
Response to the RC3

Dear Reviewer,

We sincerely thank the reviewer for your care and support of our research. Your valuable comments and suggestions have been of tremendous help in continuously refining and improving this study. Upon receiving the review comments, we promptly revised the manuscript in accordance with your suggestions, striving to fully address all revision requirements. The revised portions are highlighted in red in the manuscript for your convenience. Our point-by-point responses to your comments are provided below.

Thank you for your time and kind assistance.

Best regards,
Haoyu Jin

General comments

This study explores historical and future changes in the characteristics of compound heatwave-extreme precipitation events and the statistical linkage between heatwave and extreme precipitation using global reanalyses products and CMIP6 model projections. This topic is relevant given rising climate-driven extremes and the increasing importance of understanding compound hazards. The manuscript is clearly structured and the analyses are potentially valuable. However, in its current form, the analytical framework remains somewhat superficial. The study would benefit from more explicit justification of key methodological decisions, clearer articulation of its scientific novelty, and additional explanation to strengthen transparency and interpretability. Several assumptions are stated but not sufficiently supported, and important methodological steps lack the detail needed to ensure reproducibility. Addressing these issues would substantially improve the clarity, credibility, and overall impact of the work. With these enhancements, the study could make a meaningful contribution to understanding CHWEP events, but substantial conceptual, methodological, and interpretive clarifications are required before the conclusions can be fully supported and before the manuscript meets the standards expected for publication in HESS.

Specific comments

1. Your description of preprocessing of datasets is straightforward. However, I am concerned about the motivation for using ensemble mean as the final reference datasets. Given the uncertainties inherent in global reanalyses, the rationale for preferring ensemble mean over the best-performing reanalyses should be well articulated. Similarly, what is the justification for selecting four specific CMIP6 models? Is this based on their transient climate responses to avoid 'Hot Model' problems associated with CMIP6 (e.g. Hausfather et al., 2022)?

Reference

Hausfather, Z., Marvel, K., Schmidt, G.A., Nielsen-Gammon, J.W., Zelinka, M., 2022. Climate simulations: recognize the 'hot model' problem. Nature 605, 26–29. https://doi.org/10.1038/d41586-022-01192-2

Response: The authors selected multiple models and used the ensemble mean as the final time series for identifying extreme precipitation and heatwave events to enhance robustness. Reanalysis datasets, which assimilate multiple data sources, particularly in situ station observations, offer relatively high accuracy; therefore, we chose three commonly used reanalysis datasets and computed their mean to obtain a more reliable and stable result. The four CMIP6 GCMs were selected because they exhibit high accuracy, high spatial resolution, and provide daily maximum temperature data, essential for heatwave detection in this study. Moreover, as the reviewer noted, this approach helps avoid bias introduced by so-called "hot models" that may overestimate warming. We thank the reviewer for raising this point, which has deepened our understanding of best practices in GCM selection and application.

2. The quantile mapping approach is mentioned only superficially, it is unclear whether temperature and precipitation were corrected separately, future projections were adjusted using historical distributions, and potential risks of overcorrection, particularly for extremes?. Additionally, since CHWEP events potentially rely on joint behavior of temperature and precipitation, it might be helpful if the authors note whether the bias correction approach preserves multivariate dependence and temporal structure. Quantile mapping can distort these if applied independently.

Response: The authors applied Quantile Delta Mapping (QDM) to bias-correct precipitation and temperature projections for the future period. The bias-correction formula for precipitation is given in Equation (2) of Section 3.1, and that for temperature in Equation (3) of the same section. Because QDM preserves the relative structure of the data, it does not alter the spatial or temporal occurrence patterns of heatwaves or extreme precipitation events. In this study, high data accuracy is essential when comparing single extreme events and CHWEP events between the future and historical periods. However, when comparing single extreme events with CHWEP events within the same period, absolute data accuracy is less critical, as the analysis focuses on the differences between the two event types rather than their absolute magnitudes. We thank the reviewer for raising this point, which has helped the authors further refine and improve the study.

3. "Historical daily maximum temperatures" is vague. Please clarify the baseline climate period used to calculate threshold, and whether the chosen period affects the comparability between historical and future events?. The authors should add a bit more context (e.g. land-atmosphere memory, soil moisture decay timescales) to support the choice of 7-day window. Also clarify whether intensities represent mean values per event or aggregated means across all events.

Response: Indeed, the selection of thresholds for extreme precipitation and heatwave events is critical to their identification. In this study, the heatwave threshold at each grid cell is defined as the 90th percentile of the 45-year (1980-2024) local daily maximum temperature series during the historical period. Similarly, the threshold for extreme precipitation is set as the 90th percentile of the wet-day (>1 mm) precipitation series over the same 45-year period at each grid point. The 90th percentile is chosen to ensure a sufficient number of extreme events for robust statistical analysis.

A 7-day window is adopted to balance the need for physically plausible linkage between heatwaves and subsequent extreme precipitation while maintaining an adequate sample size; this window length follows the approach used in You and Wang's study. In Section 3.2, we have revised the formulations of all relevant indices to enhance clarity. Specifically, we compute the annual mean of all events of a given type, ensuring that each year contributes only one averaged value per extreme-event metric. We thank the reviewer for raising these points, which have helped us further refine and improve the quality of this study.

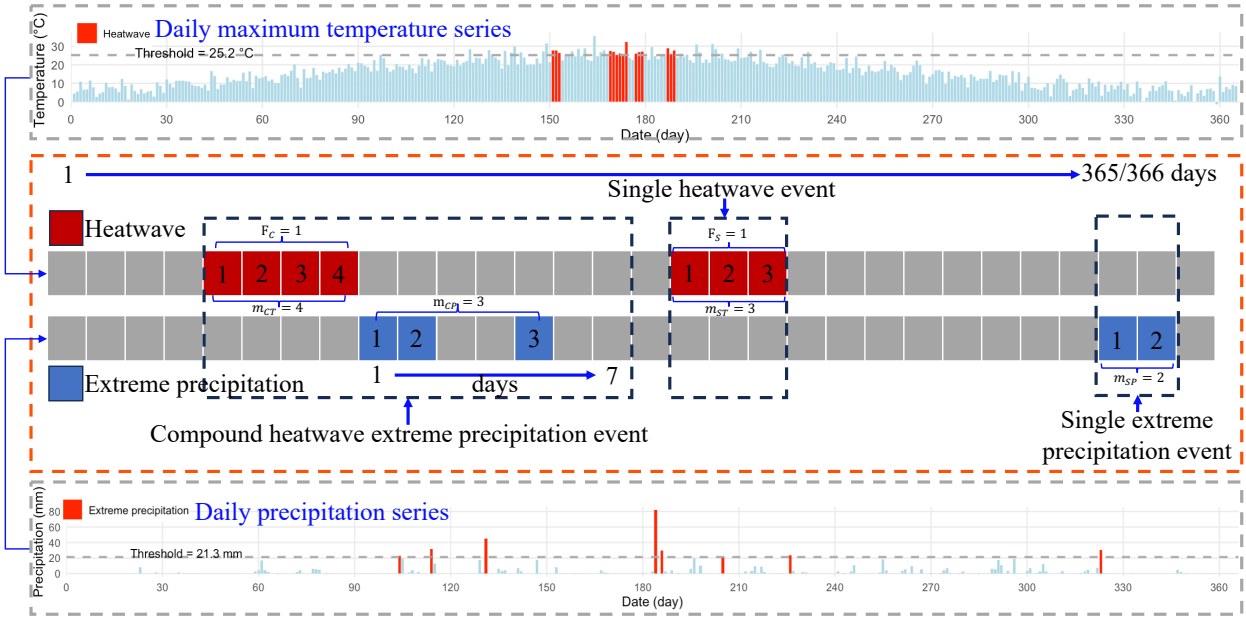

Figure 1. Schematic illustration of CHWEP and single extreme precipitation and heatwave events extracted from daily precipitation and daily maximum temperature time series over a year.

4. Please clarify whether ECA uses events derived from the earlier definitions or whether counts are based on individual days. ECA may be sensitive to the way the underlying event is defined. In addition, consider clarifying ECA only tests for statistical dependence, not physical causality. The text currently states it can "identify possible causal relationships,.." which may be an overstatement.

Response: In this study, we calculated two probabilities based on the ECA algorithm: one is the observed co-occurrence probability of heatwave and extreme precipitation events within a 7-day time window, and the other is the random co-occurrence probability obtained by randomly shuffling the timing of heatwave and extreme precipitation events across a year and then calculating the likelihood of their co-occurrence within a 7-day window. Both extreme precipitation events and heatwaves were identified using thresholds specific to each event type. The authors have carefully revised this sentence to ensure more accurate wording and to avoid overstating the role of the ECA algorithm. We thank the reviewer for pointing out this issue, which has helped us improve the precision of our presentation.

5. A brief mechanistic explanation why some patterns (e.g. "hotspots in the Sahara Desert, the Middle East, and Australia", "CHWEPs are more pronounced in mid-to-high latitudes") emerge or what they imply would strengthen the narrative. Statements such as "CHWEPs occur more

frequently" or "intensity is significantly higher" would benefit from at least approximate magnitudes (e.g., percent differences)

Response: The authors suggest that the stronger extreme precipitation following heatwaves in the mid- to high-latitude regions of the Northern Hemisphere, as well as the higher frequency of isolated heatwave events in tropical and desert regions, may be attributed to the fact that rising temperatures in the mid- to high-latitude Northern Hemisphere enhance the hydrological cycle, thereby promoting extreme precipitation, whereas tropical and desert regions experience distinct wet and dry seasons, leading to more frequent and longer-lasting individual heatwave events. To further investigate the spatiotemporal distribution differences between isolated extreme events and CHWEPs, the authors additionally extracted regional extreme event attribute values and their ratios. The authors thank the reviewer for raising this point, which helps them continuously improve and refine this study.

6. The statement that "CHWEP precipitation intensity under SSP2-4.5 exceeds single-event intensity under SSP5-8.5" is interesting, please provide a short explanation e.g. heatwave-induced atmospheric instability?

Response: One of the key findings of this study is that more intense extreme precipitation tends to occur following heatwaves. Heatwave events accelerate moisture evaporation and enhance the hydrological cycle, particularly in the mid- to high-latitude regions of the Northern Hemisphere, where the climate is generally colder. The heatwaves in these regions boost evaporation, increasing atmospheric instability and thereby promoting precipitation. We gratefully acknowledge the reviewer for your valuable comments and suggestions, which have greatly helped the authors further refine and improve this study.

7. The authors mentioned widely known ideas (e.g., compound events cause more damage than single events) without tying them closely to your specific results or demonstrating how your findings confirm, extend, or challenge this existing knowledge. Also you state that integrated intensities exceed those of single events, but do not explain what this means physically (e.g. more moisture availability? stronger thermal anomalies?). A more explicit comparison would help interpret the significance of CHWEP intensification.

Response: The authors have revised the relevant sections, placing greater emphasis on the significant contribution of this study to understanding CHWEP events. The study consists of three main components. First, using daily precipitation and daily maximum temperature data from the historical period (1980-2024), we identified individual extreme events and CHWEP events, and further analyzed their differences. We found that in the mid- to high-latitude regions of the Northern Hemisphere, CHWEP events occur more frequently and with greater precipitation intensity compared to individual extreme events. Second, applying future daily precipitation and daily maximum temperature data (2056-2100), we extracted future individual extreme events and CHWEP events and observed similar spatial distribution patterns. Third, we employed the ECA method to compare the actual probability of extreme precipitation following a heatwave with the probability expected under random co-occurrence. The results indicate that extreme precipitation events are significantly more likely to occur after heatwaves than by chance alone. The authors propose that heatwave events intensify the hydrological cycle and enhance atmospheric instability,

thereby triggering extreme precipitation, particularly in the mid- to high-latitude regions of the Northern Hemisphere. We sincerely thank the reviewer for your insightful comments and constructive suggestions, which have greatly assisted us in further refining and improving this study.

8. '..both CHWEP and single events are increasing significantly in frequency, intensity, and duration', it is unclear which regions or magnitude of change? More details should be added to make the discussion more insightful.

Response: The authors have added a description in the Discussion section regarding the regions where extreme events are projected to intensify in the future. Specifically, CHWEP and individual heatwave events are expected to increase more in frequency in equatorial regions; CHWEP and individual heatwaves will exhibit greater increases in temperature intensity in the mid- to high-latitude regions of the Northern Hemisphere; CHWEP and individual extreme precipitation events will show larger increases in precipitation intensity in equatorial regions; and the duration of CHWEP and individual heatwave events will lengthen more significantly over the southwestern United States, the Sahara Desert, and India. The authors further extracted and compared metrics of CHWEP and single extreme events across different regions, presenting box plots in the supplementary materials to provide a clearer comparison of regional changes. We appreciate the reviewer for pointing out this issue, as it has helped the authors further refine and enhance the quality of this study.

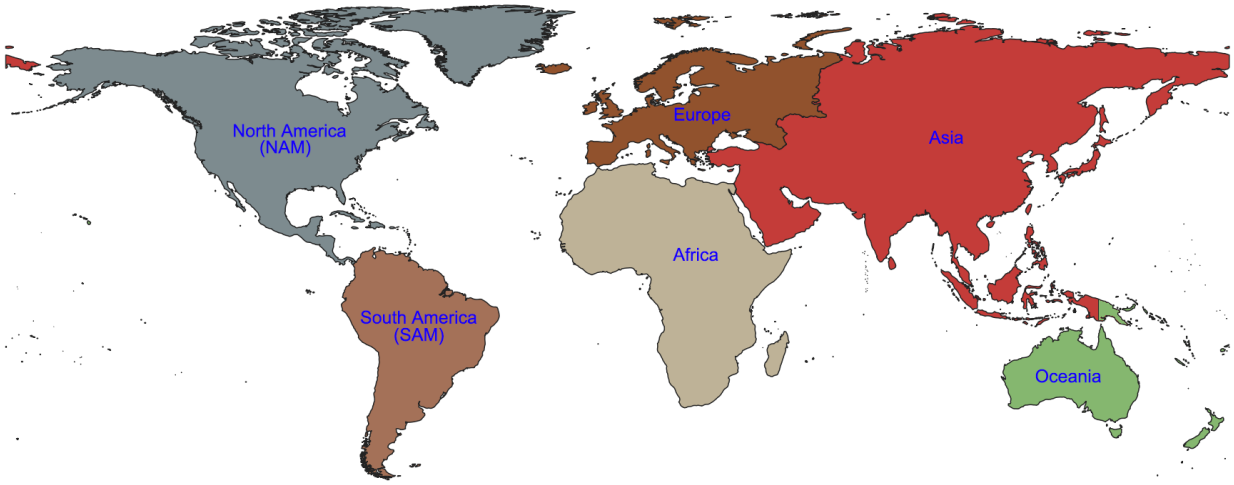

Figure S1. Regional division based on continental boundaries.

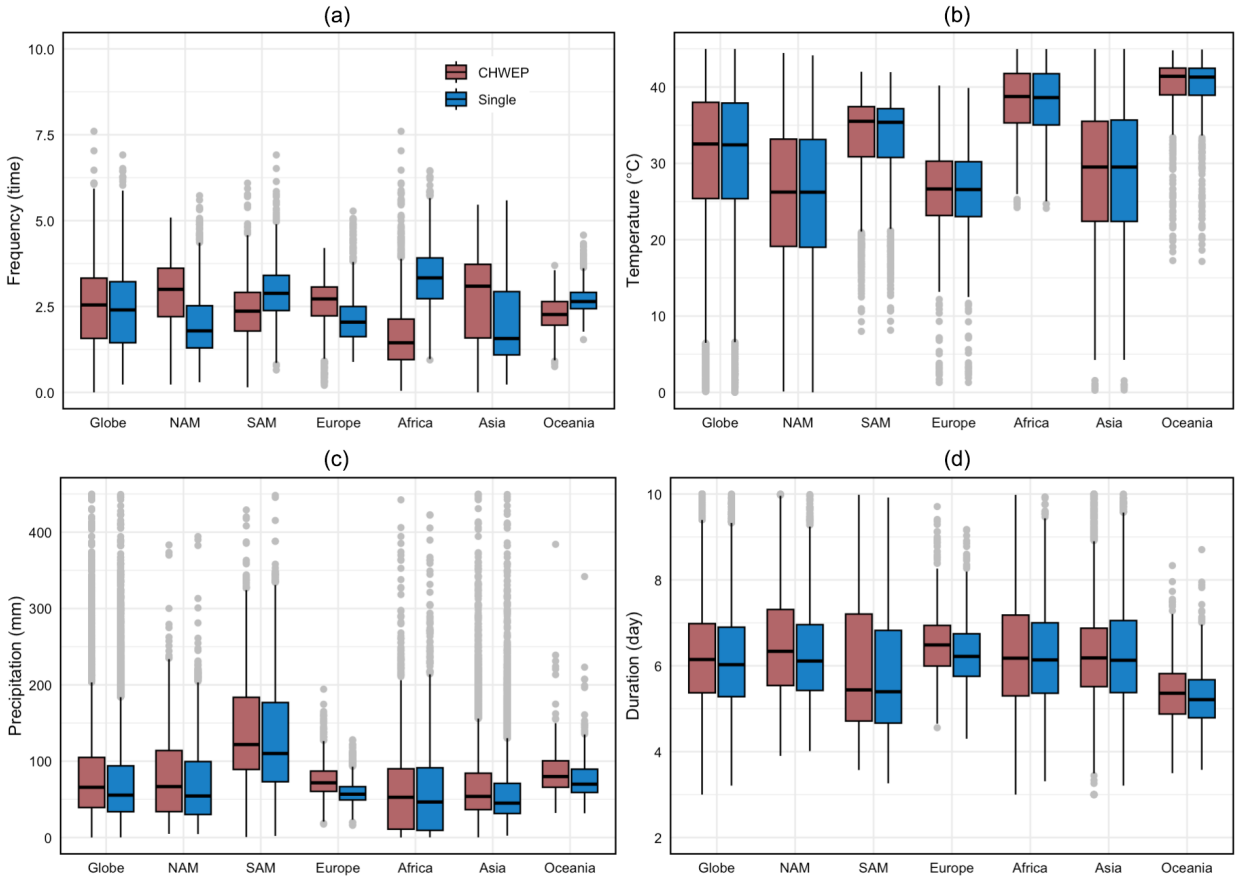

Figure S2. Box plots of the frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (f) for CHWEP and single extreme events.

9. '..but also reveals a dangerous "rapid transition" phenomenon…' This is one novel contribution that should be elaborated (currently the discussion is brief).

Response: The authors have added a more detail description of rapid-transition extreme events in the Discussion section. "Rapid transition from heatwave to extreme precipitation" refers to the phenomenon in which a prolonged heatwave abruptly shifts to intense or even extreme precipitation within a short period, typically several hours to a few days. Such events exemplify the dynamic connections and rapid evolution between distinct types of extreme weather in the climate system. They have been increasingly observed in many parts of the world in recent years, with particularly pronounced occurrences in mid- to high-latitude regions. The plausible physical mechanisms include: intense surface heating during heatwaves, which increases atmospheric instability, and enhanced evapotranspiration, which supplies additional moisture to the atmosphere. When favorable large-scale circulation conditions, such as cold-air intrusion or low-level jets emerge, the accumulated energy and moisture are rapidly released, triggering strong convection and extreme precipitation. This rapid "dry-to-wet" transition between contrasting extremes not only amplifies compound disaster risks, such as flash flooding following heat stress, but also poses heightened challenges for climate forecasting, early-warning systems, and emergency response frameworks. The rapid interconversion between different types of extreme events has become a focal topic in recent hydrometeorological research (Chen et al., 2022; Tan et al., 2023; Woolway

et al., 2021). We sincerely thank the reviewer for your valuable comments and suggestions, which have greatly helped the authors further refine and improve this study.

Chen, Y., Liao, Z., Shi, Y., Li, P., and Zhai, P.: Greater Flash Flood Risks From Hourly Precipitation Extremes Preconditioned by Heatwaves in the Yangtze River Valley, Geophys. Res. Lett., 49, https://doi.org/10.1029/2022GL099485, 2022.
Tan, X., Wu, X., Huang, Z., Fu, J., Tan, X., Deng, S., Liu, Y., Gan, T. Y., and Liu, B.: Increasing global precipitation whiplash due to anthropogenic greenhouse gas emissions, Nat. Commun., 14, 2796, https://doi.org/10.1038/s41467-023-38510-9, 2023.
Woolway, R. I., Kraemer, B. M., Zscheischler, J., and Albergel, C.: Compound Hot Temperature and High Chlorophyll Extreme Events in Global Lakes, Environ. Res. Lett., 16, 124066, https://doi.org/10.1088/1748-9326/ac3d5a, 2021.

10. This section is missing the acknowledgment of potential limitations of the methods/results (e.g. uncertainties in climate data, bias correction, sensitivity to thresholds). This is important to strengthen credibility and transparency.

Response: The authors have added a discussion in the Discussion section regarding potential limitations of this study and aspects that warrant further improvement. In the present study, we enhanced the robustness of our results through careful experimental design, for example, by using the ensemble mean of outputs from multiple models, defining extreme events using the 90th percentile as the threshold, and applying a 7-day time window to identify sequences of compound events, in order to obtain a sufficient number of extreme event samples. In future work, it would be valuable to include a broader range of climate models, test alternative percentile thresholds for defining extremes, and explore different time windows between successive extreme events to further verify the reliability and accuracy of our findings. We sincerely thank the reviewer for your insightful comments and valuable suggestions, which have greatly helped the authors to continuously improve and refine this study.

Minor comments
L50-55: It will be useful to connect which category CHWEP belongs to (e.g. temporally compounding). This will help readers who may not be familiar with the terminology.

Response: We have already clarified at this point that our study primarily focuses on heatwaves and extreme precipitation events that are temporally consecutive, namely, temporally linked CHWEP events. We thank the reviewer for raising this issue, as it has helped the authors further refine and improve the quality of this study.

L70-75: I would be careful with the use of the phrase ‘ the first comprehensive, global scale’. Ensure your phrase is defensible or rephrase to avoid overclaiming.

Response: The authors have appropriately revised this sentence to achieve a more balanced expression. An important improvement of this study compared to previous work is the systematic comparative analysis of the spatiotemporal distribution differences between CHWEP events and single extreme events, with greater emphasis placed on the distinct regional patterns exhibited by

CHWEP events relative to single extreme events. We thank the reviewer for pointing out this issue, which has helped the authors further refine and enhance the quality of this study.

L75-80: The authors mentioned 'statistical significance of differences among event types', however, it is unclear whether this pertains to frequency, duration, temporal lag, etc.?. As I mentioned previously, the authors should consider clarifying that CHWEP events are defined both in terms of temporal thresholds and sequence, if that is indeed the approach.

Response: The authors have appropriately revised this paragraph. CHWEP events are composed of consecutive heatwaves and extreme precipitation events, with a time window of no more than 7 days. Single heatwave events and single extreme precipitation events each have their own respective metrics. We compare the heatwave metrics within CHWEP events against those of single heatwaves, and similarly compare the extreme precipitation metrics within CHWEP events against those of single extreme precipitation events. This allows us to isolate the distinctive characteristics of CHWEP events relative to single extreme events, thereby enabling an evaluation of their spatiotemporal differences. We thank the reviewer for your valuable comments and suggestions, which help the authors continuously refine and improve this study.

L85: Use standard citations instead of hyperlinks throughout the texts. Links should be provided in the appropriate 'data availability' section

Response: The authors have removed the direct links to these data and instead provided appropriate references. Links to the data are included in the Data Availability section. We thank the reviewer for highlighting this issue, which has helped the authors further improve the content and structure of the manuscript.

Fig 1: Caption is too short. Consider adding more information.

Response: The authors have revised and redrawn Figure 1 and updated its caption accordingly. We thank the reviewer for pointing out this issue, which has helped the authors continuously refine and enhance this study.

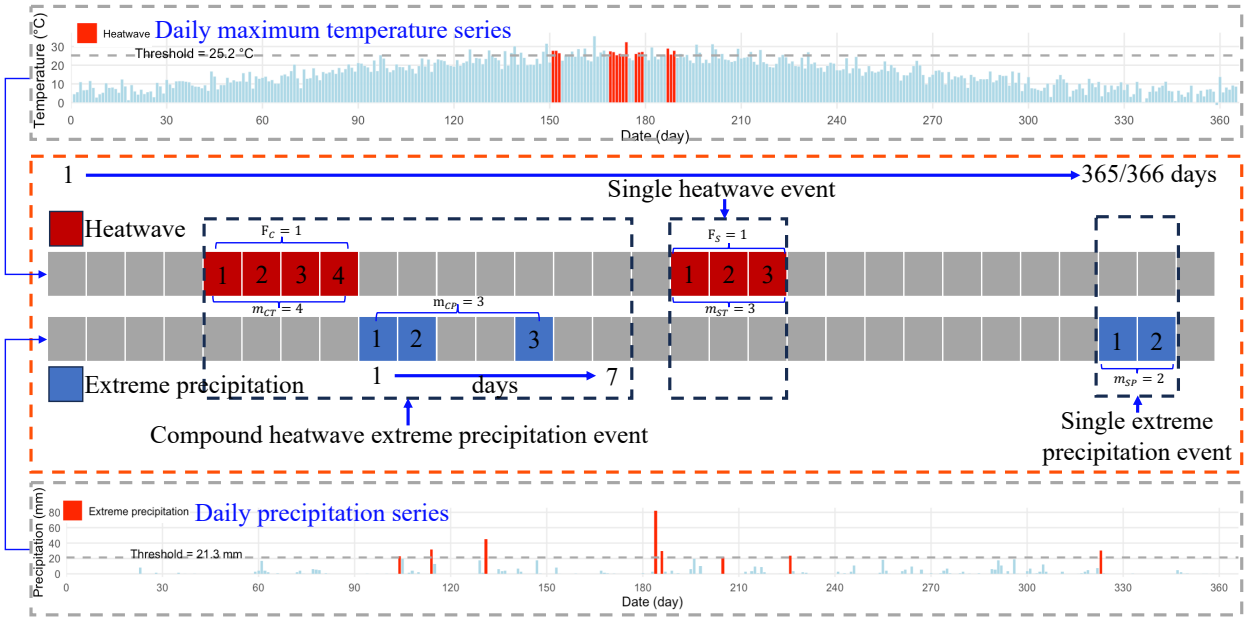

Figure 1. Schematic illustration of CHWEP and single extreme precipitation and heatwave events extracted from daily precipitation and daily maximum temperature time series over a year.