Responses to Reviewer #5

Dear reviewer,

The manuscript presents an interesting analysis of spatiotemporally contiguous heatwave events across mainland China using a three-dimensional clustering approach. The topic is timely and relevant, and the manuscript is generally well organized and clearly written. The figures are of good quality, and the analyses consistently show that recent heatwaves are characterized by increasing persistence, severity, spatial extent, and mobility. Overall, I consider the study to be scientifically sound and suitable for publication after minor revision. Most methodological and presentation issues have already been raised by the other reviewers. Therefore, my comments focus mainly on aspects that could further strengthen the scientific contribution and interpretation of the study.

Response: Thank you for this encouraging assessment. We appreciate the reviewer's recognition of the scientific value, organization, figures, and central findings of the study. We will address the four focused comments through targeted revisions, completed parameter-sensitivity analyses, and a strengthened Discussion, while retaining the scope of the study as an event-based characterization rather than extending it into a full physical-attribution analysis. The corresponding textual and supplementary revisions will be integrated consistently after the discussion stage has concluded.

R5C1:

First, although the manuscript cites several previous studies that have applied three-dimensional or event-based approaches to characterize heatwaves, the specific novelty of the present work could be articulated more explicitly. It would be beneficial to clearly distinguish which elements represent methodological innovation and which constitute an application or extension of existing approaches. A concise comparison with previous studies would help readers better appreciate the unique contribution of this work.

Response to R5C1: Thank you for this important suggestion. We agree that the original manuscript does not distinguish sufficiently clearly between the methodological basis inherited from previous three-dimensional event studies and the specific contribution of the present work. The study builds on existing spatiotemporally contiguous event-identification approaches rather than introducing an entirely new clustering principle. We will revise the Introduction to state this distinction explicitly and add a concise comparison with representative previous studies. The revised manuscript will clarify that the principal contribution lies in extending the event-based framework in four related respects: (1) evaluating changes in contiguous heatwave characteristics across analysis periods with different warming backgrounds, with particular attention to the post-2012 period; (2) distinguishing changes in event occurrence from changes in the strength of individual event processes; (3) jointly examining persistence, cumulative severity, spatial footprint, and mobility within a common event catalogue; and (4) evaluating whether these event-level changes exhibit systematic intra-seasonal differences. We will present these contributions as scientific and analytical extensions of existing three-dimensional approaches rather than as an entirely new clustering method.

R5C2:

Second, while the event-identification procedure appears reasonable, the manuscript would benefit from a stronger discussion of its robustness. The selected thresholds (90th percentile, minimum duration, minimum event area, and overlap criteria) seem appropriate, but additional justification—or, where feasible, a brief sensitivity analysis—would increase confidence that the main conclusions are not strongly dependent on these parameter choices.

Response: to R5C2: Thank you for this important comment. We agree that literature-based justification alone is insufficient to demonstrate the robustness of the event-identification procedure. We have therefore completed a one-factor-at-a-time sensitivity assessment of the principal identification choices, while retaining all other

inputs, algorithms, and statistical procedures at their baseline settings. The complete set of results, including the minimum-duration test, will be summarized in the final Supplement. The most diagnostic findings from the percentile, minimum-area, and adjacent-day connection tests are reported here.

First, replacing the calendar-day 90th-percentile threshold with the more restrictive 95th percentile reduced the total event number from 609 to 515, as expected, and reduced the absolute magnitudes of several event characteristics. However, the principal phase contrast remained: under the 95th-percentile definition, event numbers changed from 133 to 192 and 190 across the three periods, whereas mean HWD, HWS, HWA, and HWL in the third period remained higher than in both earlier periods. Relative to the second period, the corresponding increases were 12.0%, 20.4%, 10.0%, and 16.0%, respectively, while event number decreased slightly by 1.0%. Thus, the central interpretation of stronger event processes without a continued increase in event number was retained, although the absolute event scale and upper-tail characteristics were magnitude-sensitive to the percentile threshold.

Second, the choice of the 1.6% minimum daily patch-area threshold was supported by both previous methodological studies and our own sensitivity assessment. In an earlier three-dimensional drought-event study, Jiang et al. (2023) systematically examined different spatial thresholds and found that the number of identified events and the proportion of minor events gradually stabilized when the threshold exceeded approximately 1.6% of the study area. Similar thresholds have subsequently been adopted in several three-dimensional drought-event studies as a practical criterion for excluding small and spatially fragmented patches. Although these studies concern drought rather than heatwaves and therefore provide a methodological precedent rather than direct validation for the present application, they support 1.6% as a reasonable initial spatial-filtering criterion. We further evaluated minimum daily patch-area thresholds of 0.5%, 1.0%, 1.5%, 1.6%, and 2.0% using representative years distributed across the study period. In the pooled assessment, the adopted 1.6% threshold removed 96.69% of candidate daily patches while retaining 96.20% of patch-level HWS and 89.30% of patch-day area. Importantly, all five settings produced identical final three-dimensional event catalogues and event-level characteristics in the tested years. Relative to the 0.5% setting, the 1.6% threshold reduced the mean runtime of the core identification procedure by 24.72%, whereas increasing the threshold further to 2.0% provided little additional computational benefit but removed more HWS and patch-day area. Based on the methodological precedent in previous three-dimensional event studies and the stability demonstrated by the present sensitivity analysis, we will retain the 1.6% threshold in the revised manuscript.

Third, the overlap criteria was evaluated under lower, baseline, and higher numerical thresholds. Under thresholds of 3200, 6400, and 9600, the direction of the third-period increases in HWD, HWS, HWA, HWL, and Speed relative to the first period was retained. However, event number changed largely as expected. We will therefore report that the process-level intensification is directionally stable, whereas event number and absolute effect magnitudes are sensitive to the connection definition. We will not describe the full result set as uniformly robust.

After the discussion stage, we will add a parameter-sensitivity subsection to the Methods, summarize the principal results in the Results, and provide the detailed scenario tables and figures in the Supplement. The Discussion and Conclusions will explicitly distinguish conclusions that are directionally stable from quantities that are magnitude- or definition-sensitive.

Jiang, T., Su, X., Zhang, G., Zhang, T., and Wu, H.: Estimating propagation probability from meteorological to ecological droughts using a hybrid machine learning copula method, Hydrol. Earth Syst. Sci., 27, 559–576, https://doi.org/10.5194/hess-27-559-2023

R5C3:

Third, the Results and Discussion sections are dominated by descriptive statistical analyses. Although the observed intensification of heatwave persistence, severity, and mobility is convincingly demonstrated, the manuscript provides relatively limited discussion of the physical mechanisms that could explain these patterns.

Expanding the discussion to include the possible influence of large-scale atmospheric circulation, blocking events, land–atmosphere interactions, or other climatic drivers would substantially strengthen the scientific interpretation and broaden the impact of the study.

Response to R5C3: Thank you for this valuable suggestion. We agree that the current Discussion emphasizes the statistical characteristics of the identified events more strongly than their possible physical interpretation. After the discussion stage, the revised Discussion will be expanded, based on a focused review of the relevant literature, to consider plausible atmospheric and land-surface processes that may help interpret the observed changes in event persistence, cumulative severity, spatial extent, and apparent mobility. Particular attention will be given to the possible roles of large-scale circulation persistence and land–atmosphere interactions, while the specific mechanisms discussed will be determined by the available evidence and their relevance to the present results. Because these drivers are not directly diagnosed in this study, we will avoid attributing the observed changes to any individual mechanism and will clearly distinguish literature-based physical interpretation from demonstrated causal relationships.

We will also connect this discussion with the nonlinear relationships involving movement speed. A cautious interpretation is that nearly stationary events may accumulate heat locally but have limited displacement, whereas rapidly changing event centroids may provide less time for local heat accumulation; intermediate apparent movement may combine persistence with spatial propagation. At the same time, we will clarify that centroid displacement can arise not only from translational movement but also from asymmetric expansion, contraction, splitting, or merging of the affected area. Because atmospheric and land-surface drivers are not directly diagnosed in the present analysis, the revised text will clearly distinguish literature-supported physical interpretations from demonstrated causal mechanisms. Direct attribution using circulation, soil-moisture, and surface-energy diagnostics will remain an explicitly stated priority for future research.

R5C4:

Finally, the manuscript would benefit from a more explicit discussion of the practical advantages of the proposed contiguous three-dimensional framework compared with conventional grid-based or regional-average heatwave analyses. Clearly illustrating what additional scientific understanding or hazard assessment capability is gained from this event-based perspective would better highlight the broader significance of the proposed methodology.

Response to R5C4: Thank you for this helpful comment. We agree that the manuscript currently describes the methodological differences from conventional analyses but does not sufficiently explain the additional scientific and practical capabilities gained from the contiguous-event perspective. We will expand both the Introduction and Discussion to make this comparison more explicit. Grid- or station-based analyses are effective for characterizing local heatwave frequency, duration, and intensity, whereas regional-average series describe broad thermal conditions but may obscure spatial heterogeneity and asynchronous event development. In contrast, the three-dimensional framework links spatially and temporally connected hot areas into individual event lifecycles, allowing the persistence, cumulative severity, spatial footprint, centroid pathway, movement direction, and spatial evolution of the same regional heatwave process to be quantified. We will further explain that this event-based framework can support process-oriented hazard and exposure assessments by linking the complete lifetime and pathway of a heatwave event with population, agriculture, ecosystems, infrastructure, or administrative regions. This perspective can help assess whether the same heatwave process affects multiple regions sequentially or simultaneously and can therefore provide additional information for regional monitoring and coordinated risk management. We will also clarify that the contiguous-event framework complements, rather than replaces, conventional grid-based and regional-average approaches.

Final assessment

Overall, this is a valuable contribution with clear publication potential. Addressing the points above would further strengthen the manuscript by clarifying its novelty, reinforcing the methodological justification, and providing a deeper scientific interpretation of the results.

Response: We sincerely thank the reviewer for the positive assessment and constructive comments. These suggestions will help us further improve the clarity, robustness, and scientific interpretation of the manuscript.