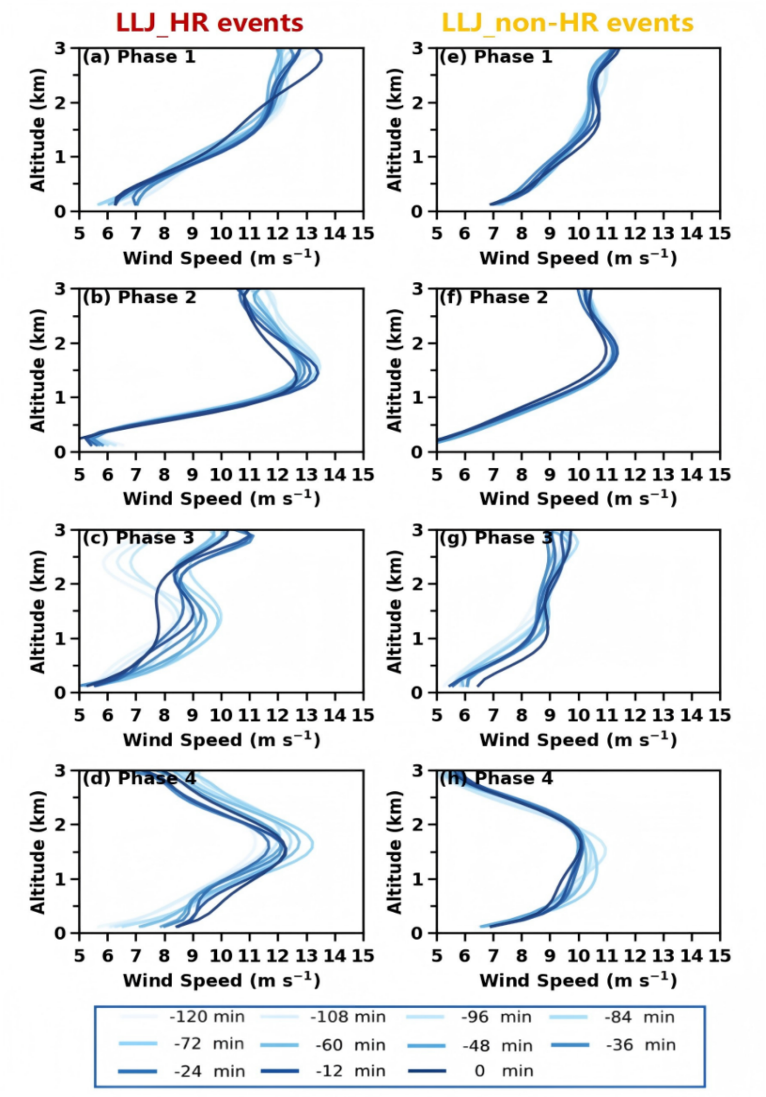

Figure S1. (a-d) Evolution of RWP-detected mean wind profiles of LLJs (blue solid lines, every 12 min) within 2 hours preceding nocturnal rainfall in LLJ-HR events (≥85th percentile) in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) in ROI-4 during Phase 4. (e-h) Same as (a-d), but for LLJ_non-HR events

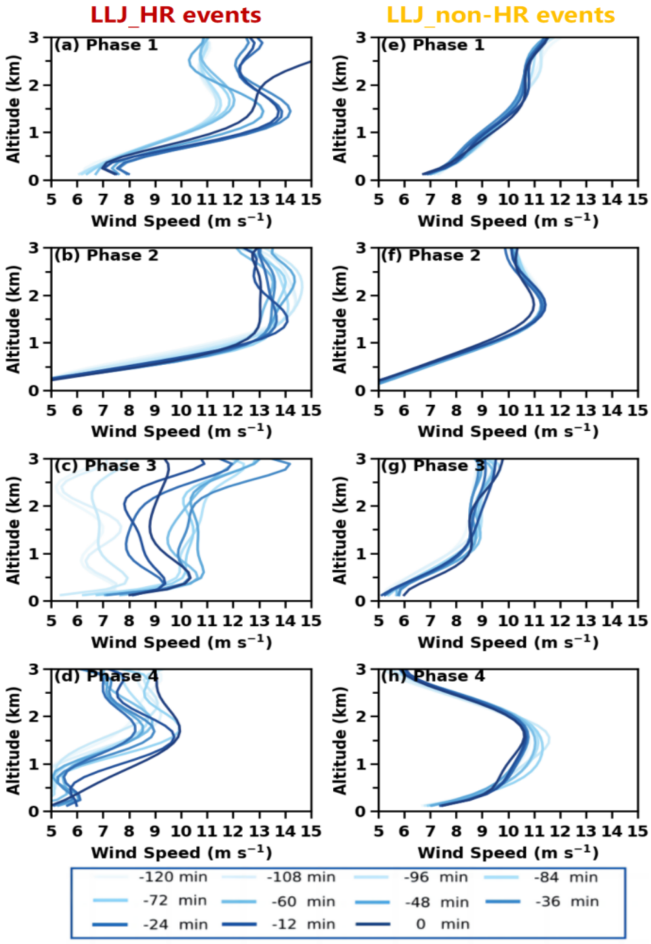

Figure S2. Same as Figure S1, but for HR events (≥95th percentile).

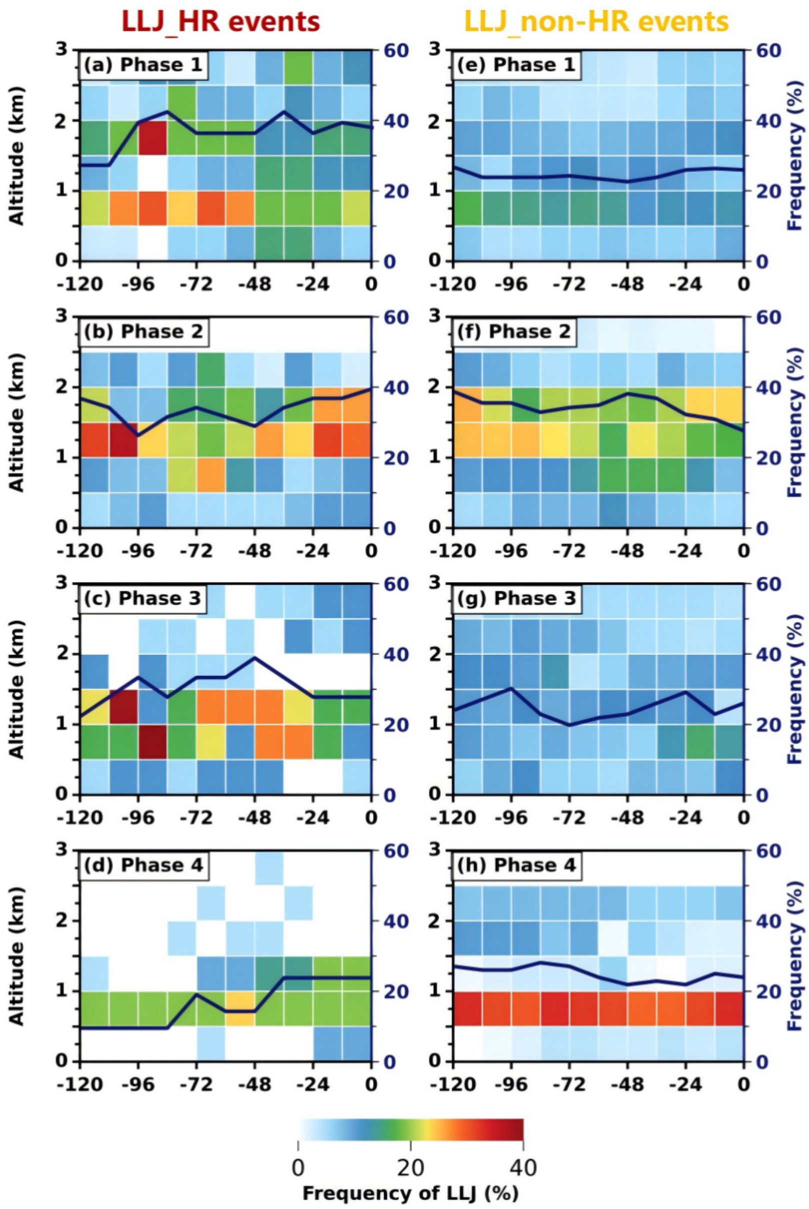

Figure S3. Time-height evolution of LLJ occurrence frequency (color shading, every 12 min, within 500 m vertical bins) detected by RWP with 2 hours preceding nocturnal rainfall in LLJ-HR (≥85th percentile) events in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) 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

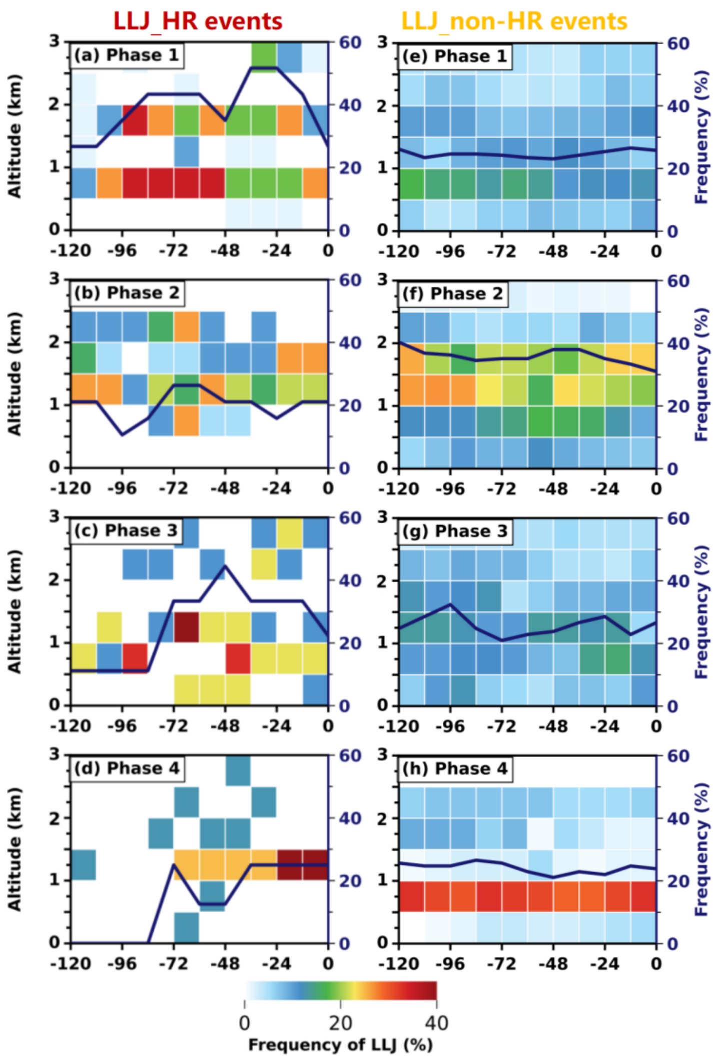

Figure S4. Same as Figure S3, but for HR events (≥95th percentile).

4. Section 2.4: The identification of LLJs in this work doesn't consider the BLJs and SLLJs. However, you investigated the BLJ (SLLJ)-induced rainfall event in your previous work. Why you just count the LLJs in this study? Additionally, the authors don't consider the position of LLJs. More study focuses on the upstream areas of rainfall to study the effect of LLJs. Is it reasonable to identify rainfall events within a 25-km radius of RWP. Is it a reason that only a little more than half of HR preceded by LLJs.

Response: We provide a point-by-point clarification as follows:

1. Regarding the distinction between BLJs and SLLJs:

First, the primary objective of this current study is to investigate the minute-scale evolution of the vertical wind profile and its direct kinematic impact on rainfall occurrence. The jet noses of LLJ and its profiles from RWP observations can directly reflect the fine vertical structure of LLJs, no matter it originates from a synoptic system or boundary layer forcing.

Second, the classification at the national scale will induce significant uncertainty and complexity. While distinguishing BLJs and SLLJs is valuable for single-site mechanism studies, it is impractical and inconsistent with the original intention for a nationwide investigation involving multiple regions, sites, and rainy seasons, especially focusing on the continuous minute-scale evolution of jets.

Moreover, further stratification would reduce the sample size and affect statistical stability. The classification of BLJs and SLLJs is subjective and therefore adopting the original LLJ profiles allows us to directly capture all rapidly developing low-level wind signals associated with imminent rainfall.

2. Regarding the LLJ position:

We acknowledge that upstream LLJs are critical for triggering rainfall and likely to affect the frequency statistics of LLJ_HR events. However, this study does not exclusively consider upstream LLJs, mainly due to the following reasons:

First, many previous studies focus on upstream areas of rainfall to investigate LLJ impacts, but most rely on reanalysis data (e.g., Zhang et al., 2025). In contrast, our study used the high-resolution wind measurements from RWP networks in China to analyze the fine vertical structure and evolution of LLJs preceding rainfall. The current RWP network has an uneven spatial distribution density compared to the reanalysis data, with inter-station distances ranging from about 30 km to several hundred kilometers. Consequently, it is technically infeasible to systematically track upstream trajectories for every station, as many sites lack corresponding upstream profilers.

Second, we aim to reveal the fine-scale, “point-to-point” coupling between vertical wind structure and local rainfall initiation. Therefore, this study employs a high-resolution observational approach that anchors to a single RWP site, directly establishing a direct link between LLJs (observed by single RWP) and associated local rainfall events (identified by rain gauges within a 25 km radius centered on the RWP). Focusing on LLJs detected directly overhead can provide the most direct evidence of local dynamic triggering. While this strict criterion excludes cases where only the upstream jet is active, it ensures that the observed wind profile evolution is physically co-located with the rainfall event. And the influence of upstream flow (e.g., advection) is indirectly addressed in our large-scale circulation analysis (Figs. 10–11).

3. Regarding the 25-km radius

The 25-km radius serves as a strict spatial constraint, which can effectively ensure the identification of rainfall centered on RWP and the time matching between rainfall events and RWP observations, thereby enabling a more reliable identification of LLJ-related rainfall processes. The reasons are as follows:

Firstly, a single rain gauge often misses local convective cells due to the limited spatial representativeness or potential data gaps of a single rain gauge. The 25-km radius ensures that at least two gauges are included, providing a more reliable detection of rainfall occurrence centered on the RWP. This ensures better spatial coverage and reduces the risk of missing rainfall events near the profiler site.

Secondly, a sensitivity test was conducted by varying the radius (25, 50, and 100 km) to validate the temporal consistency in rainfall onset times between the rain gauge co-located with RWP and those within different respective radius. As shown in Figure S5, the time difference increased significantly as the radius increases. The median time difference for the 25-km radius is minimal (nearly simultaneous), confirming that precipitation systems at this scale are spatially coherent with the rain gauge co-located with the RWP. The high temporal synchrony within 25-km radius ensures that the overhead wind profile detected by the RWP serves as a valid precursor dynamically linked to the rainfall initiation. An overly large radius (e.g., >50 km) would include rainfall events that are dynamically decoupled from the RWP's observation range, potentially leading to misinterpretation of the pre-convective wind field or miss LLJ detections.

Although the strict spatiotemporal criteria may limit the number of detected LLJ-HR events, they ensure that every identified event represents a robust, physically coupled process. We appreciate the reviewer's valuable comments, which not only help clarify the design logic of this study but also point to clear directions for future research.

The above-mentioned response and clarification have been well incorporated in this revised manuscript in the section 2.4 and the Supplementary Material.

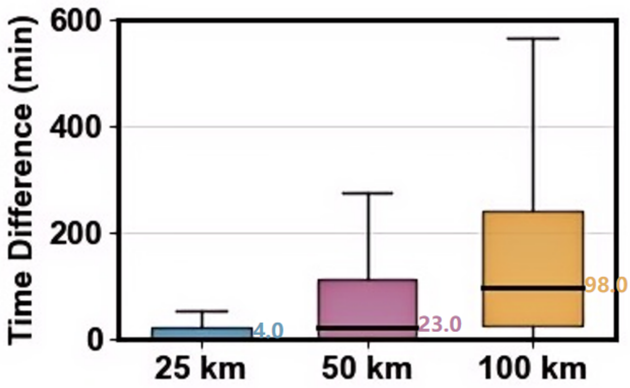

Figure S5. Sensitivity of temporal differences in rainfall event onset to the selection radius. The boxplots display the absolute time difference between the onset of each rainfall event identified by rain gauges within a 25-km, 50-km, or 100-km radius area and the onset of the temporally closest rainfall event identified by the rain gauge co-located with the RWP within four ROIs during correspondent phases.

5. The authors emphasize the importance of LLJs prior to nocturnal rainfall. However, the statistics show that only 56% of HR preceded by LLJs and less than half (40%) of nocturnal HR were associated with LLJs. Moreover, some regions in Fig. 6 show that more HR event are not associated with LLJs, particularly in ROI-4 and ROI-1. The relationship between HR and LLJs seems not close, how the authors consider the contradictory between the importance of LLJs and the small proportion of LLJ_HR.

Response: We think that the "importance" of LLJs is defined by their physical efficiency in enhancing rainfall intensity and their distinctive precursor signals related to their dynamical structure, rather than solely by their occurrence frequency. We clarify this through the following points:

1. The observed proportion aligns with recent studies using reanalysis data (e.g., Du and Yi, 2025), which reported that approximately 30% of HR events were associated with LLJs. Our result (~45% for nocturnal LLJ_HR) is consistent with, and even slightly higher than, these results. This proportion already clearly establishes the LLJ as a prevalent and fundamentally important precursor environmental and key factor influencing nocturnal rainfall.

2. The proportion of LLJ_HR events should be understood in light of our study's objective: to examine the fine-scale evolution of LLJs in the immediate 2 hours preceding nocturnal rainfall. As detailed in our response to Comment 4, our strict spatiotemporal criteria require an LLJ to be detected directly overhead within 2-hour window preceding rainfall. This approach inherently excludes HR events where LLJs exerted an indirect or earlier influence (e.g., occurring > 2 hours before rainfall or without the jet core passing over the station), thereby underestimating the broader climatological contribution but ensuring that the analyzed events represent the most direct dynamic coupling.

3. The lower proportions in ROI-1 and ROI-4 (Fig. 6) reflect genuine regional climatological differences rather than a lack of LLJ importance. In ROI-2 (Meiyu season) and ROI-3 (North China rainy season), the large-scale circulation patterns favor LLJs as a frequent trigger, hence the higher proportion of LLJ_HR events. In contrast, in ROI-1 (South China pre-summer rainy season) and ROI-4 (West China autumn rainy season), nocturnal rainfall triggering is more complex, involving diverse mechanisms such as topographic lifting (Bai et al., 2021), coastline (Lee et al. 2019), or cold pools (Du et al., 2020), which may occur without a pre-existing LLJ within 2 hours prior to rainfall. However, crucially, the fine-scale structure of LLJs remains a key precursor (e.g., a surge in LLJs frequency at -84 min in Phase-1; a rapid increase in LLJ frequency and intensity from -48 min in Phase-4) and has a critical influence on the subsequent rainfall intensity during different phases and regions. When LLJs do occur in these regions, they often lead to more intense rainfall compared to non-LLJ events.

4. The core value of studying LLJs lies in their mechanism of action rather than just their frequency. Our core finding is that LLJ_HR events exhibit a unique, rapid minute-scale dynamical evolution tightly coupled with thermodynamic instability before rainfall. This specific evolution pattern is largely absent in LLJ_non-HR events. Therefore, the "importance" of LLJs is predicated on their role as a highly efficient dynamical driver that, when present, decisively modulates rainfall intensify and provides a clear, physically interpretable precursor for nowcasting.

Overall, the significance of LLJs for nocturnal HR cannot indeed be directly captured by the statistical proportions presented in this study. We have revised all relevant descriptions in the manuscript accordingly to explicitly distinguish between "statistical frequency" and "dynamical significance".

6. The authors mention the nocturnal rainfall accounted for 51.6% of total warm-season rainfall in Fig. 2g (L210-211). However, the figure depicts the ratio of 50.9%. Moreover, the caption in Figs. 2g-2i show that it is the contribution ratios of heavy rainfall. So, I recommend the authors using nocturnal heavy rainfall in L215-217.

Response: Apologies for the confusions caused by the by the incorrect value and the unclear descriptions in our original manuscript. We sincerely thank the reviewer for their careful reading and for pointing out these inconsistencies. We will make the following specific corrections in the revised manuscript to ensure full accuracy and clarity:

1. In lines 210-211, the value "51.6%" will be corrected to "50.9%".

2. Regarding the term "heavy rainfall", we acknowledge that our initial description was imprecise. Only Figure 2i pertains specifically to heavy rainfall (＞75th percentile intensity). Figures 2g and 2h show the nocturnal contribution to total rainfall amount and total frequency, respectively. To eliminate ambiguity, the caption for panels (g)-(i) will be revised from "(g-i) Nocturnal contribution ratios of accumulated rainfall, frequency, and occurrence frequency of heavy rainfall." to the more precise description "Nocturnal contribution ratio to (g) the total accumulated rainfall, (h) the total rainfall

frequency and (i) the frequency of heavy rainfall (＞75th percentile intensity).”

7. The legend of all events in Fig 4a is easy for readers to misunderstand. I recommend modifying it to all nocturnal events. In L240-244, the ratio of non-LLJ and LLJ in HR events are lower than all nocturnal events, both the four ROIs occur the same reduction. Why the authors state the statistics demonstrate the crucial role of LLJs in nocturnal rainfall?

Response: Per your suggestion, we have corrected the legend in Figure 4a to “all nocturnal events” to avoid ambiguity. The revised figure is included below and has been updated in the manuscript.

The conclusion drawn from the statistics in lines 240-244 is imprecise and potentially misleading. we agree that these aggregated statistics alone cannot be used to claim a “crucial role” of LLJs for nocturnal rainfall. They are mainly used to describe a statistical phenomenon. Our primary intention was not to assert crucial role of LLJs based solely on relative proportions and related explanation have provided in Comment 5. We have revised the relevant text in Section 3.1 to reflect this more objective interpretation.

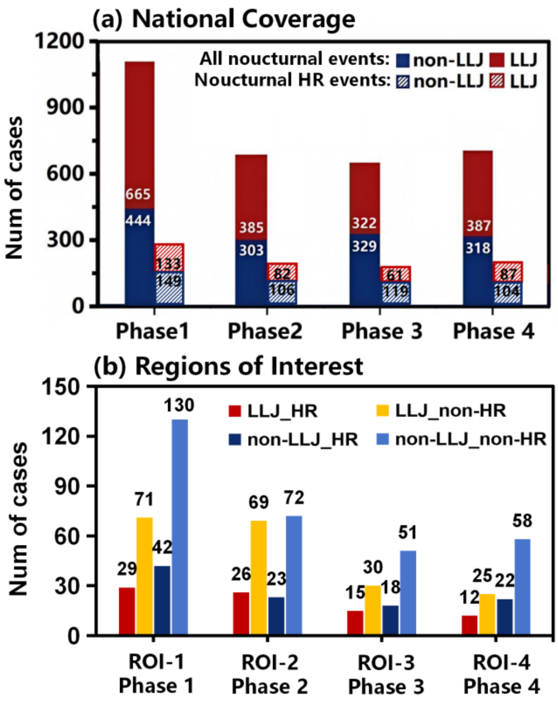

Figure 4. (a) Statistic of all nocturnal rainfall events (solid-filled bars) and heavy rainfall (HR; diagonally striped bars) events selected across China during four phases, including LLJ events (red) and non-LLJ events (blue); (b) Statistic of nocturnal HR events in from ROI-1 to ROI-4 during corresponding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

8. L247-249: The number of nocturnal HR events are mistake. The authors plus LLJ_HR, LLJ_non-HR, and non-LLJ_HR. Actually, the LLJ_non-HR is redundant, and the number of HR events are smaller than the article described. Additionally, the red column of LLJ_HR in Fig. 4b is smallest, more events are LLJ_non-HR and non-LLJ_HR, how to explain this phenomenon.

Response: Apologize for the oversight in the statistical calculation and have corrected the results in the revised manuscript. The numbers have been thoroughly rechecked and corrected in the revised manuscript. The counts for LLJ_HR and non-LLJ_HR events (71, 49, 33, and 34 in the four ROIs) are now accurately presented.

Regarding the observation that LLJ_HR events are fewer than non-LLJ_HR and LLJ_non-HR events, we provide the following explanation:

Firstly, non-LLJ_HR events are substantial because they can be initiated by alternative forcing mechanisms independent of overhead LLJs, such as strong orographic lifting, cold frontal passages, or propagating mesoscale convective systems (MCSs). These events fall into the non-LLJ_HR category.

Secondly, the prevalence of LLJ_non-HR events indicates that the mere presence of an LLJ is often a necessary but insufficient condition for HR (Du and Yi, 2025). While LLJs frequently provide background moisture and shear, they often lack the specific minute-scale dynamic adjustments of the LLJ itself and sufficient thermodynamic instability required to trigger HR, thus resulting in only light-to-moderate precipitation (as verified in Figs. 7 and 8).

Consequently, LLJ_HR events represent a more stringent subset, making them naturally less frequent than general LLJ activities or rainfall driven by other synoptic systems. This difference in proportion precisely reflects the diversity of mechanisms underlying nocturnal HR and highlights that the relationship between LLJ occurrence and nocturnal rainfall intensity is not straightforward. Our study precisely aims to elucidate the differential contributions of LLJs to HR versus non-HR events and to identify the specific fine-scale structural characteristics that distinguish the LLJ_HR from LLJ_non-HR.

We have clarified these statistical corrections and physical interpretations in Section 3.1 of the revised manuscript.

9. How do the authors define the heavier rainfall in L259? Why the authors consider the differences were less pronounced only during Phases 2 and 4.

Response: In Figure 6, "heavier rainfall" means that the tendency for LLJ_HR events to exhibit a higher probability density in the upper tail of the intensity distribution (specifically ⩾2 mm/6 min) compared to non-LLJ_HR events. Physically, this implies that the presence of an LLJ shifts the rainfall distribution toward more extreme intensities.

The statement "the differences were less pronounced during Phases 2 and 4" means that during these two phases, the probability distributions for LLJ_HR (black lines) and non-LLJ_HR events (gray lines) largely overlap across most intensity ranges. LLJ_HR events show no obvious probability advantage for intensities ⩾2 mm/6 min and, in some intervals, even exhibit lower probabilities. In contrast, during Phase 1 and 3, LLJ_HR events show a distinct probability advantage in the high-intensity range (⩾ 2 mm/6 min).

We have revised the corresponding text in the manuscript to clarify that "heavier rainfall" and the above-mentioned response now reads as follows:

"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. "

10. Fig 5f. shows the Phase 2 with non-LLJ_HR events. The high values of rainfall intensity appear at the North China, rather than Yangtze River Basin. How this explain?

Response: The pattern in Figure 5f indeed differs from the typical spatial distribution of Meiyu reason, but it truthfully reflects the accumulation of events that happened at different times and were driven by distinct synoptic systems during this phase, for the following reasons:

1. Figure 5 displays the spatial distribution of average rainfall intensity of all non-LLJ_HR events that were independently identified by rain gauges around each RWP station over the entire Phase 2 period. Therefore, we have carefully examined the rainfall records in ROI-2 and ROI-3 during Phase 2 (Fig. S6). The results confirm that several regional HR events not associated with LLJs did occur over ROI-3, e.g., during 10–12 July 2023, 4–6 July 2024, and 14 July 2024, with the site-averaged daily accumulated rainfall reaching about 8–14 mm. These events are consistent with the official CMA reports (e.g., https://www.cma.gov.cn/; http://www.gd.xinhuanet.com/20230713/6e85daa45b8e484aa6e5ce8fda3b4c0/c.html), and they were not contemporaneous with the non-LLJ_HR events identified in ROI-2. While ROI-2 has a higher frequency of rainfall during Phase 2, the non-LLJ events in ROI-3 includes distinct, high-intensity HR, which significantly elevated the regional average intensity in ROI-3 for the non-LLJ category.

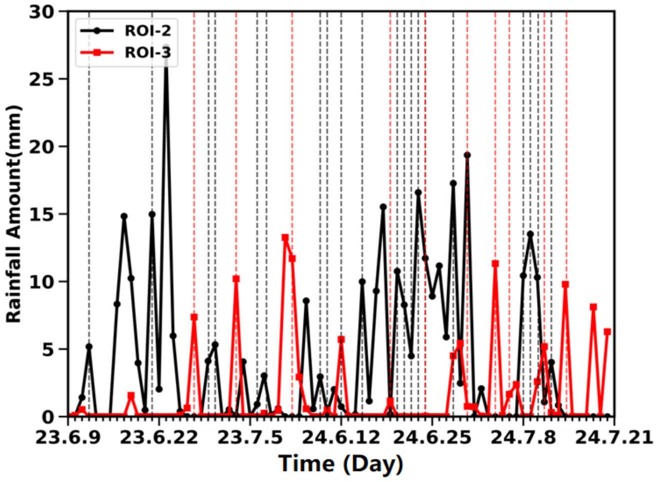

Figure S6. The average daily accumulated rainfall within ROI-2(black line) and ROI-3(red line) during Phase 2. The dotted lines represent the occurrence times of non-LLJ_HR events identified within ROI-2 (black) and ROI-3 (red).

2. The non-LLJ_HR events in the two regions during Phase 2 is predominantly driven by different synoptic systems.

Over the Yangtze River Basin, more than half of the HR events belongs to the typical "LLJ-driven Meiyu heavy rainfall" (Fig. S7b). When we isolate the non-LLJ subset, we are effectively removing the most intense Meiyu rainfall events. The remaining non-LLJ events in ROI-2 are typically associated with weaker forcing mechanisms (e.g., decaying fronts or weak shear lines) although a high warm-moisture zone still covers the region (Figs. S7c and d), resulting in widespread but generally less intense rainfall. This further reflects the key role of LLJ in primary rain belts.

The non-LLJ HR events in ROI-3 are predominantly driven by mid-latitude cold vortices, westerly troughs, or shear lines (i.e., "trough/cold-vortex-type" rainstorms). As shown in Figs. S7e and f, even in the absence of a strong low-level jet, the combination of deep large-scale ascent (induced by the upper-level trough) and strong baroclinic instability is sufficient to trigger severe convection with high rainfall intensity.

In conclusion, the spatial pattern in Figure 5f reflects the statistical aggregation of independent events across Phase 2. Our results objectively captures the spatially heterogeneous intensity distributions and localized maxima occurred in areas outside the primary rain belts (Fig. 5) in non-LLJ_HR events, which further reflects the dominant role of LLJ coupling in primary rain belts region. We have added this explanation to Section 3.2 of the revised manuscript.

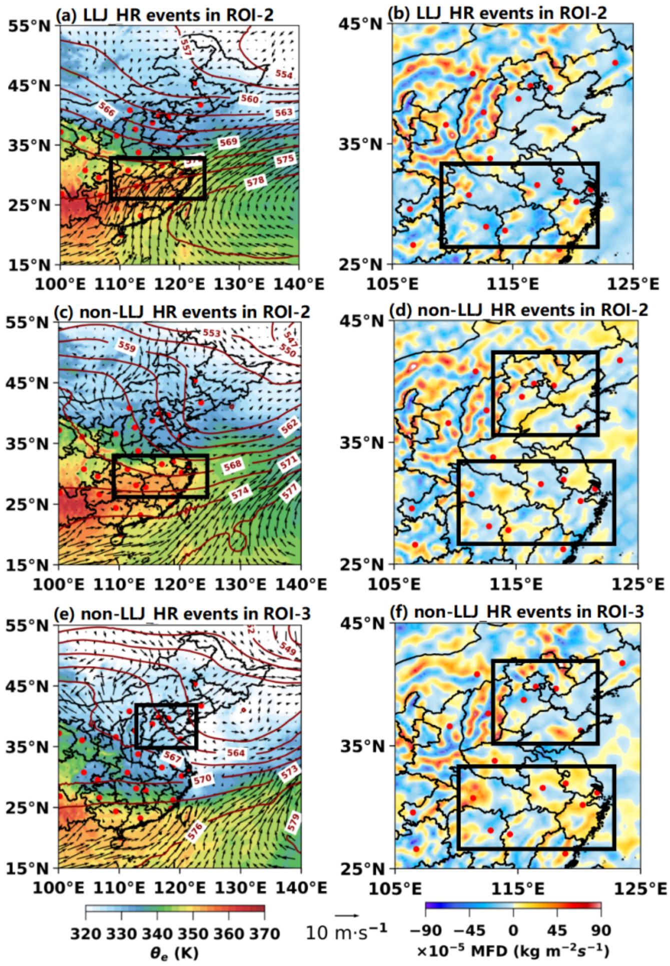

Figure S7. Distributions of (a) equivalent potential temperature (shading, unit: K) at 850 hPa, superimposed with 850 hPa horizontal wind vectors (black arrows) and 500 hPa geopotential height contours (red solid lines) and (b) the integrated moisture flux divergence (shading, unit: kg·m^{-2} s^{-1}) between 1000–700 hPa for LLJ-HR events within 1-hour time window preceding nocturnal rainfall onset in ROI-2 during Phase 2. The reference vector (10 m s^{-1}) is shown at the lower corner. (c-d) and (e-f) Same as (a-b), but for LLJ_non-HR events in ROI-2 and LLJ_non-HR events in ROI-3, respectively.

11. The authors just describe some figures' features in Section 3.2 but don't explain its possible reasons and mechanisms. How are the differences in the relationship between different phases and LLJs? And why the statistics show these results? For example, why LLJs featured a bimodal vertical distribution with frequent occurrence layers and just a single peak in non-HR events? Why the height of LLJ_HR events is lower than non-HR events in Phase 2?

Response: Thanks for your insightful and constructive comment. We agree that describing features is insufficient and need the deeper mechanistic interpretation. In our response, we will have extensive discussions on the physical mechanisms governing these differences, and address your specific questions regarding the bimodal distribution (Phase 1) and height differences (Phase 2), followed by a summary for Phases 3 and 4.

1. Reason for bimodal vertical distribution in Phase 1 (ROI-1):

The observed double-peak vertical structure in LLJ_HR events is often associated with the coexistence of BLJ and SLLJ—referred to as a double low-level jet (DLLJ), which in the southwesterly moist flow play a significant role in the HR over southern China (e.g., Uccellini and Johnson, 1979; Du and Chen, 2018). Examination of wind profiles for each LLJ-HR event shows that approximately 40% (11/29) of LLJ_HR events exhibit DLLJs, whereas only 20% of LLJ_non-HR events show such a structure. This is consistent with results of previous studies Li and Du, 2021). DLLJ events generally produce stronger rainfall compared to the general LLJ events (Zhang and Meng, 2019; Liu et al., 2020). This is because the DLLJ tends to generate a deep layer of forced ascent due to the convergence at the BLJ exit region and divergence at the SLLJ entrance. This coupling markedly enhances vertical motion, moisture convergence, and release of convective instability, thereby favoring organized deep convection and HR (Du and Chen, 2019). In contrast, the bimodal vertical distribution with frequent occurrence layers in LLJ_non-HR events is not significance. They mainly concentrated within the height range of 0.5–1 km, lacking such multi-level dynamical forcing and resulting in lower convective initiation efficiency.

Our results underscore the importance of SLLJ–BLJ coupling in regulating HR over ROI-1. Note that the composite wind profile (Fig. 8) does not show a distinct bimodal vertical distribution due to smoothing from averaging; however, the feature is evident in the distribution of LLJ frequency and height (Fig. 7 and 9).

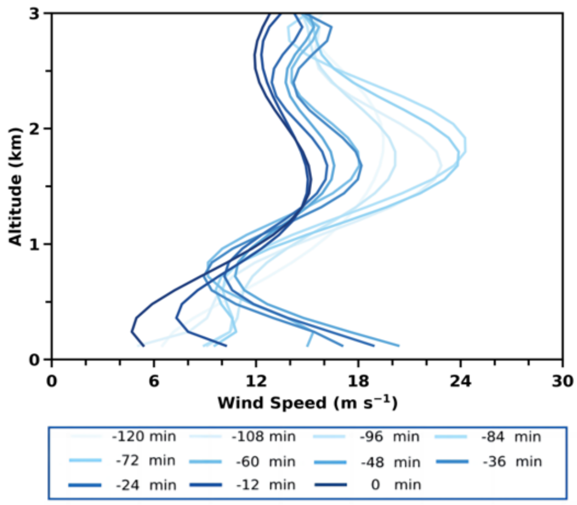

Figure S6 A case used to show DLLJs in LLJ_HR events based on the RWP measurements, which occurs on 0630 (UTC) April 5, 2023.

2. Mechanism for lower jet height in Phase 2 (ROI-2):

The LLJ_HR events are characterized by a two-stage dynamical process with rapid lowering of the LLJ core below 1 km, followed by a subsequent rebound. In LLJ-non-HR events, the jet core remains relatively stable between 1-2 km, directly explaining the lower core height observed in LLJ_HR events.

Stage 1: The "sudden drop" of the LLJ core likely results from downward momentum transfer. Intensification of an upper-level jet can generate turbulence or gravity-wave breaking that mixes momentum downward, thereby reducing the height of the maximum wind speed. We further calculated the kinetic energy of wind (KE) and the transport of kinetic energy in the vertical direction (TV), which are considered to reflect the change of LLJ nose height being caused by momentum transfer (Fu et al., 2020). The equations are as follows:

$$KE=(u^2+v^2)/2 \quad (1)$$

$$TV=-w\frac{\partial KE}{\partial z} \quad (2)$$

where u, v, and w represent the u and v wind components and vertical velocity as measured by the RWP, respectively, and z is altitude.

Figure S6a show that the downward stretching of high KE occurred from about 2–2.8 km to 1.7 km within 120-84 min preceding LLJ_HR events (Figure. S7a). Meanwhile,a significant downward transport of KE (negative TV) appeared from 120 min to 60 min preceding HR (Figure. S7c), peaking below 1 km around 66 min before HR, which was consistent with the observed changes of LLJ (cited in Fig. 7b and 8b) in the same period. This process efficiently enhance dynamic forcing into the boundary layer and increase low-level disturbances, which can serve as an effective indicator of HR 1–2 hours later (Liu et al. 2003). In LLJ-non-HR events, however, such downward momentum-transfer signals are weak, even when regions of high KE and some downward transport exist between 1–2 km (Fig. S7c and d).

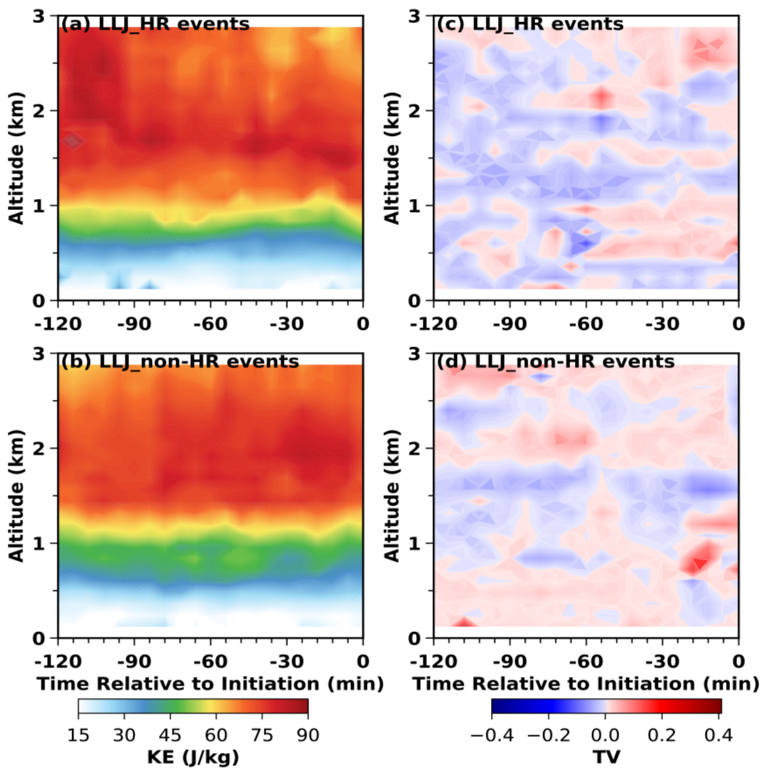

Figure. S7 (a) Evolution of mean wind kinetic energy (units: $J\ kg^{-1}$) and (b) the transmission of kinetic energy in the vertical direction preceding nocturnal rainfall in ROI-2 during Phase 2 in LLJ_HR events. (c-d) The same as panel (a-b), but for LLJ_non-HR events.

Stage 2: The subsequent LLJ height recovery and secondary enhancement are likely tied to cold pool-LLJ interactions and intensified upward motion or latent heat release in convective clouds. Convective systems during the Meiyu season over the Yangtze-Huai region often exhibit less-organized, transient organizational modes, e.g., embedded convective systems (e.g., J. Li et al. 2021; Markowski & Richardson 2010; Púčik et al. 2011). Therfore, earlier (or adjacent) rainfall associated with alternation of convective systems may have generated a shallow cold-pool outflow, which can affect regions away from their border (Luiz & Fiedler, 2023). The resulting dense cold air wedging beneath the warm and moist LLJ can lift the jet axis above the cold-pool interface (Luo et al. 2014). This is consistent with the rapid surface cooling beginning 60 min before HR (Fig. 12b) and the re-intensification and upward shift of the LLJs (Fig. 7b and 8b). Importantly, this configuration sharply enhances low-level vertical wind shear and horizontal convergence (Fig. 12b), further promoting HR development.

3. Differences and common in four phases

During Phase 1 in ROI-1, the bimodal vertical distribution of the frequent occurrence layers of LLJs and its rapid intensification from 84 min before rainfall are key precursors to HR.

During Phase 2 in ROI-2, the most distinctive precursor to HR is a rapid decrease of LLJ strength and lowering of LLJ core below 1 km followed by a subsequent rebound.

During Phase 3 in ROI-3, the rapid changes in LLJs between -96 and -48 minutes and the final-stage intensification, along with the compensatory effect of thermal instability, likely reflect a key trigger mechanism conducive to the initiation of HR.

During Phase 4 in ROI-4, the distinctive two-stage intensification process—especially the rapid LLJ surge within 48 min of onset—serves as a critical precursor distinguishing LLJ_HR events from the significantly weaker dynamical structures of non-HR events.

Although LLJ has different internal dynamic adjustments due to the different dominant mechanisms influencing rainfall in each phase, a common feature across all phases is that LLJ frequency and wind profiles show a rapid strengthening or stabilization within the final 30 min before HR, accompanied by a general lowering of the LLJ height.The key to triggering HR lies in whether there is a minute-scale rapid reorganization of the LLJ vertical structure within the 2 hours prior to rainfall.

However, we will consider further conducting relevant research in our future work rather than this national-scale study. The above content has been supplemented and revised in the original text.

12. The Jet height in ROI-2 experienced a process that initially declined followed by a rise in Fig. 7b. However, why this trend doesn't occur in the wind profiles in Fig.8b? It depicts a modest decrease in jet height as time moves. Does the averaging process in Fig. 8b smooth out the signal of this vertical redistribution? And wind speed decreased with the time close to the rainfall occur, so why the LLJs didn't strengthen before rainfall?

Response: Apologize for a coding error that affected the result of wind profiles for the LLJ_HR events (Fig. 8), we have thoroughly corrected it in the revised manuscript.

1. Result consistency after revision

After correction, the evolution of wind profiles in Fig. 8b now show a high degree of consistency with the jet height and frequency evolution in Fig. 7b during Phase 2. Both figures now clearly depict a coherent "oscillation" process: 1) Initial phase: At -120 min, both LLJ frequency and wind speed maximum peaked (exceeding 12 m s^{-1}), with the core situated 1.5–2 km AGL; 2) Decline phase: The the frequency and intensity of LLJ significantly decreased, reaching the minimum value approximately 84–72 min preceding HR, accompanied by a rapid descent of frequently occurring height of LLJs to below 1 km AGL; and 3) Recovery phase: A subsequent re-ascent and re-intensification of the jet core occurred from -60 min, coinciding with the rapid frequency increase just before HR onset. This consistency across Figs. 7 and 8 reinforces our central mechanism rather than contradicting it.

2. Reasons for "decrease in wind speed"

Our corrected analysis reveals that during the final 30 minutes before HR, both LLJ frequency and wind profiles do consistently exhibit a rapid increasing or stabilizing trend across all phases.

However, a distinct transient weakening of jet intensity is indeed observed prior to this final intensification (e.g., -60 to -48 min in Phase 1; -120 to -84 min in Phase 2; -48 to -24 min in Phase 3; and -60 to -48 min in Phase 4). We propose that this temporary decline may be a physically consistent signature of the adjustment of dynamic environment essential for convective initiation. Possible mechanisms include: 1) Momentum consumption by developing convection; or 2) Flow deceleration due to strong convergence (the "blocking effect"), where horizontal momentum is converted into the vertical lift required for updrafts (Markowski & Richardson, 2010).

Therefore, the critical precursor for HR is not a simple monotonic strengthening at a fixed altitude. Instead, it is this minute-scale oscillatory behavior—characterized by a "weakening-then-strengthening" or "descent-then-ascent" pattern—that marks the rapid reorganization of LLJs. This dynamic volatility is crucial for triggering HR and contrasts sharply with the weaker, quasi-steady evolution observed in LLJ_non-HR events.

It is also important to note that the composite wind profiles in Fig. 8 represent a spatiotemporal average. This inherently smooths highly transient signals, resulting in a more modest representation of intensity changes (8–13 m s^{-1}) compared to the frequency analysis in Fig. 7. Together, these figures provide a complementary view: Fig. 7 highlights the rapid, discrete nature of vertical reorganization, while Fig. 8 depicts the smoothed evolution of the background mean flow.

We have meticulously updated Section 3.2 (and other relevant text) to accurately reflect the coherent narrative presented by the corrected figures. We are grateful to the reviewer for this critical observation, which prompted a comprehensive re-verification of our data processing, ultimately strengthening the clarity and robustness of our findings.

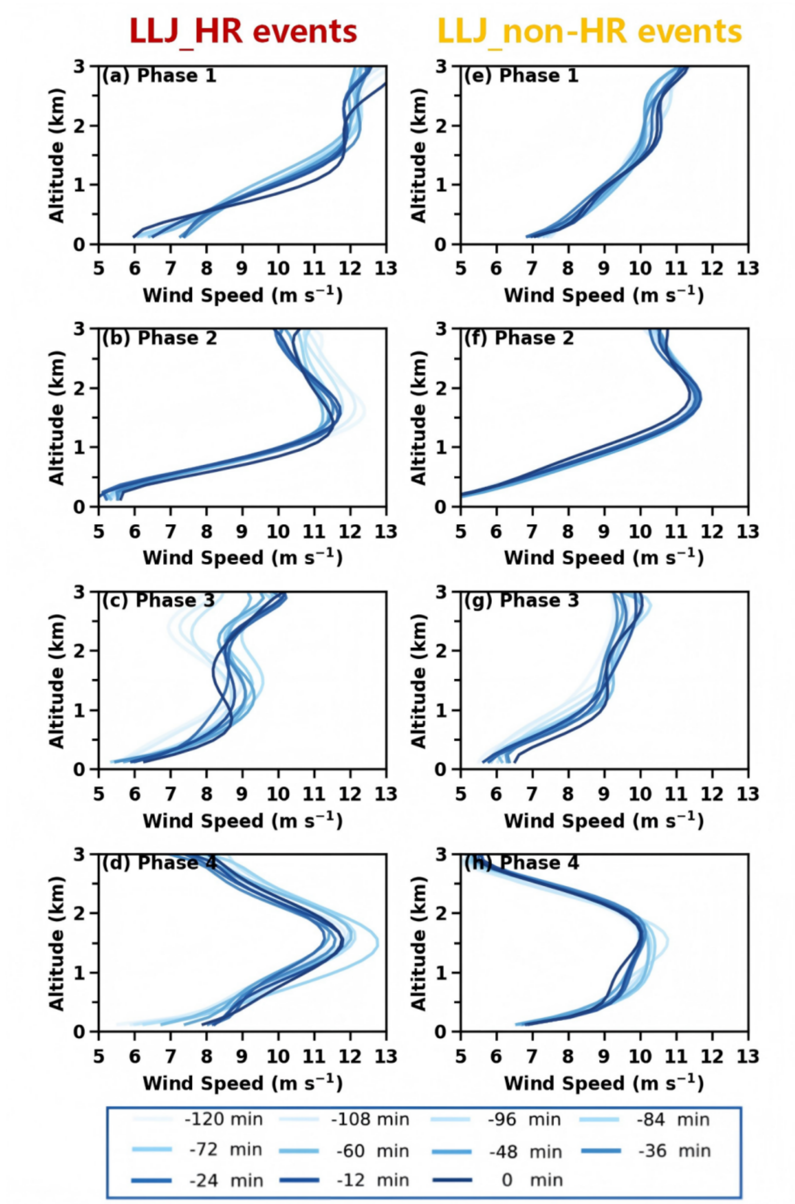

Figure 8. (a-d) Evolution of RWP-detected mean wind profiles of LLJs (blue solid lines, every 12 min) within 2 hours preceding nocturnal rainfall in LLJ-HR events in (a) ROI-1 during Phase 1, (b) ROI-2 during Phase 2, (c) ROI-3 during Phase 3, and (d) in ROI-4 during Phase 4. (e-h) Same as (a-d), but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

13. In Fig. 10c, the wind blow from high values of equivalent potential temperature to low values. Why the authors consider it's the interacting with cold air advection from westerly troughs in L376?

Response: The descriptions are incorrect in our original manuscript. Within the specific domain of our analysis (ROI-3 during Phase 3) in Fig. 10c, the low-level flow is characterized by a southwesterly LLJ transporting high-θ_e air northward, with no direct indication of cold air advection from other directions in the shown wind field.

The explanation after revision for this issue is as follows:

"During Phase 3 in ROI-3, intensified southwesterly LLJs in HR events drove substantial northward transport of abundant moisture and high-θ_e air northward into a lower θ_e environment (Fig. 10c), enhancing convectional 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 $m^{-2}s^{-1}$ greater than those in LLJ_non-HR events, thereby driving nocturnal HR."

14. The wind rotates counterclockwise near the Sichuan Basin. Why the authors describe a stronger anticyclonic circulation in L383? Additionally, the easterly wind encounter the orographic forcing will be uplifted to promote nocturnal HR, but why this happen on the eastern lee slope rather than windward slope?

Response: Thanks for points these errors out. The "anticyclonic circulation" is an incorrect description, we have removed the incorrect term.

The use of term "lee slope" is indeed inaccurate. The physical mechanism is that the accelerated easterly LLJ forcing warm, moist air against the steep eastern margin of the Tibetan Plateau. This barrier effect causes flow deceleration and strong low-level convergence, resulting in strong dynamic lifting along the windward slope. We have revised the text and explicitly describe the mechanism as dynamically forced ascent along the steep topography driven by the impinging LLJ. The text after revision for this issue is as follows:

"*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 θe 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."*

15. The differences in thermodynamic fields and MFD between LLJ_HR and LLJ_non-HR events in Figs. 10 and 11 appear subtle. The authors should more explicitly guide the reader to the key differentiating features in these figures.

Response: Amended as suggested.

16. The authors don't clarify why they introduce the LLJ index and VWS in L390-391. And these two variables need to be obtained through calculation. Thus, I recommend the authors to explain not only the calculation method but also the reason to select these two variables. A more robust rationale for this index will be favorable for readers to understand.

Response: Agreed. Per your kind suggestion, we have revised the manuscript to explicitly state both the calculation procedures and the reason for selecting these two variables.

The LLJ index and vertical wind shear (VWS) were used to quantify the minute-scale dynamical coupling between jet intensity and vertical structure immediately prior to rainfall onset, which provides more integrated insights than analyzing wind profiles in isolation.

For LLJ index, it is calculated as the maximum wind speed below 3 km divided by the height where the wind speed first exceeds 10 m s^{-1} (Liu et al., 2003). This index compactly links jet intensity and the vertical position where the jet becomes established. A rapid rise in LLJ index indicates a stronger jet and/or a lower occurrence height, quantitatively reflects the downward extension and pulsing intensity of the LLJ. And its magnitude has been shown to be positively correlated with subsequent precipitation intensity 1-2 hour later, providing indicative value for nowcasting.

For VWS, it is calculated as the wind-speed difference between the near-surface level and the jet level divided by the jet height (Wei et al., 2014), which measures the bulk shear from the surface to the jet layer. Enhanced VWS provides a more favorable environment for lifting and organization or intensification of convection.

The above-mentioned response and clarification have been well incorporated in this revised manuscript in the section 3.3.

17. The difference in LLJ index is not significant in Fig. 12. Compared to your previous study in the North China, LLJ index doesn't surge before rainfall occur in this study. Thus, why the curve shows a small difference between HR and non-HR events and why it's gentle before rainfall? I did not see significant difference in LLJ behaviors between HR and non-HR events. Their behaviors are also varied in different regions and phases, which are not explained.

Response: The differences in LLJ behavior are explained by followed key factors:

1. Regarding the gentle change

Firstly, our previous study focused exclusively on a typical "Southwesterly Synoptic Pattern" where strong forcing drives a dramatic jet surge. In contrast, this study characterizes the general features of entire rainy season phases across distinct regions. Consequently, the composite curves in Fig. 12 represent a climatological average of varied synoptic forcing, which cannot present the ideal state where the LLJ index suddenly increases under a single typical strong strong synoptic forcing. However, it provides a more robust representation of the general behavior of LLJs across diverse real-world scenarios.

Secondly, as a composite ratio that responds concurrently to wind speed and jet height, the "gentle" evolution of the LLJ index also reflects the complex coupling between them in a minute-scale window. As observed in ROI-2 during Phase 2, the jet core decrease while simultaneously weakening in the first stage, causing the gentle change of LLJ index. This physically reflects the critical vertical reorganization of the jet, rather than weak dynamics.

2. Regarding the differences

In this nationwide study, it is normal for their behaviors to vary in different regions and phases. And it's worth noting that the distinction of LLJ index between LLJ_HR and LLJ_non-HR events lies in the evolutionary trend rather than absolute magnitude.

LLJ_HR Events: Exhibit coordinated evolution with other thermodynamic environment and final-stage intensification driven by LLJs in the final 30–60 minutes. As seen in ROI-1 (Phase 1), the LLJ index rises (from ~0.05 to ~0.08) in lock-step with sharply increasing VWS from -90 min, with a rapid low-level warming (θ_e rising). This joint intensification is consistent with the concurrent rapid increase in LLJ frequency.

LLJ_non-HR Events: Show decoupled or decaying trends (e.g., LLJ index dropping from ~0.06 to ~0.04 preceding rainfall in Phase 1), lacking the final-stage dynamic organization required to trigger HR.

We have strengthened the relevant descriptions in the manuscript accordingly to guide readers more clearly in interpreting the distinguishing features of LLJ index in Fig. 12.

Minor Comments:

1. L122: The meaning of MFC is unclear. I suggest using the whole name of "moisture flux convergence (MFC)".

Response: Amended as suggested.

2. L180-181: The time in the North China Rainy Season is inverted. It should be July 15 to August 31, 2023, and July 22 to August 31, 2024, which are continuous in time.

Response: Apologies for the incorrect descriptions in our original manuscript. We have revised the original text.

3. L212: The font is different in "In contrast,".

Response: Amended as suggested.

4. L335: Is it the higher probability above 1.7 km? The peak of LLJ_non-HR

seems at nearly 1.5 km in Fig. 9g.

Response: Amended as suggested.

5. L378: kg m-2s-1 -> kg m-2 s-1

Response: Amended as suggested.

6. L427: 1.5 m s-1 -> 1.5 s-1

Response: Amended as suggested.

7. L435: Phase 4. -> Phase 4

Response: Amended as suggested.

8. Some mistakes occur in the caption of Fig. 1: There are two ROI-3 in Line 739; The rain gauges depicted with blue dots and the RWP seems a red circle rather than red star in Fig. 1b.

Response: Apologies for the incorrect descriptions in our original manuscript. We have revised the original text.

9. I recommend adding the title in each column in Fig. 3. For example, "Daytime" over the Fig. 3a, and "Nighttime" over the Fig. 3e.

Response: Amended as suggested.

10. I do not think that the Fig. 4b is same as panel (a) in L778, and (b) is not for nocturnal HR events, the authors also count the non-LLJ_non-HR events.

Response: Per your kind suggestion, we will make rigorous corrections to the figure captions. The specific modifications are as follows:

"Figure 4. (a) 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."

11. L796: I suggest adding color description of pie chart in caption. LLJ-HR (red) and non-LLJ_HR (blue).

Response: Amended as suggested.

12. The reference vector in Fig. 10 at the lower-left corner is incorrect. It should be 10 m s-1.

Response: Apologies for the incorrect figure in our original manuscript. We have revised Fig. 10.

13. L827: 850 Pa -> 850 hPa

Response: Amended as suggested.

14. L831: unit: kg m-2 s-1; 1 hour -> 1-hour

Response: Amended as suggested.

15. The authors use "LLJ-HR" in the caption of some Figures to describe the LLJs associated with HR. I recommend using the same abbreviation as in the main text. For example, in L781, 792, 796, 802, 808, 815, 824, 838, and 841. Modifying the "LLJ-HR" to "LLJ_HR".

Response: Amended as suggested.