

Response to Reviewers' Comment

Reviewer #1

I appreciate the efforts made by the authors in addressing the concerns from mine, as well as those from other reviewers. Now the manuscript has been well improved after a round of revision. I recommend “acceptance” of the manuscript, after some minor points (as shown below) are considered.

Response: First of all, we thank you for taking the time to review our revision and we are glad to receive your positive and encouraging comments! Per your kind comments, we have carefully revised the manuscript. For clarity purpose, here we have listed the reviewer's 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. L104–108: These two sentences seem repetitive between each other. Please consider reorganizing them into one sentence.

Response: Per your kind suggestion, we have reorganized these sentences into a single, more concise statement to improve the flow and clarity of the introduction. The revised text is as follows:

“The insufficient spatiotemporal resolution of conventional observing systems limits the ability to capture rapid pre-storm environmental changes (Weisman et al., 2015; Cao et al., 2025; Roots et al., 2025), thereby hindering systematic analysis of the fine-scale structure and minute-scale evolution of LLJs within the critical 2-hour window preceding rainfall.”

2. L183: Do you mean “successive occurrence”? The definition of “a valid rainfall” is not so clear here.

Response: No. We did not require strict “successive” (uninterrupted) rainfall occurrence at every six-minute interval in a rainfall event. Instead, to account for the natural

intermittency of rainfall on minute scales, we defined that a valid event requires the initial onset to be followed by at least two subsequent occurrences within 30 minutes, allowing for both continuous and intermittent rainfall. This criterion can effectively filter out transient noise while capturing significant rainfall events. We have revised the text in section 2.3 to ensure this definition is precise, which is shown as follows:

“To account for rainfall intermittency and filter out transient noise, a valid rainfall event required the initial detection to be followed by at least two subsequent occurrences within 30 min.”

3. L244–246: “... more frequently... increase...” , relative to what?

Response: The statement refers to the increased frequency of nocturnal LLJs relative to diurnal LLJs. We have revised the sentence to explicitly include this comparison for clarity.

4. Figure 4: “noucturnal” , typo in the plot.

Response: Corrected as suggested.

5. L363: correct the minus sign.

Response: Amended as suggested.

6. L365: add period sign

Response: Amended as suggested.

7. L388: “a rapid increasing and height of core decreased in around the final” , this sentence is very confusing. Please consider rewriting it.

Response: Agreed. We intended to describe that the LLJ wind speed increased rapidly while the jet core height decreased. We have rewritten the sentence to ensure grammatical correctness and clarity:

“Synthesizing the evolution across all phases, although a distinct transient weakening of the jet profile was consistently observed, LLJs exhibited a rapid re-

intensification of wind speed accompanied by a lowering of the jet core height during approximately the final 30 min preceding HR.”

8. L404: A more common statement is “land-sea breeze”.

Response: Amended as suggested.

9. L442 – 467: many wrong minus signs in this paragraph.

Response: Apologize for the formatting errors regarding the minus signs. We have corrected them in the revised manuscript.

10. L521: delete (.

Response: Amended as suggested.

11. L558: what do you mean “probability advantage” ?

Response: By “probability advantage,” we intended to describe a higher probability density or greater likelihood of heavy rainfall occurrence in LLJ events compared to non-LLJ events. We have rephrased the sentence to use standard statistical terminology for clarity:

“Overall, LLJ-related events were significantly more prone to producing heavier rainfall than non-LLJ events across most regions, underscoring the strong coupling between LLJs and nocturnal HR.”

Reviewer #2

The authors have made substantial revisions in response to the previous round of reviews, significantly improving the manuscript. The responses are thorough, and numerous explanations and refinements have been incorporated, resulting in a more fluent and well-structured text. This study holds significant potential for systematically and comprehensively comparing and distinguishing regional variations at the national level. It investigates the precursor signals and effects of the low-level jet stream preceding heavy precipitation across different regions and time periods, offering broader insights. However, a few critical aspects still require clarification and stronger justification. The manuscript also contains several typos and requires careful proofreading. I recommend a minor revision before it can be accepted by ACP.

Response: We sincerely appreciate you for taking the time to review our revision and we are glad to receive your positive and encouraging comments! Your insightful feedback has been invaluable in identifying critical areas for improvement. 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:

12. L33–35: This sentence in the abstract is not clearly reflected or elaborated in the main text and conclusion. Is it corresponding to the L262–264? And why the authors didn't specifically list the percentages of the four phases like the L260–262?

Response: No. We clarify that the statement in the Abstract (L33–35) referring to “approximately 45%” corresponds to the analysis of key monsoon regions of interest (ROIs), emphasizing the strong LLJ-rainfall coupling in primary rain belts, which is detailed later in the text (around L280): “From the HR perspective, nearly 45.0% of HR events were associated with LLJs...”. This differs from the national-scale statistic in

L262–264.

However, the statistics analysis between national and ROIs was not clearly articulated, we have revised expression of the original text and reorganized the relevant paragraph in Section 3.1 to ensure consistency and clarity as suggested. And we chose not to list the specific percentages for all four phases in the Abstract to maintain conciseness and highlight the overall statistical characterizing LLJ_HR events.

13. L40: The authors considered LLJ serves as a decisive triggering mechanism for HR in abstract. However, only 45% nocturnal HR preceded by LLJs in the monsoon regions and the authors acknowledge their physical efficiency in enhancing rainfall intensity and their distinctive precursor signals related to their dynamical structure in the response. Thus, I suggest the author rephrase this sentence using more specific and restrictive wording., rather than referring to it as a decisive factor.

Response: Per your kind suggestion, we have revised the Abstract to use more precise wording. We have replaced “decisive triggering mechanism” with “a primary dynamical forcing mechanism and a key precursor signal for the initiation of HR”

14. The authors mentioned cold pool outflow associated with alternation or propagation of convective nearly one-hour prior rainfall in ROI-2. However, the cold pool outflow means a mature convective cell appear near the RWP. How the authors consider that the development of LLJs wind profile is the reason of the precursor signal of rainfall? Or the result of the nearby convective system?

Response: We thank the reviewer for this insightful comment regarding the potential dual role of the LLJ evolution—whether it acts as a precursor to rainfall or results from nearby convective activity.

We acknowledge that the cold pool outflows generated by nearby or pre-existing convective systems can indeed modulate the local wind field prior to rainfall onset (e.g. Li et al., 2024). These modifications, such as enhanced low-level shear or localized lifting, serve as a dynamical driver influencing the subsequent nocturnal HR.

Simultaneously, the reinforced low-level inflow preceding convective triggering may further accelerate the development of LLJs, suggesting a synergistic relationship between the jet and the convective environment.

However, as shown in Figure 12b, while the cold pool signature (surface θ_e drop) appears around 60 min before rainfall, the LLJ structural reorganization (e.g., core descent) begins earlier (around -120 min), and even continues throughout the pre-rainfall window. This supports the interpretation that the observed LLJ evolution is not merely a consequence of local mature convection, but rather a dynamical precursor that characterizes the pre-convective environment.

Crucially, the key finding of this study is that the observed fine-scale vertical restructuring of the LLJ—particularly its rapid intensification in the final 30 min—can provide a robust and detectable precursor signal for imminent local HR. This signature is statistically significant and systematically absent in LLJ_non-HR events. Regardless of whether the distinct observational signature of the LLJ evolution is autonomous or modulated by convective feedback, they can offer a critical observational basis for nowcasting accuracy.

We clarify that the potential physical mechanisms proposed are plausible interpretations based on the observed data. But a comprehensive and further analysis of these complex dynamical-thermodynamic interactions is beyond the scope of this study on a national scale and will require high-resolution numerical simulations in future research.

The above content has been incorporated into this revised manuscript.

15. L369–371: Is this inference robust? As shown in Figures 8c and 8d, the wind speeds are significantly lower in ROI-3 than ROI-4. However, both the probability of heavier rainfall in LLJ_HR events is low in Figures 6c and 6d.

Response: The statement that “weaker wind profiles explain the lower probability in ROI-3” is reasonable but not absolute. We acknowledge that while LLJ intensity is a critical driver, its relationship with rainfall intensity may be non-linear and subject to regional modulation. However, we maintain that for ROI-3, the lack of dynamic forcing

remains a primary explanation for its lowest probability of heavier rainfall response.

Firstly, in ROI-3 during Phase 3, the substantially weaker wind profile (peak ~ 9.5 m s⁻¹, Fig. 8c) can constitute a primary dynamical bottleneck that directly limits the potential for heavier rainfall.

Secondly, although ROI-4 also exhibits a relatively low probability of heavier rainfall compared to other regions, a closer inspection of the tail of the distributions (> 2.5 mm/6 min) reveals that ROI-4 maintains a slightly higher probability for these intensities compared to ROI-3, which may be associated with its stronger LLJs in ROI-4 (peak ~ 12.8 m s⁻¹, Fig. 8d). In contrast, ROI-3 shows the sharpest decay in probability density for heavier rainfall among all regions, consistent with its weakest dynamic forcing.

Therefore, while strong winds in ROI-4 do not guarantee the higher probability of heavier rainfall (due to other factors like moisture or complex terrain), the insufficient dynamic forcing in ROI-3 is a robust explanation for weaker rainfall intensity.

We have revised the relevant text in Section 3.2 to articulate this inference more rigorously.

16. L294–296: How the authors define the “extreme rainfall”? The blue (non-LLJ_HR) and red (LLJ_HR) lines seem overlap in heavier rainfall (≥ 2 mm/6 min). Why the authors consider they have difference in ROI-3?

Response: Apologize for the incorrect description. We agree with the reviewer that in the range of heavier rainfall (≥ 2.0 mm/6 min), the probability density curves for LLJ_HR (red) and non-LLJ_HR (blue) events in ROI-3 closely overlap (Fig. 6c), which indicates that the probability of generating heavier rainfall is statistically comparable between LLJ-HR and non-LLJ-HR in ROI-3 during Phase 3. And this result highlights that LLJs do not exhibit a dominant advantage in generating heavier rainfall intensities in ROI-3 compared to non-LLJ-HR events, which contrasts with the prevailing view in other regions (e.g., ROI-1) where LLJs are often the primary drivers of the heavier rainfall.

We have revised the text to more accurately reflect the probability distribution

characteristics of rainfall in Section 3.1 ensuring the description matches the evidence in Figure 6c.

17. L461: Where are the cold highs located relative to ROI-4? The authors should clearly indicate their position in the text or figure. Additionally, the numerical labels in Figures 10 and 11 are suggested to be optimized, as they cause long interruptions in the isoline.

Response: Regarding the location of the cold highs, we have clarified in the revised manuscript that they are located to the northeast of ROI-4.

Per your kind suggestion, we have optimized the numerical labels in Figures 10 and 11. We adjusted the label density and placement to minimize interruptions to the isolines, ensuring the results are presented more clearly and the contour lines remain continuous.

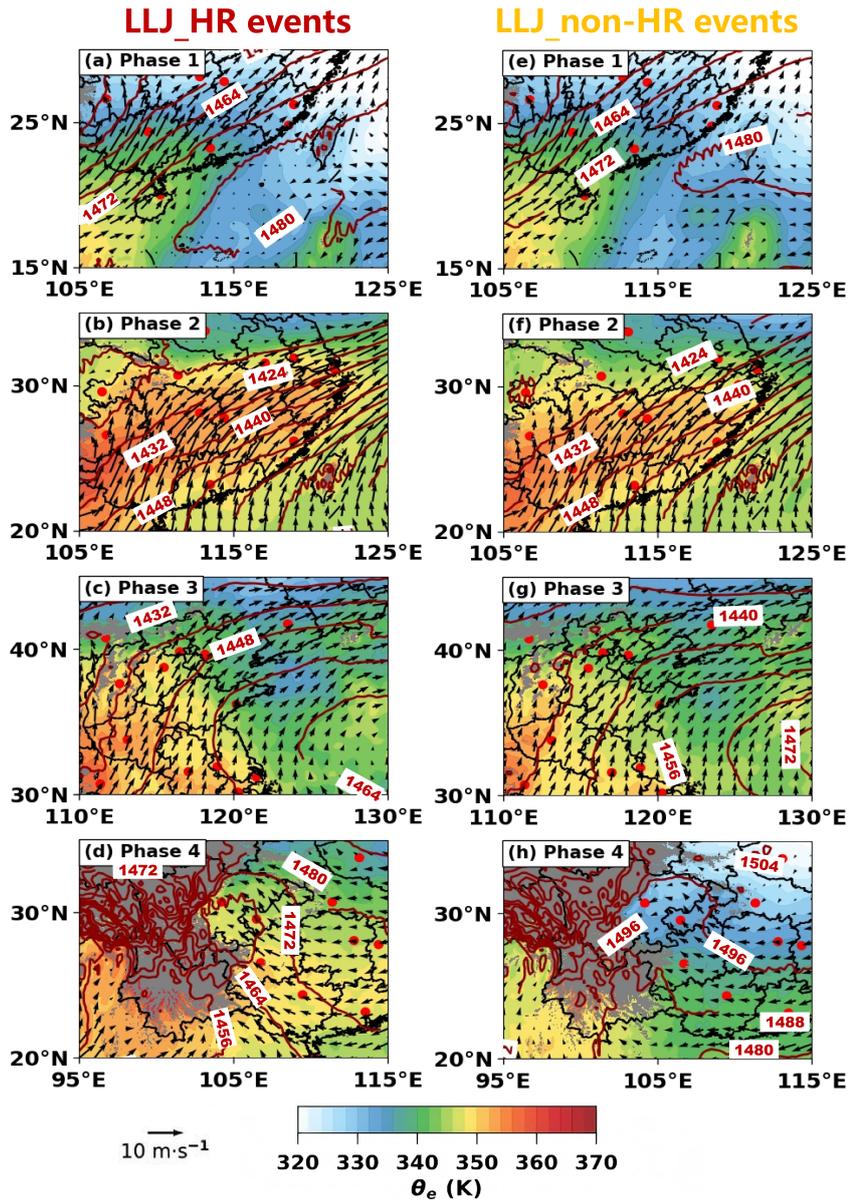


Figure 10. Distributions of equivalent potential temperature (shading, unit: K) at 850 hPa, superimposed with 850 hPa horizontal wind vectors (black arrows) and geopotential height contours (red solid lines), for LLJ_HR events within 1-hour time window preceding nocturnal rainfall onset in (a) ROI-1 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

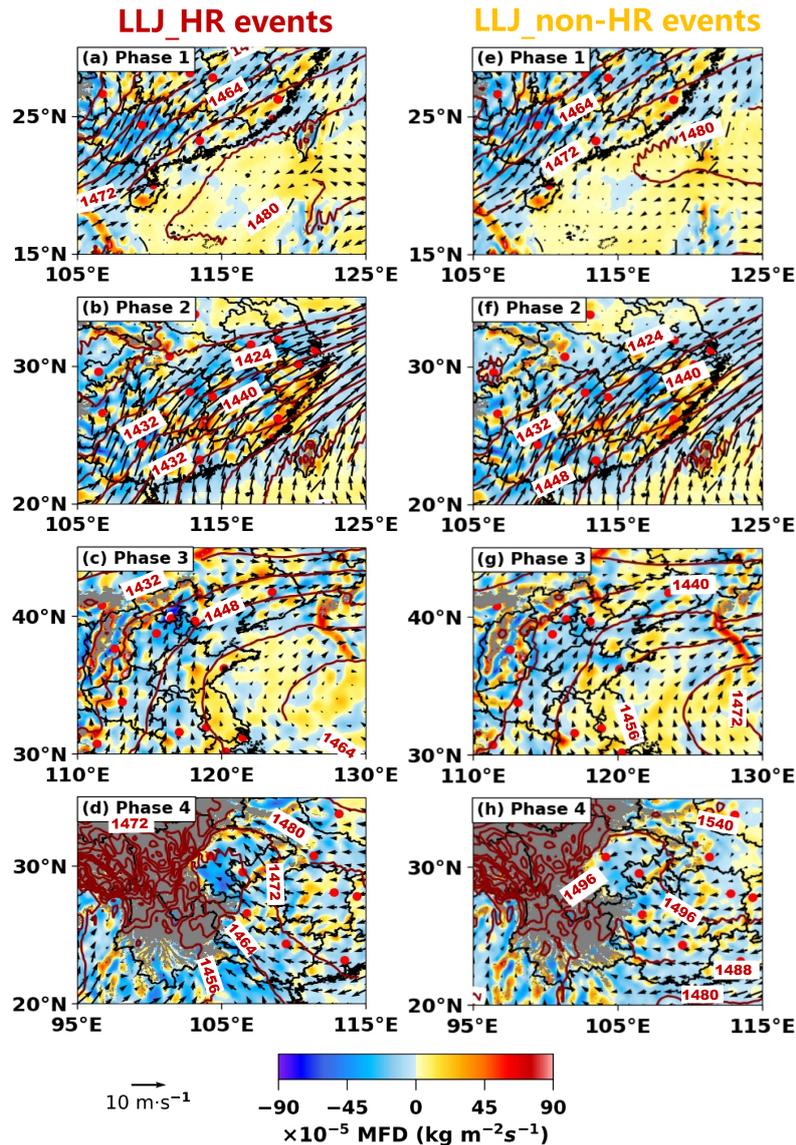


Figure 11. Same as Figure 10, but showing the integrated moisture flux divergence (shading, unit: $\text{kg m}^{-2} \text{s}^{-1}$) between 1000–700 hPa at 1 hour prior to preceding nocturnal rainfall onset

18. L483: 0.5 s^{-1} is an obvious mistake. As shown in Figure 12, the values of VWS were multiplied by 100. So, the correct value is 0.005 s^{-1} .

Response: Apologize for the incorrect value. We have revised the original figure.

19. L107: Cao et al -> et al

Response: Amended as suggested.

20. L151: defined -> were defined

Response: Amended as suggested.

21. L237: frequent -> frequently

Response: Amended as suggested.

22. L241: Double “was” and need to delete one.

Response: Amended as suggested.

23. L319: low-level lets -> jets

Response: Amended as suggested.

24. Figure .1 -> Figure 1.; add “red dots” after RWP in L864. And change “black dots” to “blue dots” in L867.

Response: Amended as suggested.

25. L965: Delete “I”.

Response: Amended as suggested.

26. Some mistakes occurred in supporting materials: Figure S1. correspondent-> corresponding; Figure S3. Same as Figure S1-> S2; Figure S5. Same as Figure S3-> S4; Figure S7. The description of S7b is actually for S7c.

Response: Amended as suggested.