

Responses to Reviewer #4

Dear Reviewer,

This manuscript examines heatwave events over mainland China during May-September of 1986-2024 using a three-dimensional, spatiotemporally contiguous event framework. The topic is timely and relevant to Natural Hazards and Earth System Sciences. The event-based perspective is useful because it allows heatwaves to be interpreted as evolving regional processes rather than as isolated grid-cell anomalies. Overall, the manuscript is clearly organized, the methodology is generally appropriate, and the results provide useful information on changes in heatwave persistence, severity, affected area, and mobility. I recommend minor revision. The following comments may help improve the clarity and readability of the manuscript.

We thank Reviewer #4 for the constructive assessment and helpful suggestions. We have carefully considered all comments and will incorporate the corresponding revisions into the revised manuscript after the discussion stage. Our point-by-point responses are provided below.

R4C1: The introduction explains the value of a three-dimensional event perspective, but the specific novelty of this study relative to previous studies on contiguous heatwaves in China could be stated more directly. Several recent studies have already examined heatwave migration, propagation, and three-dimensional heatwave characteristics. The authors may wish to clarify more explicitly whether the main contribution of this study lies in the phase-based comparison, the joint analysis of persistence, severity, affected area, and track length, or the interpretation of track length as a process-level indicator.

Response to R4C1: Thank you for this helpful suggestion. We agree that the original manuscript did not sufficiently distinguish the methodological basis inherited from previous studies from the specific contribution of the present work. The underlying three-dimensional contiguous-event principle is not entirely new. The principal contribution of this study lies in extending this framework to compare heatwave events across different temporal periods, distinguish changes in event number from changes in event-level characteristics, and jointly examine persistence, cumulative severity, spatial extent, and mobility. We will revise the Introduction to make this distinction explicit and avoid presenting the basic clustering framework itself as the primary methodological novelty.

R4C2: Some abbreviations and technical terms could be introduced more carefully when they first appear. For example, event-level indicators such as HWD, HWS, HWA, HWL, and Speed are central to the analysis, and their meanings should be easy for readers to follow throughout the manuscript. The authors may consider briefly reminding readers of the meaning of these indicators in key result sections, especially when several metrics are discussed together.

Response to R4C2: Thank you for pointing this out. We will improve the introduction and use of abbreviations throughout the manuscript. In the revised manuscript, event-level indicators will be defined consistently when they first appear, including heatwave duration (HWD), heatwave severity (HWS), heatwave area (HWA), heatwave track length (HWL), and moving speed (Speed). We will also add short reminders in key result sections when several indicators are discussed together. For example, at the beginning of Section 3.2, we will briefly remind readers that HWD, HWS, HWA, and HWL refer to event duration, cumulative severity, affected area, and track length, respectively. This change is intended to improve readability without adding unnecessary repetition.

R4C3: The discussion of track length is one of the most interesting parts of the manuscript. However, the current interpretation could be made slightly more cautious. A strong correlation between HWL and HWD, HWS, or HWA does not necessarily imply that migration itself causes longer duration or greater severity. The authors may revise the wording to emphasize that track length is statistically associated with these characteristics and can serve as an integrated descriptor of event evolution, rather than implying a direct causal mechanism.

Response to R4C3: We agree that the reported relationships should not be interpreted as evidence that migration causes longer duration, greater severity, or broader affected area. We will revise the Discussion to describe HWL as the cumulative centroid displacement over the event lifetime. Because this cumulative quantity is partly dependent on event duration, its correlations with HWD, HWS, and HWA reflect both empirical covariation and construction-based relationships among event metrics. We will therefore avoid treating HWL as an independent causal factor and use more cautious expressions such as “is associated with” and “tends to co-occur with.”

R4C4: Some figure captions could be made more self-contained. For multi-panel figures, especially Figures 6, 7, and 10, the captions should briefly indicate what each group of panels represents, how phases are organized, and what the main visual elements mean. This would improve readability, particularly for readers who first inspect the figures before reading the detailed text.

Response to R4C4: Thank you for this practical suggestion. We will revise the captions of the main multi-panel figures to make them more self-contained. For Figure 6, the revised caption will specify which panels show migration directions, directional proportions, and duration-class composition. For Figure 7, the caption will define the panel organization by phase and by the relationship between HWL and other event metrics, and will also clarify that 'ALL' refers to all identified heatwave events during 1986–2024. For Figure 10, the caption will briefly describe the spatial distribution, centroid trajectory, and temporal evolution panels of the selected high-severity case event. These changes will allow readers to understand the figure structure without relying entirely on the main text. In the revised manuscript, the captions will be expanded 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 the full study period (ALL), Phases I, II and III, 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.*

Figure 7: *Relationships between heatwave track length (HWL) and other event characteristics. Rows correspond to the full study period (ALL, 1986–2024), Phase I (1986–1998), Phase II (1999–2011) and Phase III (2012–2024), respectively. Columns show the relationships between HWL and HWD, HWL and HWS, and HWL and HWA. Solid curves represent the best-fitting relationships, and shaded areas indicate the 95% confidence intervals. "ALL" represents all identified heatwave events during 1986–2024.*

Figure 10: *Selected high-severity heatwave event during Phase I (5 May–3 June 1995). (a) Three-dimensional spatiotemporal evolution of the heatwave event. (b) Migration trajectory of the event centroid from initiation to termination. (c) Temporal evolution of heatwave severity (HWS), heatwave area (HWA), and heatwave intensity (HWI) throughout the event lifetime. The event shown had the maximum HWS among all identified heatwave events in Phase I.*

R4C5: The conclusions are generally clear, but they could further emphasize the broader implication of the contiguous-event framework. The authors may consider adding one concise sentence explaining how this framework can complement conventional grid-cell or regional-average heatwave analyses, for example by better capturing event persistence, spatial expansion, and migration as connected components of regional heatwave hazards.

Response to R4C5: Thank you for this constructive comment. We agree that the broader implication of the contiguous-event framework should be emphasized more explicitly in the Conclusions. Accordingly, we will add the following sentence to the final paragraph of the Conclusions: "This contiguous-event framework complements conventional grid-cell and regional-average heatwave analyses by better capturing event persistence, spatial expansion, and migration as interconnected components of regional heatwave hazards, thereby providing a more process-based understanding of heatwave evolution under climate warming."

R4C6: In Figure 6, please clarify what the length of the arrows represents.

Response to R4C6: Thank you. In Figure 6, the arrow direction indicates the displacement from the centroid at the development stage to that at the decay stage, while its map length corresponds to the straight-line displacement between the two centroid locations. It does not represent the cumulative track length HWL.

R4C7: In Figure 10, the color scheme could be made more intuitive. Although the current color assignment is not incorrect, it would be clearer if the colors of the axes, labels, and corresponding legend elements were matched consistently.

Response to R4C7: Thank you for this helpful suggestion. In the revised manuscript, we will adjust the colors of the axes, labels, and corresponding legend elements so that each variable is represented consistently throughout the figure. This revision will make the relationships between the plotted variables more intuitive and easier to interpret while preserving the original data presentation.

R4C8: Several important findings should also be highlighted in the Abstract. For example, although the number of contiguous heatwave events does not differ substantially among the three phases, the events in Phase III are characterized by much greater duration, severity and affected area. This is one of the key findings revealed by the three-dimensional event framework and deserves to be summarized in the Abstract.

Response to R4C8: Thank you for this valuable suggestion. We agree that this is one of the key findings of the study and should be highlighted more explicitly in the Abstract. Accordingly, we will revise the Abstract by adding the following sentence: "Although the number of contiguous heatwave events did not continue to increase from the second to the third analysis period, event-level duration, cumulative severity, affected area, and track length showed stronger increases after 2012. This indicates that recent heatwave change was expressed more through the strengthening of event processes than through a continued rise in event number."

R4C9: Table 1: Please explicitly state that track length is calculated from the movement of the event centroid.

Response to R4C9: Thank you for this helpful suggestion. In the revised manuscript, we will revise the definition of HWL in Table 1 to clarify that it is the sum of the geodesic distances between event centroids at consecutive daily time steps over the event lifetime.

Closing note: We sincerely thank the reviewer once again for the careful, constructive, and insightful comments. We have carefully considered all suggestions and will incorporate the corresponding revisions into the revised manuscript. These revisions will improve the presentation and interpretation of the study, enhance the clarity of the methodology and figures, and better emphasize the novelty and broader methodological significance of the contiguous-event framework.