

Response to Reviewer #1's Comments

This study draws on five years (2021–2025) of minute-resolution rain-gauge records, ERA5 reanalysis, and a radar wind profiler (RWP) mesonet to establish an objective identification framework that separates warm-sector heavy rainfall (WSHR) from other heavy rainfall over the eastern China plains, and then to characterize its spatiotemporal distribution, event-scale properties, contribution to the regional heavy-rainfall total, and the low-level dynamic precursors recorded by the RWPs prior to convective onset. The analysis is generally careful and the writing is clear. Some of the conclusions—the nocturnal preference of WSHR, the warm, humid, high- θ_e environment, and the role of the low-level jet—echo previous studies from South China, but a notable contribution of this work is to establish, through a consistent multi-year objective framework, that these features also hold over the eastern China plains, where the coastal forcing central to the South China regime is largely absent. The genuine added value lies in the objective identification and contribution quantification across five years and 493 stations, and in the high-frequency, RWP-resolved time evolution of the pre-onset low-level dynamic environment together with its implications for nowcasting, which give the paper some merit.

Reply: Thanks for taking the time to review our manuscript, especially for your thorough and constructive comments, which indeed help improve the quality of our manuscript. Meantime, we appreciate it for recognizing the unique contribution of RWP-resolved time evolution of the pre-onset low-level dynamic environment and the objective multi-year identification framework proposed in our manuscript.

Per the reviewer's kind suggestions, we have carefully revised the manuscript. The major revisions made in this round include a warm-sector non-heavy rainfall comparison, additional sample-structure and dependence assessments, and more qualified statements about mechanisms and predictive applications. The individual changes are documented below.

For clarity, reviewer comments are listed below in italics, our responses in plain blue font, and the corresponding changes to the manuscript in blue italics.

Specific Comments

(1) *Absence of a control group leaves the specificity of the precursor signals undetermined. The authors themselves acknowledge this in Sect. 4.1. All RWP precursor composites are drawn only from WSHR events, so it is not possible to tell whether these signals are specific to WSHR or are simply the generic prelude to warm-season convection—which is precisely what determines whether they can serve as forecast indicators. I suggest the authors either add a brief control composite (for example, the "other heavy rainfall" events at the same co-located RWP stations) or*

correspondingly temper the forecast-oriented statements in Sects. 4.3 and 5, positioning these signals as "candidate, to-be-evaluated" indicators and stating explicitly that their specificity remains to be established.

Reply: Thank you for raising this important point. We agree that WSHR-only composites cannot establish whether a signal distinguishes WSHR from other conditions. We have added a comparison sample of 271 warm-sector non-heavy rainfall (WS non-HR) events from the same 37 co-located stations that contributed the 62 WSHR events, providing a warm-sector baseline from the same station set. Both samples use the same RWP quality-control criteria, onset alignment and 180-min analysis window, as described in Sect. 2.4.

The revised Fig. 11 compares low-level wind and LLJ characteristics, and Fig. 12 compares ascending-motion frequency and layer-maximum ascent speeds. The new Fig. S6 provides the WS non-HR KE composite for comparison with the WSHR composite in Fig. 9c. WS non-HR shear composites are provided in Fig. S7, and hodographs for WSHR and WS non-HR are shown in Figs. S8 and S9, respectively. Low-level shear, clockwise wind turning and ascent occur in both categories. The KE comparison shows a more pronounced late enhancement at approximately 1–3 km AGL in the WSHR composite. The late increase in LLJ occurrence and the upper part of the ascent-speed distribution at 1–2 km are also more pronounced in WSHR, although the LLJ core characteristics and ascent-speed distributions overlap substantially between the samples.

Accordingly, we now describe these features as candidate indicators and make no claim of WSHR-specific or validated predictive skill. The Abstract and Sections 3.4, 4.1, 4.3, and 5 now distinguish the observed composite differences from event-level prediction. Section 4.1 also states that non-raining warm-sector conditions and other heavy rainfall events remain outside the present comparison.

The specific changes made accordingly in this revised manuscript are listed below:

In the 1st paragraph in Sect. 2.4: *“A comparison sample consisted of 271 warm-sector non-heavy rainfall (WS non-HR) events from the same 37 co-located stations that contributed the 62 WSHR events. This sample was used to assess which features of the pre-onset kinematic evolution distinguish WSHR from non-heavy rainfall within the warm sector. WS non-HR events were defined as rainfall events that satisfied the warm-sector criteria at onset but never reached the station-specific heavy-rainfall threshold. The two samples were processed using the same RWP quality-control criteria, onset alignment and 180-min analysis window.”*

In the paragraph following Eq. (6) in Sect. 2.4: *“The same KE diagnostic was calculated for both WSHR and WS non-HR events, with the corresponding time–height composites shown in Fig. 9c and Fig. S6, respectively.”*

In the 3rd paragraph of Sect. 3.4: *“The wind kinetic energy generally increases with height in both the WSHR and WS non-HR composites (Fig. 9c and Fig. S6). The WSHR composite shows a more pronounced enhancement at approximately 1–3 km AGL during the final hour before local rainfall onset, whereas the corresponding*

evolution in WS non-HR is comparatively gradual.”

In the 8th paragraph of Sect. 3.4: “However, substantial overlap between the samples remains, and neither a causal jet–ascent pathway nor event-level predictive skill is established by these composites.”

In the paragraph 3 of Sect. 4.1: “The WS non-HR comparison provides a baseline within the warm sector; but non-raining warm-sector conditions and other heavy rainfall remain outside the present comparison. Event-level predictive skill therefore remains untested.”

Fig. 12. Comparison of ascending-motion frequency and layer-maximum ascent speeds for WSHR and WS non-HR. The two samples share low-level ascent, while the late upper-tail enhancement at 1–2 km is more pronounced in WSHR.

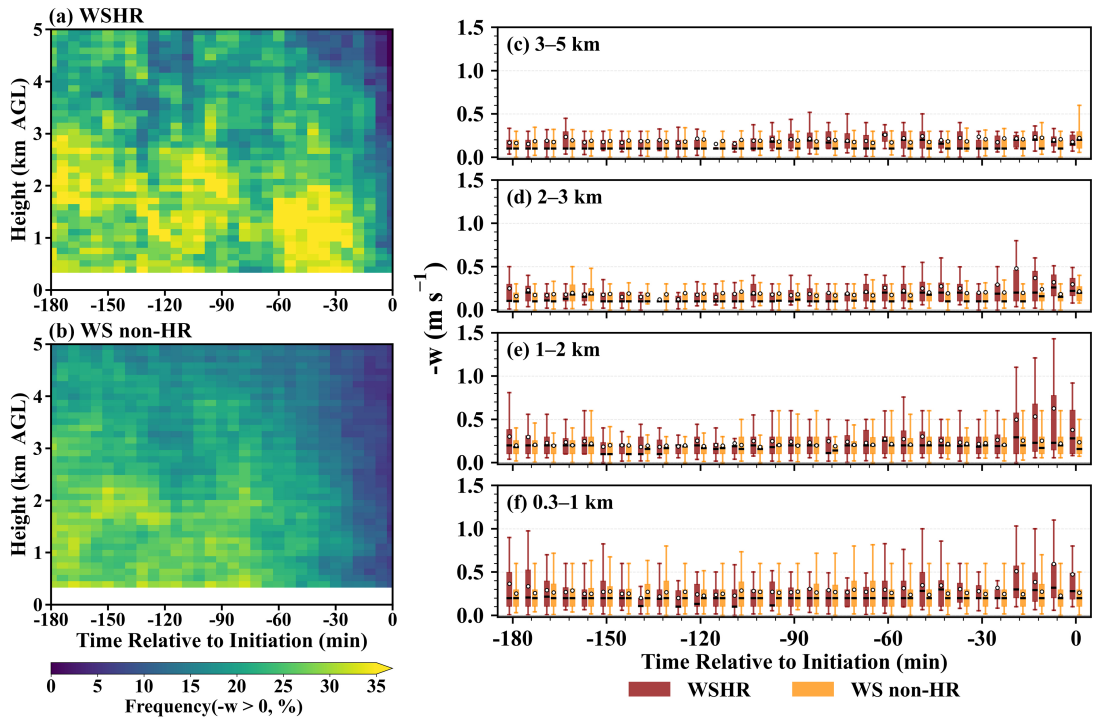


Figure 12. Composite ascending motion preceding the onset of WSHR events and WS non-HR events. (a, b) Frequency of ascending motion ($-w > 0$; %) as a function of height (km AGL) and time relative to the rainfall onset (min) for (a) WSHR events and (b) WS non-HR events. (c–f) Box plots of the across-event distributions of layer-maximum ascent speed ($-w$; m s^{-1}) at each 6-min lead time for the WSHR (dark red) and WS non-HR (orange) events in the (c) 3–5 km, (d) 2–3 km, (e) 1–2 km, and (f) 0.3–1 km AGL layers.

Fig. S6. Composite time–height evolution of KE for WS non-HR events from the same 37 co-located stations as the WSHR sample, using the same color scale as Fig. 9c.

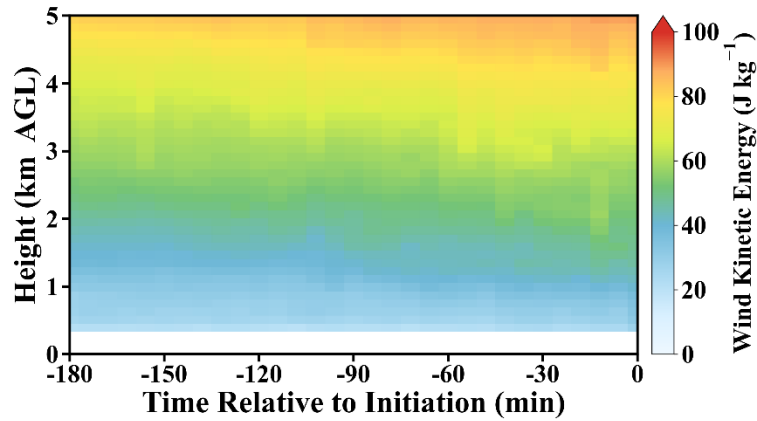


Figure S6. Composite time–height evolution of wind kinetic energy (shading, J kg^{-1}) during the 180 min preceding local rainfall onset for 271 warm-sector non-heavy rainfall (WS non-HR) events from the same 37 co-located stations as the WSHR sample. Time zero denotes local rainfall onset at the rain gauge, and height is above ground level. The color scale is the same as in Fig. 9c to facilitate comparison with the WSHR composite.

(2) Section 3.4 observationally provides mainly the LLJ occurrence frequency (Fig. 11c) and the core-height/core-speed scatter (Fig. 11b), yet from these it draws a series of mechanistic assertions—for instance, that the jet generates low-level convergence near its terminus, organizes and sustains convection, and places the strongest convergence and ascent at 1–2 km (L475–482, L563–573). The single metric of a rising occurrence frequency is not by itself sufficient to support this convergence-and-triggering chain of reasoning. I suggest the authors add observational evidence linking the "jet" to "convergence/ascent/triggering," or at least distinguish explicitly in the text between what the observations directly support (the time evolution of LLJ frequency) and what is inferred mechanistically from the existing literature.

Reply: Thank you for this helpful clarification. We agree that the LLJ occurrence statistics and single-site profiles do not demonstrate a causal jet–convergence–ascent–triggering sequence. We have revised Sect. 3.4 to separate the directly observed evolution of wind, LLJ occurrence, shear and ascent from the proposed physical interpretation.

Sect. 4.2 now states explicitly that the present analysis does not locate the jet terminus, resolve its associated horizontal convergence, or establish a causal link between the LLJ and ascent. The possible role of jet-exit convergence is presented as an interpretation informed by previous studies, including Du and Chen (2018, 2019). The potential contribution of inertial acceleration and the role of shear in organizing or sustaining convection are likewise identified as untested interpretations.

We have retained the literature-based discussion of how ascent, moisture and convective organization can contribute to heavy rainfall. The manuscript explicitly states that the proposed organizational explanation cannot be resolved by the present single-site analysis and remains a hypothesis for radar-based testing. The Conclusions

similarly retain the possible physical pathway while stating that its causal links are unverified.

The specific changes made accordingly in the revised manuscript:

In the 5th paragraph of Sect. 3.4: *“Its possible connection to convergence and convective triggering is a literature-based interpretation discussed in Section 4.2, rather than a causal relationship established by these profiles.”*

In the 2nd paragraph of Sect. 4.2: *“This provides a possible interpretation of the observed evolution, but the present analysis does not locate the jet terminus, resolve the associated horizontal convergence, or establish a causal link between the LLJ and ascent. Nocturnal inertial acceleration is another possible contribution (Blackadar, 1957), which is not tested here.”*

In the 3rd paragraph of Sect. 4.2: *“Its potential role in organizing or sustaining convection remains a literature-based hypothesis because convective organization is not resolved in the present analysis.”*

In the 4th paragraph of Sect. 4.2: *“The present single-site analysis cannot resolve this organizational mode directly, so the inference remains a hypothesis to be tested with radar.”*

In the 3rd paragraph of Sect. 5: *“These precursor dynamic signals are compatible with a possible jet-related lifting pathway, but the causal links remain unverified.”*

(3) Because events are grouped by fixed station along time (Sect. 2.3), a single weather process affecting several stations is recorded as multiple events. For the composite analysis, the effective number of independent samples may therefore be smaller than the nominal event count. I suggest the authors: (i) state once in the text that the count is of "station-based events" rather than "independent weather systems"; and (ii) provide, in the main text or the Supplement, a simple distribution of the number of events per station, so that readers can gauge the independence of the composites.

Reply: Thank you for highlighting this concern. We agree that station-based event counts are not counts of independent weather systems. Sect. 3.4 now makes this distinction explicit, and Fig. S4 provides the requested distributions of events per station for both the full WSHR sample and the RWP subset. The full sample contains 477 events at 297 stations with at least one WSHR event; the remaining 196 of the 493 study stations have none. The RWP subset contains 62 events at 37 stations. The previous statement of 48 RWP stations has been corrected to 37.

We have also added a dependence assessment in Supplement, Sect. 3. Under spatial and onset-time thresholds of 500 km and 24 h, the full WSHR sample contains 148-episode clusters, 47 of which contain the 62 RWP events. The main composites retain equal station-event weighting. Equal-episode composites (Fig. S5) assess sensitivity to episodes contributing multiple station events, and episode-cluster

bootstrap intervals (Fig. S10) assess uncertainty while retaining potentially related events together.

This additional assessment changes the strength of the LLJ interpretation. The event-mean early-to-late increase is 7.04 percentage points, with a 95% episode-cluster bootstrap interval of -0.25 to 14.18 percentage points. The interval includes zero, so the revised manuscript describes an uncertain composite mean tendency instead of a statistically robust increase. We explicitly avoid treating the 47 clusters as a verified number of independent weather systems.

The specific changes made accordingly in the revised manuscript:

In the 1st paragraph of Sect. 3.4: *“Following the procedure described in Section 2.4, 62 station-based WSHR events at 37 co-located stations were retained for the precursor analysis. Most stations contributed a single event (Fig. S4b). Using spatial and onset-time difference thresholds of 500 km and 24 h, respectively, these events were assigned to 47 episode clusters (Fig. S4d). These clusters are operational groupings of potentially related events; their statistical independence is not established. RWP profiles were aligned with each event’s local rainfall onset and composited over the preceding 180 min.”*

In the 1st paragraph of Sect. 3.1 of Supplementary materials: *“Rainfall events were defined at individual stations, so multiple station-based events could be associated with the same weather episode. The distributions of event counts per station are shown in Fig. S4a, b. Under the selected spatial and onset-time difference thresholds of 500 km and 24 h, the full WSHR sample contains 148 episode clusters. The 62 RWP-observed WSHR events belong to 47 of these clusters, comprising 37 clusters with one RWP event, six with two, three with three, and one with four events (Fig. S4d). These clusters are operational groupings of potentially related events; their statistical independence is not established.”*

In the 2nd paragraph of Sect. 3.1 of Supplementary materials: *“The main composites give equal weight to station-based events. To assess sensitivity to episodes contributing multiple events, equal-episode composites were also examined (Fig. S5). Event diagnostics were first averaged within each cluster and then averaged across clusters with equal weight. Each station event retained its own local rainfall-onset reference time.”*

In the 2nd paragraph of Sect. 3.3 of Supplementary materials: *“The mean paired change is 7.04 percentage points. Resampling the 47 episode clusters with replacement 5000 times, with all member events retained and a random seed of 42, gives a percentile-based 95% confidence interval of -0.25 to 14.18 percentage points.”*

Fig. S4: Event counts per station and episode-cluster structure. Panel (a) includes the 297 stations with at least one WSHR event. The selected 500-km/24-h grouping yields 148 full-sample clusters and 47 clusters represented in the RWP subset.

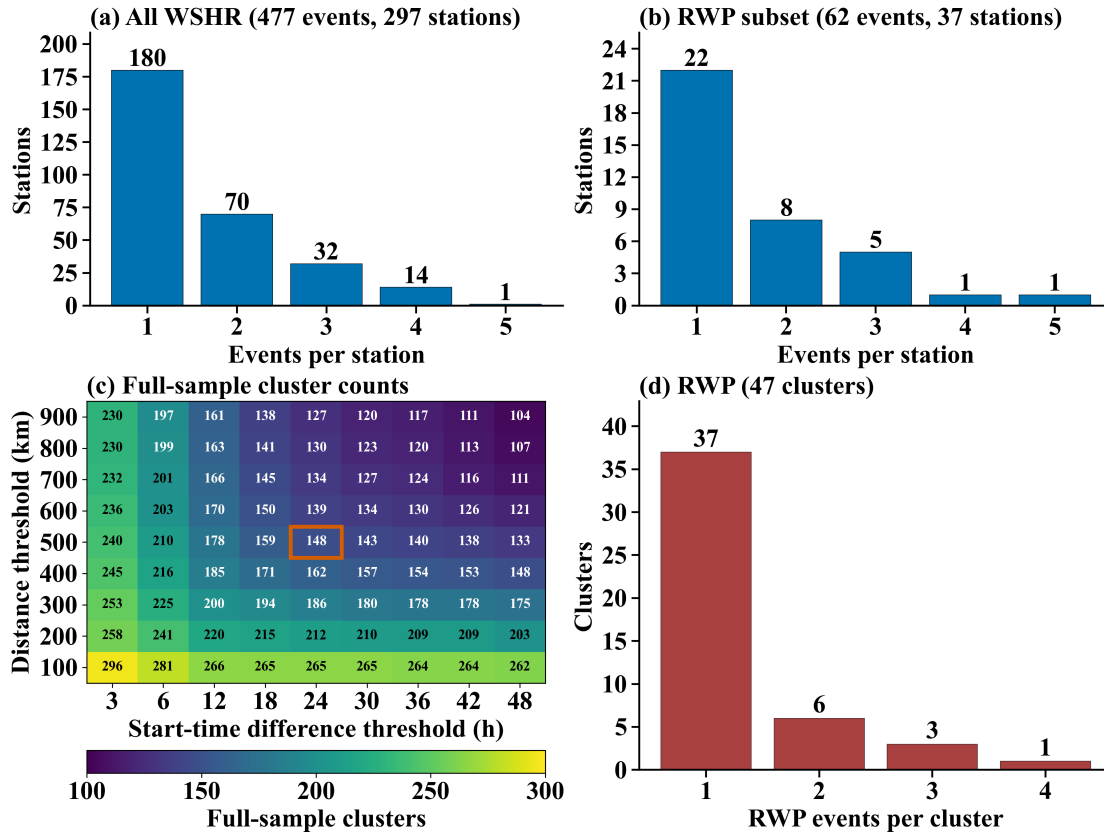


Figure S4. Distribution and clustering of warm-sector heavy rainfall (WSHR) events. (a, b) Numbers of stations with different event counts in the full sample (477 events) and the radar wind profiler (RWP) subset (62 events), respectively. (c) Episode-cluster counts for different spatial and temporal thresholds; the orange box marks the selected thresholds of 500 km and 24 h. (d) Distribution of RWP-observed events per episode cluster, using the 500 km and 24 h thresholds highlighted in (c). Panel (a) includes only the 297 stations with at least one WSHR event; the 196 stations without WSHR are excluded.

(4) *Inconsistency between L356–357 and the Fig. 6c legend. The text gives the median cumulative rainfall of other heavy rainfall events as "76.2 mm" (L357), whereas the Fig. 6c legend annotates the same quantity (the other-category P_{50}) as 56.2 mm. Please confirm whether these refer to the same statistic.*

Reply: Thank you for pointing out this inconsistency. Both values were intended to represent the same statistic—the median cumulative rainfall of other heavy rainfall events. The 76.2 mm reported in the original text was incorrect; the correct value is 56.2 mm as shown in Fig. 6c. We have corrected the text accordingly, so that the passage now reports 70.3 mm for WSHR and 56.2 mm for other heavy rainfall, in agreement with the figure.

The correction has been incorporated into this revised manuscript.

Technical Correction

(1) *Standardize unit notation. Physical-unit notation is mixed throughout: specific humidity is mostly written as "g kg⁻¹" in the text but as "g/kg" on some figure axes/legends (Fig. 7), and wind speed appears both as "m s⁻¹" and "m/s" (Fig. 9 axes/caption). Please adopt a single form as required by the journal.*

Reply: Following the reviewer's suggestion, all physical-unit notation has been standardized throughout the revised manuscript to a single form, with a space between unit symbols and negative superscript exponents (e.g., m s⁻¹, g kg⁻¹, mm h⁻¹), in line with the journal's requirements. The slash notation (m/s, g/kg, mm/h) has been removed.

Beyond the two figures identified by the reviewer (Figs. 7 and 9), we checked all figures in the main text and found the same inconsistency in Figs. 1, 3, 11, and 12, where precipitation rate was labeled "mm/h" and wind speed "m/s". The axis labels, color-bar labels, and captions of Figs. 1, 3, 7, 9, 11, and 12 have all been revised accordingly, so that specific humidity, wind speed, and precipitation rate are now given as g kg⁻¹, m s⁻¹, and mm h⁻¹, respectively, throughout the text and figures.

(2) *L37: "they contributed 13.8%" is in the past tense, inconsistent with the present tense used throughout the abstract.*

Reply: Per your kind suggestion, the sentence has been rewritten in the present tense.

(3) *Sect. 2.4 should define "target station" (L256). The term is used from Sect. 2.4 onward but is never defined in the paper. Please add a sentence at its first occurrence to help the reader.*

Reply: In this revision, we have defined "target station" at its first occurrence in Sect. 2.4 as "the rain-gauge station where each WSHR event occurred", per your kind suggestion.