

Responses to Reviewer #2

Dear Reviewer,

This manuscript investigates heatwaves over mainland China during May–September of 1986–2024 from a three-dimensional, spatiotemporally contiguous event perspective. Using ERA5-Land daily maximum temperature data, the authors identify heatwave events and quantify their persistence, severity, affected area, track length, and moving speed. The study shows that recent heatwave changes, especially after 2012, were characterized less by a continued increase in event numbers than by the strengthening of event-level characteristics. This event-based perspective is valuable because it helps describe heatwaves as evolving regional processes rather than as isolated local temperature anomalies.

Overall, I find the manuscript scientifically meaningful, generally well structured, and relevant to the scope of Natural Hazards and Earth System Sciences. The methodology is appropriate for the research question, and the main conclusions are potentially useful for understanding changes in regional heatwave hazards under warming. I also appreciate the authors' provision of supporting data and code, which improves the reproducibility and transparency of the work. However, several methodological details, figure/table descriptions, and formatting issues still require clarification or improvement. These issues are mostly minor and should be straightforward to address. I therefore recommend minor revision.

We sincerely thank you for your positive assessment of our manuscript and for the detailed and constructive comments. We have carefully considered all suggestions and have prepared corresponding revisions, which will be incorporated into the revised manuscript after the discussion stage. Because this is a discussion-stage response, we do not reproduce the full revised tables or figures here. Instead, we summarize the planned revisions and clarify how each comment will be addressed.

General comments

R2-G1. Some methodological details should be clarified to improve reproducibility and interpretation. For example, the manuscript should state the reference period used to calculate the calendar-day-specific 90th percentile threshold, explain the rationale for the 1.6% area threshold and the 6400 km² overlap threshold, clarify the exact definition of heatwave area, and define the weighting factor used in centroid calculation. These points are further detailed in Specific Comments 6-8 and 12-13.

Response: We agree that these methodological details should be stated more explicitly. In the revised manuscript, we will clarify that the calendar-day-specific 90th percentile threshold was calculated independently for each grid cell using the full study period of 1986-2024 and a 15-day moving window. We will also explain that the 1.6% area threshold and the 6400 km² overlap threshold were adopted from previous event-based studies to suppress isolated small hot patches while preserving the continuity of regionally coherent heatwave events. In addition, we will revise the definition and equation of heatwave area (HWA) to specify that it represents the union area of all unique grid cells affected during the event lifetime, rather than a cumulative space-time area. Finally, the weighting factor used in the centroid calculation will be defined explicitly as the local temperature exceedance multiplied by grid-cell area, so that the centroid calculation can be reproduced.

R2-G2. The presentation of the manuscript should be improved before publication. For example, Table 2 is difficult to read in its current layout, some figure captions are too brief for multi-panel figures, and unit formatting is not fully consistent, such as the mixed use of “°C days km²,” “°C days km²,” “km day⁻¹,” and “km yr⁻¹.” In addition, there are minor formatting issues such as missing spaces before citations, for example “different events(Ren et al., 2025; ...).” These issues are further noted in Specific Comments 9-10, 14, 17, 19, and 20.

Response: Thank you for pointing out these presentation issues. We will split the original dense table into two separate tables, expand the captions of the relevant multi-panel figures, and standardize all units throughout the manuscript using consistent notation, such as °C days km², km day⁻¹, and km yr⁻¹. We will also proofread the manuscript carefully to correct minor formatting problems, including missing spaces before citations and inconsistent figure/table labels.

Specific comments

R2-S1. Lines 11-20. The abstract is clear, but it may be useful to briefly mention that the heatwave definition is based on the calendar-day-specific 90th percentile threshold and a 3-day duration criterion. This would make the abstract more self-contained. For example, the authors may add the following sentence after introducing the ERA5-Land daily maximum temperature data: “Heatwave events were defined using a calendar-day-specific 90th percentile threshold with a minimum duration of three consecutive days and were then tracked as spatiotemporally contiguous three-dimensional events.”

Response: We agree. We will add a concise sentence to the abstract after the description of the ERA5-Land daily maximum temperature data, stating that heatwave events were defined using a calendar-day-specific 90th percentile threshold with a minimum duration of three consecutive days and were then tracked as spatiotemporally contiguous three-dimensional events.

R2-S2. Lines 23-32. The opening paragraph effectively introduces the broad impacts and increasing risks of heatwaves, including their effects on human health, ecosystems, agriculture, and energy systems. However, these background statements are relatively general. The authors may consider slightly condensing this part and moving more quickly to the key motivation of the study, namely the need to understand heatwaves as spatiotemporally contiguous regional processes. For example, the sentence beginning with “Over recent decades...” could be shortened or linked more directly to the following discussion of heatwave persistence, expansion, and migration.

Response: Thank you for this suggestion. We will condense the opening paragraph by shortening the general background on heatwave impacts and linking the trend of increasing heatwave risk more directly to the motivation for studying heatwaves as persistent, expanding, and migrating regional processes. This revision will help the introduction move more quickly from general context to the specific research gap addressed in this study.

R2-S3. Lines 40-46. The limitation of lower-dimensional heatwave analyses is well stated. However, the phrase “such dimensional reduction” could be made more specific. For example, specify whether it refers to grid-cell, station-based, or regional-average analyses.

Response: We agree that the phrase should be more specific. We will revise this part to state explicitly that the dimensional reduction refers to conventional grid-cell-based, station-based, and regional-average analyses. This change will make the methodological contrast with the three-dimensional event-based perspective clearer.

R2-S4. Lines 87-90. The study objectives are clearly stated, but the sentence is rather long. Please consider splitting it into two shorter sentences to improve readability.

Response: Thank you for the suggestion. We will split the long objective sentence into two shorter sentences. In the revised manuscript, the text will be revised as follows:

"By doing so, this study aims to clarify whether recent changes in heatwave events over mainland China are characterized primarily by increasing event numbers or by the joint intensification of multiple event characteristics. Furthermore, it investigates whether migration distance has particular process significance for understanding the evolution of contiguous heatwave events under rapid warming."

R2-S5. Figure 1(a) should include a scale bar where appropriate.

Response: We will add a scale bar to Figure 1(a) to provide clearer spatial reference for the study area map.

R2-S6. Lines 106-108. The caption of Figure 1 could be more informative. Please indicate the data period used for the mean daily maximum temperature in panel (c), and clarify whether the inset bar shows monthly means from May to September.

Response: Thank you for this helpful suggestion. We agree that the caption of Figure 1 should provide more complete information. In the revised manuscript, the caption will be revised as follows:

Figure 1: *Geographic setting and temperature background of mainland China. (a) Location of the study area; (b) topography; (c) spatial distribution of the mean daily maximum temperature during May–September over 1986–2024, with the inset bar showing the monthly mean daily maximum temperatures from May to September.*

R2-S7. Lines 110-117. The authors should add a brief note on potential uncertainties or biases in reanalysis temperature from ERA5-Land, especially in complex terrain such as the Qinghai-Tibet Plateau and mountainous regions. A short limitation statement would be sufficient.

Response: We agree. We will add a brief statement in the dataset section noting that ERA5-Land provides spatially continuous and temporally consistent temperature data but may contain uncertainties in complex terrain regions, including the Qinghai-Tibet Plateau and mountainous areas. We will also refer to this issue again in the limitations and future work section to avoid overinterpreting local temperature magnitudes and extreme intensity over complex terrain.

R2-S8. Lines 120-124. Please clarify the reference period used to calculate the calendar-day-specific 90th percentile threshold. Was the threshold calculated using the full 1986-2024 period? This is important for interpreting long-term changes in heatwave characteristics.

Response: Yes. The threshold was calculated using the full study period of 1986-2024. We will clarify that, for each grid cell and each calendar day, the 90th percentile threshold was estimated from daily maximum temperature values within a 15-day moving window over 1986-2024. This statement will be added to Section 2.3.1 so that the reference period is clear for interpreting the identified heatwave events and their long-term changes.

R2-S9. Line 138. There is a formatting issue in “different events(Ren et al., 2025; ...).” Please insert a space before the parenthesis: “different events (Ren et al., 2025; ...).”

Response: Agreed. We will insert the missing space before the citation parenthesis so that the text reads “different events (Ren et al., 2025; ...).”

R2-S10. Lines 144-146. The caption of Figure 2 should be revised grammatically. “The 3D structure of a typical heatwave event occurred in June 2024” should be changed to “The 3D structure of a typical heatwave event that occurred in June 2024” or “A typical 3D heatwave event in June 2024.”

Response: We agree. We will revise the caption grammatically, using a concise expression such as “A typical 3D heatwave event in June 2024.”

R2-S11. Lines 150-152. The term “Speed” is capitalized differently from the other abbreviations. Please use a consistent style, for example “heatwave moving speed (HWSpeed)” or “moving speed (Speed),” and keep the same form throughout the manuscript and figures.

Response: Agreed. We will use “moving speed (Speed)” consistently in the main text, tables, and figures.

R2-S12. Table 1. The definition of HWA needs clarification. It is not fully clear whether HWA represents the maximum daily affected area, the mean daily affected area, the union area over the event lifetime, or a cumulative space-time area. Since HWA is central to the analysis, the definition should be precise.

Response: This is an important clarification. In this study, HWA represents the spatial footprint of a heatwave event, defined as the total area of all unique grid cells affected at least once during the event lifetime. It does not represent the maximum daily affected area, the mean daily affected area, or a cumulative space-time area. We will revise both the textual definition and the equation in Table 1 to make this definition explicit.

R2-S13. Table 1 and lines 153-157. The weighting factor used in the centroid calculation should be defined. Please specify whether the centroid is weighted by temperature exceedance, grid-cell area, or another quantity. This is important because centroid positions are used to calculate track length and moving speed.

Response: Thank you for pointing out this missing definition. We will define the weighting factor explicitly in Table 1 and in the explanatory text below the table. In our calculation, the weighting factor for an affected grid cell at a given time step is the local temperature exceedance multiplied by the grid-cell area, i.e., (daily maximum temperature minus the corresponding threshold) $\times$ grid-cell area. Thus, the centroid is weighted toward grid cells with larger heatwave exceedance and larger area, rather than being a purely geometric centroid. This clarification will improve the reproducibility of the track length and moving speed calculations.

R2-S14. Lines 215-225 and Table 2. The manuscript reports positive fitted slopes for several heatwave characteristics across the three phases, while Table 2 marks statistical significance only for selected indicators. To avoid potential overinterpretation, please make the wording slightly more cautious and ensure consistency between the text and Table 2. For example, the sentence may be revised as: “The fitted slopes of HWF, HWD, HWS, HWA, HWL, and Speed were generally positive across the three phases, indicating overall increasing tendencies, while the statistical significance of these fitted trends is reported separately in Table 2.”

Response: We agree that the wording should distinguish fitted tendencies from statistically significant trends. We will revise the relevant sentence to state that the fitted slopes were generally positive across the three phases, indicating overall increasing tendencies, while the statistical significance of these fitted trends is reported separately in the trend table. This change will avoid implying that all fitted increases are statistically significant.

R2-S15. Table 2. The table is currently difficult to read because of its dense layout and rotated/fragmented text. Please improve table formatting or try to split it into two parts.

Response: We will split the original Table 2 into two separate tables. The revised Table 2 will report the number and proportion of heatwave events in each duration class for the three phases, and the revised Table 3 will summarize the fitted trend estimates for HWF, HWD, HWS, HWA, HWL, and Speed. Including both event counts and proportions in the duration-class table will make the comparison clearer and will directly address the reviewer’s suggestion.

R2-S16. Lines 250-251. The caption of Figure 6 is too general. Please specify what the colors, directions, panels, and duration classes represent. Since Figure 6 contains multiple directional and phase-based elements, a more detailed caption would improve readability.

Response: Thank you for this helpful suggestion. In the revised manuscript, the caption will be revised as follows:

Figure 6: *Migration characteristics of heatwave events during the three study phases. Panels (a), (d), (g), and (j) show the dominant migration directions of heatwave events in Phases I, II, III, and the full study period (ALL), respectively. Panels (b), (e), (h), and (k) present the proportions of events in each migration direction. Panels (c), (f), (i), and (l) show the duration-class composition (3–6, 7–10, 11–20, 21–30, and 31–45 days) associated with each migration direction.*

R2-S17. Lines 279-292. Please standardize the terminology used for the spatial heatwave metric in this section. I suggest reserving “heatwave severity (HWS)” for the event-level indicator defined in Table 1, and

using “annual cumulative heatwave temperature” consistently for the gridded spatial metric shown in Figure S5. To avoid ambiguity, please add a short clarification when this term first appears, for example: “Here, annual cumulative heatwave temperature refers to the grid-cell-level annual sum of temperature exceedance during heatwave days, whereas HWS denotes the cumulative severity of an individual three-dimensional heatwave event.”

Response: We agree with this distinction. We will reserve “heatwave severity (HWS)” for the cumulative severity of individual three-dimensional heatwave events, as defined in Table 1. For the gridded spatial metric shown in Figure S5, we will consistently use “annual cumulative heatwave temperature.” We will also add a clarification when the term first appears, explaining that annual cumulative heatwave temperature refers to the grid-cell-level annual sum of temperature exceedance during heatwave days, whereas HWS denotes the cumulative severity of an individual three-dimensional heatwave event.

R2-S18. Lines 303-316. The description of monthly differences would be clearer if the authors added a brief interpretive sentence after summarizing the May-September patterns. This does not require additional mechanism analysis, but a cautious explanation would help readers understand why the dominant heatwave characteristics differ among months. For example, the authors may consider: “These monthly contrasts may be also related to seasonal changes in the background thermal state and regional circulation conditions during the warm season, which can influence the spatial extent, persistence, and frequency of contiguous heatwave events.”.

Response: Thank you for this suggestion. We will add the suggested sentence after the summary of the May–September patterns in the revised manuscript.

R2-S19. Figure 9. Please ensure that all six heatwave indicators have clearly labeled units.

Response: We will add or check the units for all six indicators in Figure 9: HWF in events, HWD in days, HWS in °C days km², HWA in km², HWL in km, and Speed in km day⁻¹. We will also ensure that the same unit notation is used consistently in the caption, figure labels, and tables.

R2-S20. Lines 335-341. Please clarify the terminology used for the selected case events. Since these events were selected based on the maximum HWS in each phase, they should not be described in a way that implies they are typical of all events in that phase. I suggest using “the most severe events” or “illustrative high-severity cases” instead of “representative events.”

Response: We agree. We will replace “representative events” with “selected high-severity case events” or “illustrative high-severity cases” throughout Section 3.5 and the relevant captions. We will also state clearly that these cases were selected based on the maximum HWS in each phase. We will avoid using “typical events,” because that term could still imply broader representativeness than intended.

R2-S21. Lines 364-374. The word “stalling” may imply a quantitatively defined stagnation process, but the manuscript appears to use it as a qualitative description of the event trajectory. To avoid overstatement, I suggest replacing “stalling over Qinghai, Sichuan, Shanxi, Hunan, and Ningxia” with a more neutral expression, such as “passing through Qinghai, Sichuan, Shanxi, Hunan, and Ningxia” or “showing prolonged influence over Qinghai, Sichuan, Shanxi, Hunan, and Ningxia.”

Response: Thank you for pointing this out. We will replace “stalling over” with a more neutral expression and adjust the surrounding grammar. In the revised text, we will use wording such as “passing through Qinghai, Sichuan, Shanxi, Hunan, and Ningxia” when referring to the event trajectory. This avoids implying a quantitatively diagnosed stagnation process.

R2-S22. Lines 385-409. This paragraph partly repeats the results already presented in Section 3.2, especially the statements that Phase III was characterized by concurrent increases in duration, cumulative severity, affected extent, and track length. I suggest condensing this paragraph by deleting or merging some repetitive sentences. For example, the sentence beginning with “In other words, changes in heatwaves during the rapid

warming phase...” can be merged with the preceding sentence. The sentence beginning with “Therefore, the most noteworthy feature of Phase III...” also repeats the same point and could be shortened. In addition, the final sentence beginning with “The results of this study further indicate...” overlaps with the preceding discussion and could be removed or rewritten to emphasize interpretation rather than restating the result.

Response: We agree that this part of the Discussion should do more than restate the Results. We will condense the paragraph by merging repetitive sentences and removing redundant statements about the same Phase III changes. The revised paragraph will emphasize the interpretation that, under rapid warming, heatwave-event change is better understood as a strengthening of continuous regional-scale processes rather than simply as an increase in event counts or isolated local temperature anomalies.

R2-S23. Lines 435-439. The limitation paragraph is appropriate. Please consider moving part of this limitation discussion to a broader “limitations and future work” paragraph, including ERA5-Land uncertainty and the lack of physical mechanism diagnosis.

Response: We agree. We will add a broader “Limitations and future work” paragraph in the Discussion. This paragraph will include two main limitations: uncertainties in ERA5-Land temperature data over complex terrain, especially high-altitude and mountainous regions, and the fact that this study focuses on statistical and process-based event characteristics without directly diagnosing the physical mechanisms. We will also state that future work should link the three-dimensional event framework with atmospheric circulation persistence, soil moisture anomalies, and land-atmosphere feedbacks.

R2-S24. Lines 445-470. The Conclusions are clear, but they read partly like a shortened repetition of the Results section. I do not suggest removing most numerical information, as some key values are useful for supporting the main take-home messages. However, the authors may consider retaining only the most important numbers that directly support the central conclusions, while reducing detailed numerical repetition. For example, in conclusion (1), it would be sufficient to retain the contrast that Phase III had slightly fewer events than Phase II but a larger contribution from long-duration events, without listing all duration-class proportions. In conclusion (3), the authors may keep one concise statement showing that HWL was more strongly related to HWD, HWS, and HWA than Speed, but the full set of correlation coefficients need not be repeated. In conclusion (4), the month-by-month description could be condensed into a broader take-home message that heatwave intensification showed clear intra-seasonal differences. Overall, I suggest revising the Conclusions to emphasize the conceptual contribution of the contiguous-event perspective while retaining a small number of key quantitative results for support.

Response: Thank you for this helpful suggestion. We will revise the Conclusions to reduce detailed numerical repetition and better emphasize the conceptual contribution of the contiguous-event perspective. We will retain only the key quantitative values needed to support the main conclusions, such as the total number of identified events and the contrast between event counts and event-level intensification. The conclusions on track length and intra-seasonal differences will be condensed to focus on the main take-home messages rather than repeating the full set of correlation coefficients or month-by-month results.

Closing note: We sincerely thank the reviewer once again for the careful and constructive comments. We have carefully considered all suggestions and will incorporate the corresponding revisions into the revised manuscript. We believe these revisions will improve the clarity, rigor, and overall quality of the manuscript, and we appreciate the reviewer's valuable contribution to improving this work.