Manuscript ID: egusphere-2025-4289
Title: Global escalation of more frequent and intense compound heatwave-extreme precipitation events

---

Response to the Editor

Dear Editor,

We thank the editor and reviewers for their thoughtful comments and continued guidance. We have carefully addressed all feedback and revised the manuscript accordingly, with all changes highlighted in red for your convenience. The reviewers' insightful suggestions have significantly strengthened the quality and clarity of our work, and we are grateful for their time and expertise.

Thank you again for your time and kind assistance.

Best regards,
The Authors

Response to the Reviewer

Dear Reviewer,

We sincerely thank the reviewer for the thorough evaluation and constructive feedback. Your insightful comments have been instrumental in strengthening the scientific rigor, clarity, and overall quality of our manuscript. We have carefully addressed each suggestion and incorporated the recommended revisions throughout the text. All modifications have been highlighted in red to facilitate your review. Our detailed, point-by-point responses to your comments are provided below.

Thank you again for your time and kind assistance.

Best regards,
The Authors

Comments on the manuscript: egusphere-2025-4289-ATC2.pdf

Global scalation of more frequent and intense compound heatwave- extreme precipitation events by Jin, H. et al.

General comments
I thank the authors for submitting a revised version of the manuscript. While the revision shows some effort to address the reviewers' and editor's comments, several important issues raised in the previous review have not yet been fully resolved.

The initial reviews highlighted the following main concerns:

• The absence of a quantitative comparison between historical model simulations and reanalysis data over the same historical period.

Response: We have added the CHWEP and single extreme events extracted from CMIP6 data for the historical period (1980-2024, with 2015-2024 based on the SSP2-4.5 scenario). In terms of spatial distribution and the correlation of event attributes with those derived from reanalysis data, the CHWEP and single extreme events extracted from the two datasets exhibit high similarity (Fig. S3 and S4). Furthermore, they can successfully reproduce the spatial differences in the attributes of CHWEP and single extreme events (Fig. S7). The revisions have been highlighted in red in the manuscript for your review. We thank the reviewer for pointing out this issue, which has helped us to continuously improve and enhance this study.

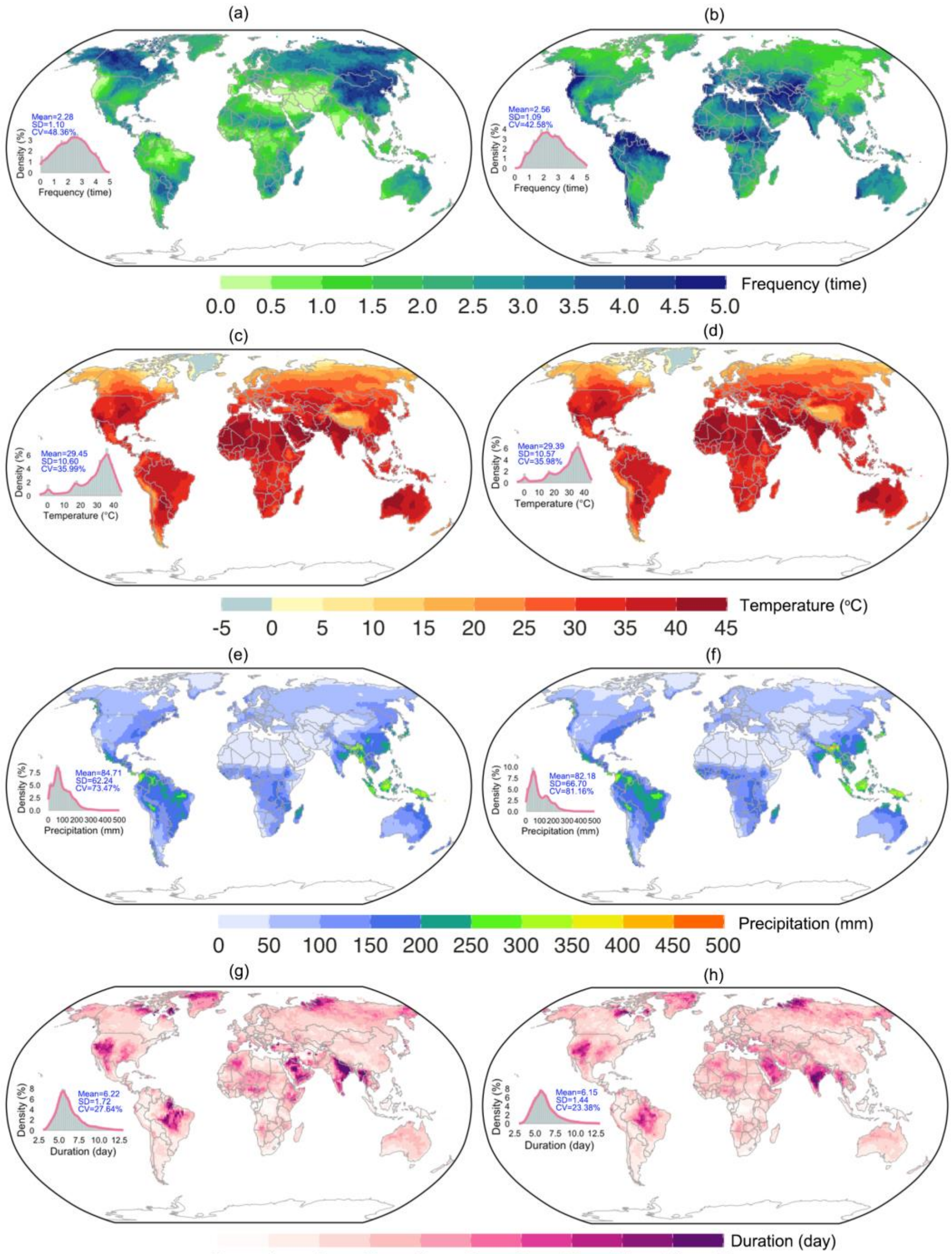

Figure S3. Spatial distribution of the mean values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 1980 to 2024 based on CMIP6 historical data.

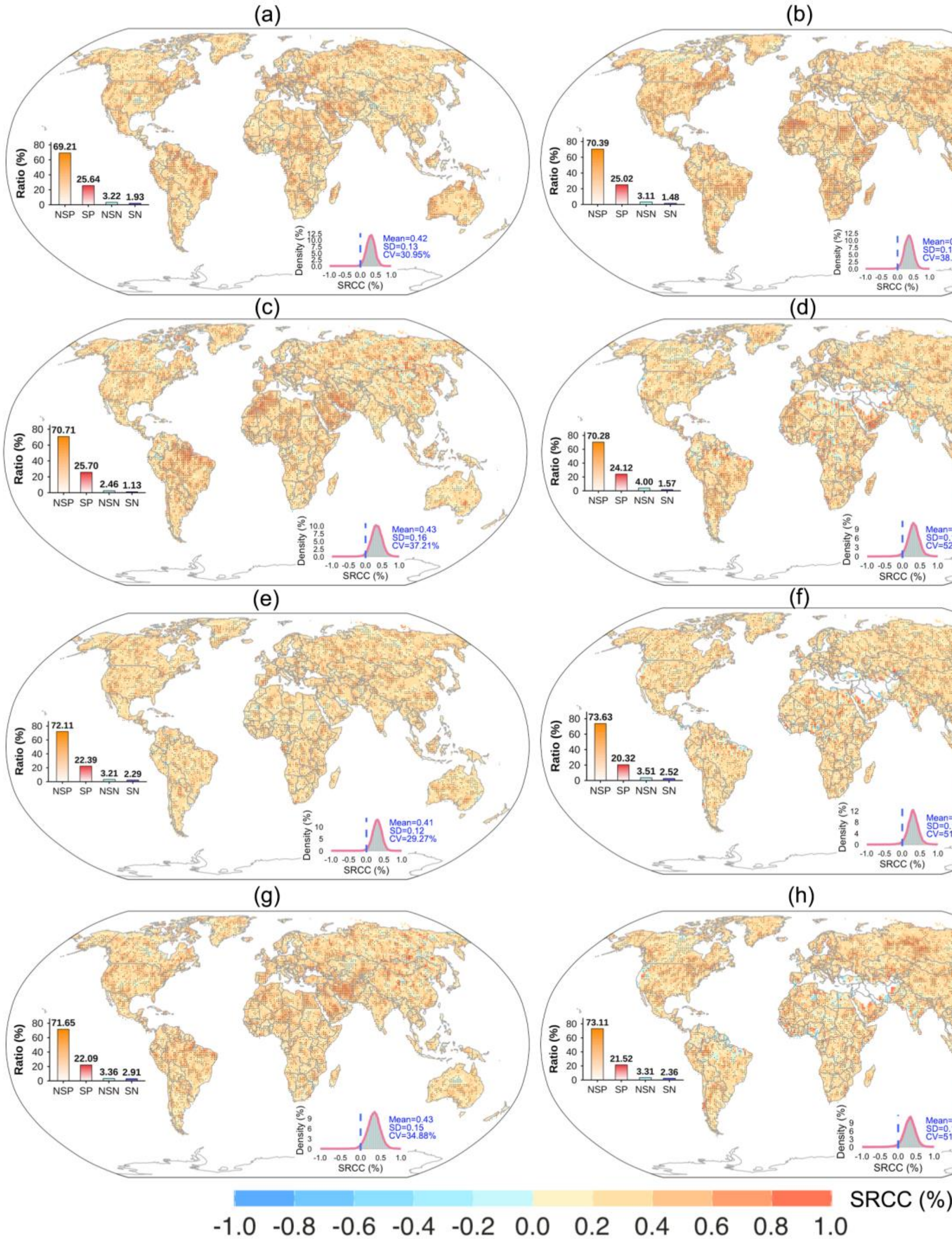

Figure S4. Spatial distribution of the SRCC values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 1980 to 2024 between reanalysis data and CMIP6 historical data.

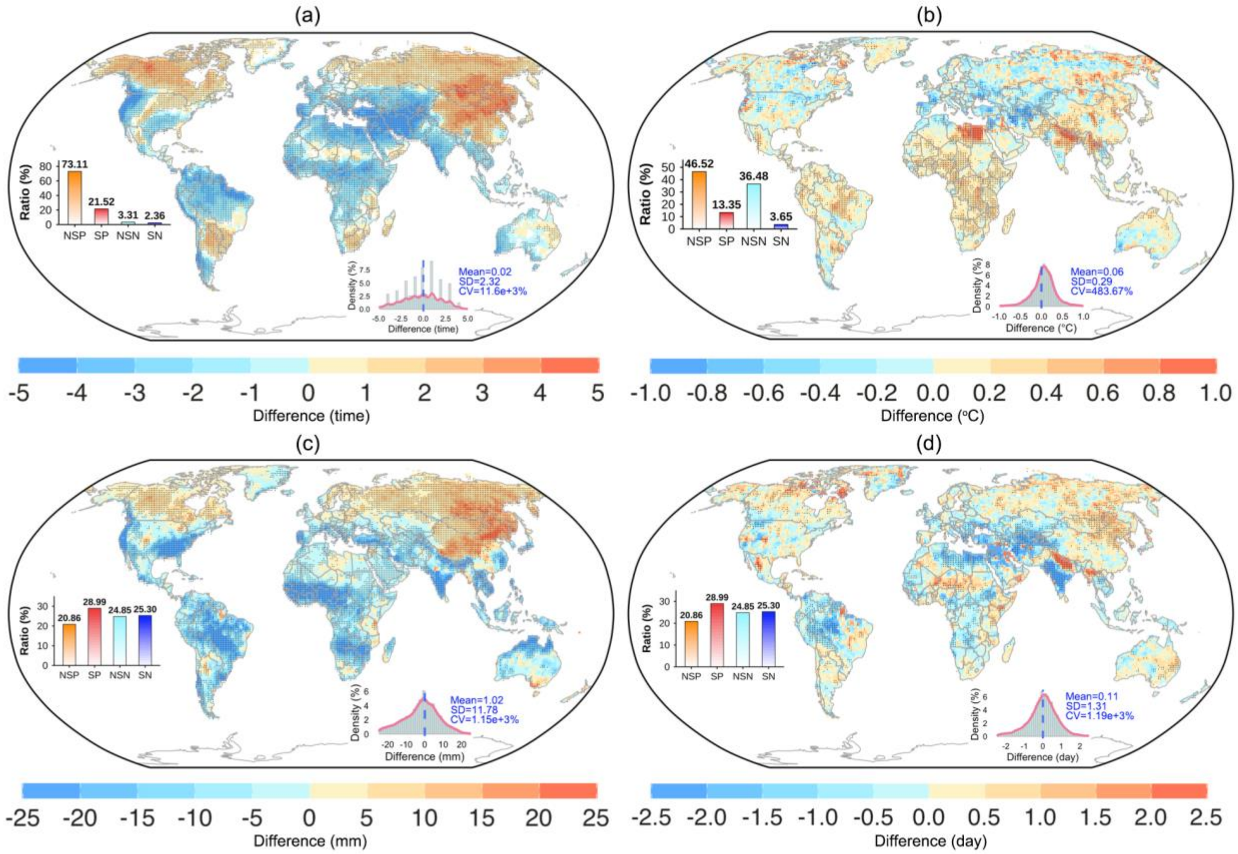

Figure S7. Spatial distribution of median differences between CHWEP and single extreme events in frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) from 1980 to 2024 based on CMIP6 data. (Note: In the left bar chart, NSP denotes Non-Significant Positive, SP denotes Significant Positive, NSN denotes Non-Significant Negative, and SN denotes Significant Negative. The same abbreviations apply hereinafter.)

• Insufficient clarity in the notation used in Equations (4) to (11).

Response: We have appropriately revised Equations (4) to (11). In this study, we extracted four metrics for CHWEPs and single extreme events to compare their differences. Specifically, the four metrics are defined as follows:

Frequency: The number of occurrences of CHWEPs and single heatwave events in a year;

Heatwave intensity: The mean daily maximum temperature during CHWEPs and single heatwave events in a year;

Extreme precipitation intensity: The mean daily precipitation during CHWEPs and single extreme precipitation events in a year;

Duration: The mean duration of CHWEPs and single heatwave events in a year.

Through these four metrics, we can systematically compare the differences between CHWEPs and single extreme events (i.e., single heatwave and single extreme precipitation events). The revisions have been highlighted in red in the manuscript for your review. We thank the reviewer for the valuable comments and suggestions, which have helped us to continuously improve and enhance the logic and readability of this study.

• Sections of the results discussion remain rather superficial and do not provide the level of physical interpretation necessary to better understand the reported analyses.

Response: We have appropriately revised the Discussion section. The revision mainly introduces the background and significance of this study, the major findings, and the reasons for the spatial distribution differences between CHWEPs and single extreme events, and finally points out the directions for further optimization and in-depth research in the future. Specifically, to understand the spatial heterogeneity of CHWEP increases, it is necessary to parse the relative contributions of thermodynamic and dynamic drivers in the climate system. For instance, the greater increase in CHWEPs and single events (frequency and precipitation intensity) in equatorial regions is primarily driven by thermodynamic responses: the Clausius-Clapeyron relationship dictates that a warmer atmosphere holds exponentially more moisture (~7% per °C), which directly accelerates the hydrological cycle and increases the likelihood of extreme precipitation following thermal convection. Conversely, the larger increase in temperature intensity in the mid- to high-latitudes of the Northern Hemisphere is heavily influenced by dynamic factors, particularly Arctic amplification. The weakened poleward temperature gradient slows down jet streams and favors persistent blocking highs (anticyclones), which not only prolong the duration of heatwaves but also create a stable, dry environment that intensifies surface heating. Incorporating this in-depth mechanistic analysis helps to further deepen the insights of our study. The revisions have been highlighted in red in the manuscript for your review. We thank the reviewer for the valuable comments and suggestions, which have helped us to continuously improve and enhance this study.

In addition, the revisions concerning the bias-correction procedure, the criteria for climate model selection, and the explanation of the Wilcoxon Rank Sum Test remain limited and would benefit from further clarification and justification to meet the standards expected for publication in HESS.

Response: The authors have revised the relevant sections accordingly. In this study, we employed multiple approaches to minimize data errors and enhance the robustness of the results. For instance, we utilized multi-model data to eliminate systematic errors, and applied bias correction methods to compensate for the discrepancies in numerical magnitude between the reanalysis data and the CMIP6 data. Additionally, we adopted highly adaptable statistical tests, such as the Wilcoxon rank-sum test, which do not require the data to follow a specific distribution, to test the significance of differences between CHWEP events and single extreme events. The revised portions have been highlighted in red text within the manuscript for your review. We sincerely thank the reviewer for the valuable comments and suggestions, which have helped us to continuously refine and improve this study.

Specific comments

Line 100: The authors state that the four selected GCMs provide relatively high accuracy and spatial resolution. However, the revised manuscript still lacks a clear and systematic comparison between historical GCM simulations and reanalysis data for the same reference period. Without this comparison, the assessment of GCM performance and accuracy remains incomplete.

Response: We have incorporated an analysis of CHWEP and single extreme events extracted from CMIP6 data for the period 1980-2024 (with the 2015-2024 period based on the SSP2-4.5 scenario). The events derived from the two datasets exhibit high similarity in terms of spatial distribution and attribute correlations with the reanalysis data (Fig S3 and S4). Furthermore, the CMIP6 data successfully reproduces the spatial variability in the attributes of both CHWEP and single extreme events (Fig. S7). The revisions have been highlighted in red in the manuscript for your review. We sincerely thank the reviewer for pointing out this issue, which has helped us improve and refine this study.

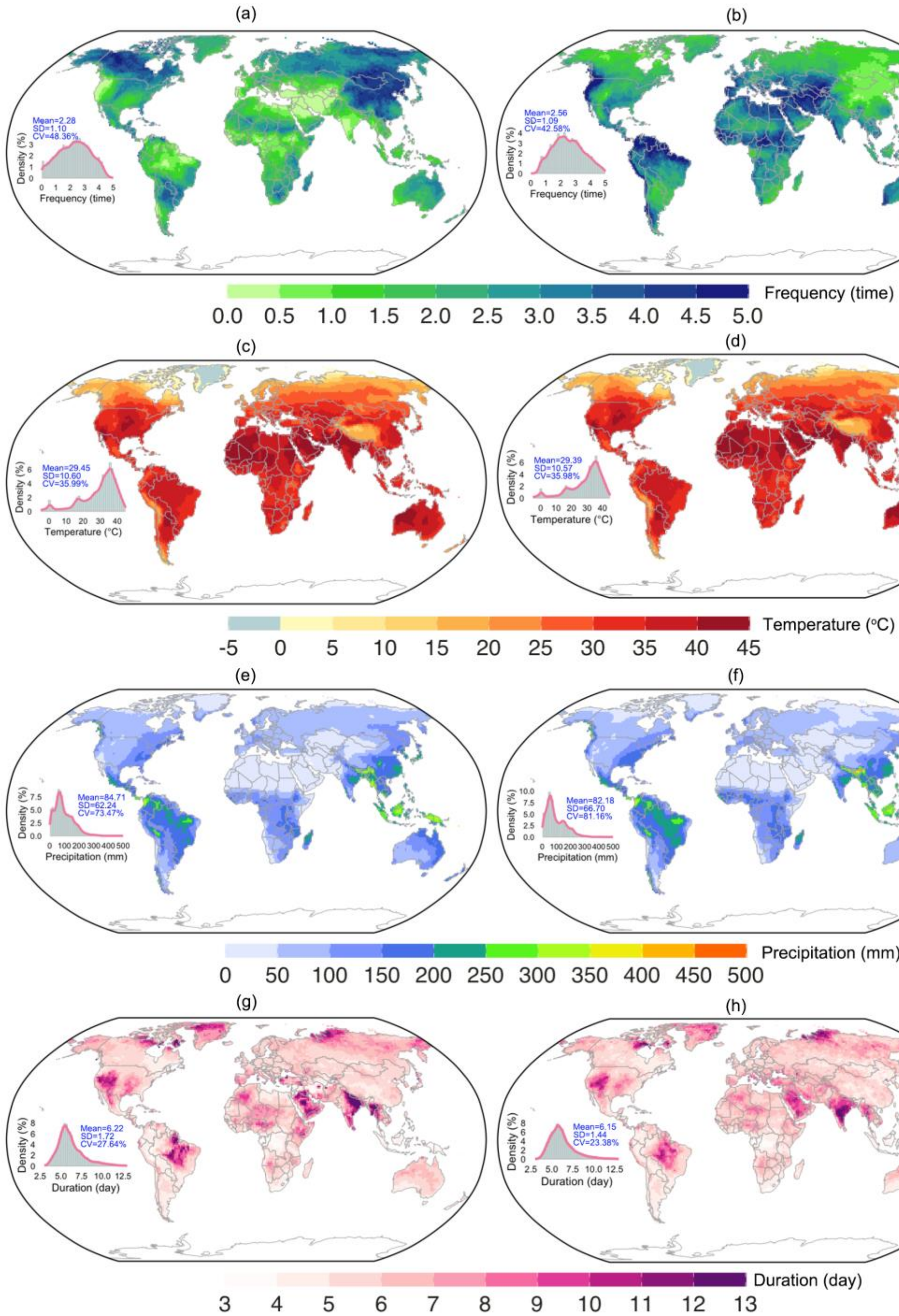

Figure S3. Spatial distribution of the mean values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 1980 to 2024 based on CMIP6 historical data.

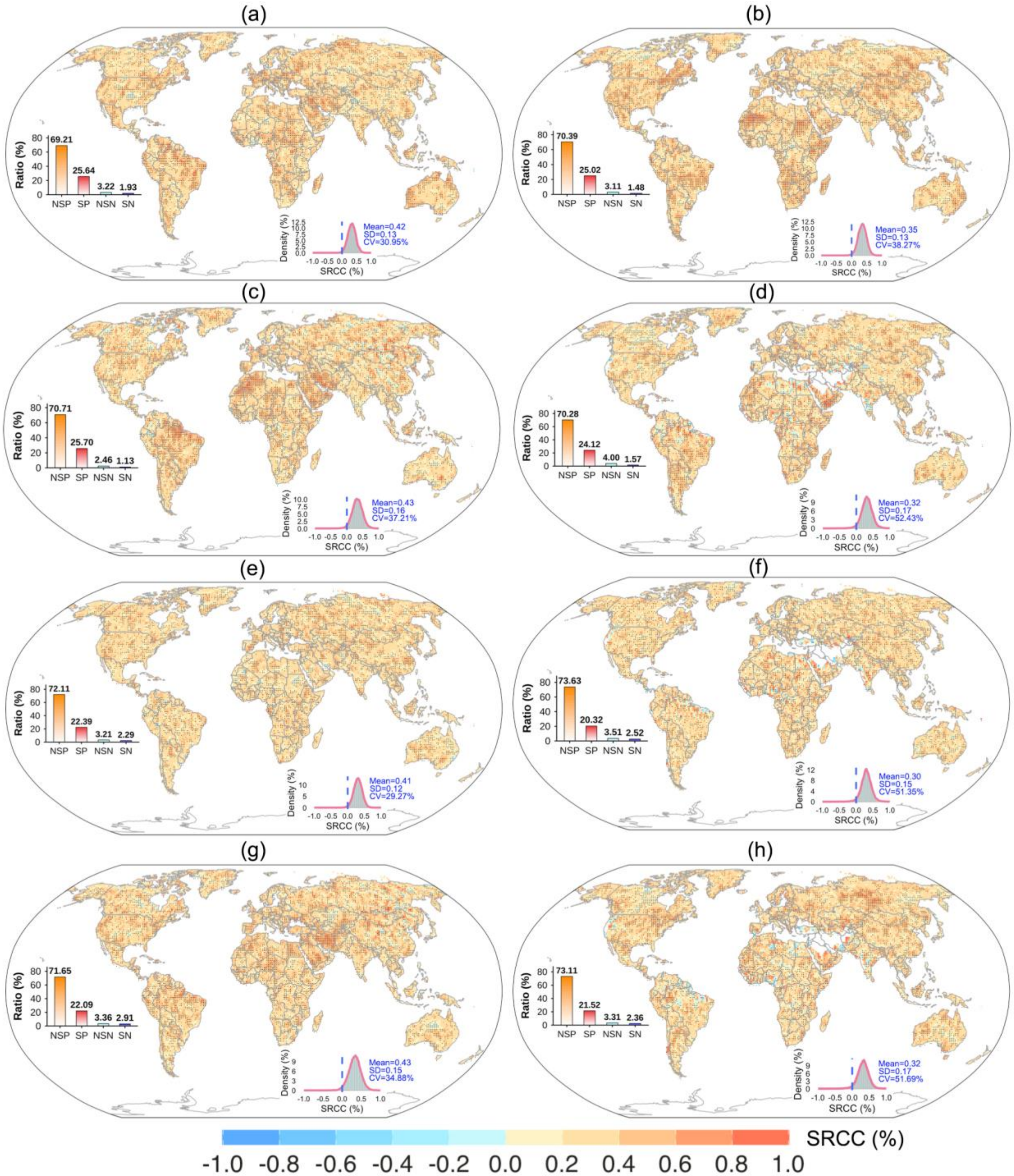

Figure S4. Spatial distribution of the SRCC values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 1980 to 2024 between reanalysis data and CMIP6 historical data.

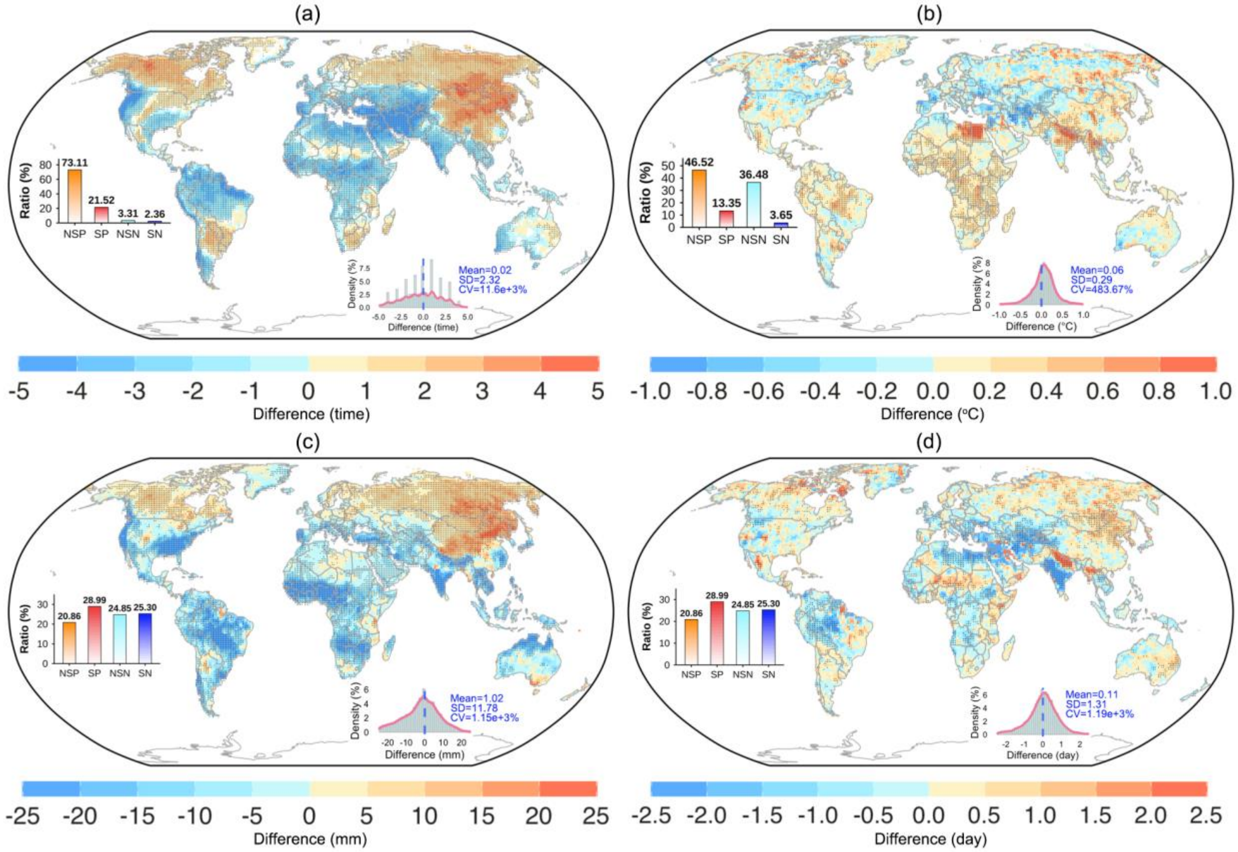

Figure S7. Spatial distribution of median differences between CHWEP and single extreme events in frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) from 1980 to 2024 based on CMIP6 data. (Note: In the left bar chart, NSP denotes Non-Significant Positive, SP denotes Significant Positive, NSN denotes Non-Significant Negative, and SN denotes Significant Negative. The same abbreviations apply hereinafter.)

Line 155: The notation used in Equations (4) to (11) is still difficult to follow. In particular, the definition and role of the operator mean(.) should be explicitly clarified to improve transparency and reproducibility.

Response: We have revised Equations (4) to (11) accordingly. In this study, we defined four metrics to compare the differences between CHWEPs and single extreme events (i.e., single heatwaves and single extreme precipitation events). These metrics are defined as follows:

Frequency: The annual number of occurrences of CHWEPs and single extreme events;

Heatwave intensity: The annual mean daily maximum temperature during CHWEPs and single heatwaves;

Extreme precipitation intensity: The annual mean daily precipitation during CHWEPs and single extreme precipitation events;

Duration: The annual mean duration of CHWEPs and single extreme events.

These four metrics enable a systematic comparison of the differences between CHWEPs and single extreme events. The revisions have been highlighted in red in the manuscript for your review.

We thank the reviewer for the valuable comments and suggestions, which have helped us improve the logical flow and readability of this study.

"We defined four metrics to quantify the characteristics of CHWEPs and individual extreme events (extreme precipitation and heatwaves) occurring within a given year: Frequency (F), Heatwave intensity (I_T), Extreme precipitation intensity (I_P), and Duration (D). The calculation formulas are as follows:

$$F_C = n_C;\ F_S = n_S \tag{4}$$

$$I_{T,C} = \frac{1}{m_{CT}}\sum_{i=1}^{m_{CT}} T_i\ ;\ I_{T,S} = \frac{1}{m_{ST}}\sum_{i=1}^{m_{ST}} T_i \tag{5}$$

$$I_{P,C} = \frac{1}{m_{CP}}\sum_{i=1}^{m_{CP}} P_i\ ;\ I_{P,S} = \frac{1}{m_{SP}}\sum_{i=1}^{m_{SP}} P_i \tag{6}$$

$$D_C = \frac{1}{n_C}\sum_{j=1}^{n_C} d_{C,j}\ ;\ D_S = \frac{1}{n_S}\sum_{j=1}^{n_S} d_{S,j} \tag{7}$$

where F denotes the annual frequency (i.e., total number of occurrences) of CHWEPs or single heatwave events, the subscripts C and S indicate CHWEPs and single extreme events, respectively, n_C and n_S are the total number of occurrences of CHWEPs and single heatwave events in a year, respectively, I_T represents the mean daily maximum temperature during the heatwave periods of CHWEPs or single heatwave events in a year, m_{CT} and m_{ST} represent the total number of heatwave days within CHWEPs and within single heatwave events in a year, respectively, T_i denote the daily maximum temperature on the $i-th$ day, I_P denotes the mean daily precipitation during the extreme precipitation periods of CHWEPs or single extreme precipitation events in a year, m_{CP} and m_{SP} represent the total number of extreme precipitation days within CHWEPs and within single extreme precipitation events in a year, respectively, P_i denote the daily precipitation amount on the $i-th$ day, D refers to the mean duration (in days) of the heatwave periods within CHWEPs or single heatwave events in a year, $d_{C,j}$ and $d_{S,j}$ denote the heatwave duration (in days) of the $j-th$ CHWEP and the $j-th$ single heatwave event, respectively."

Line 210: The manuscript introduces a "random probability" in Equation (13). It appears that the authors aim to estimate the probability that at least one rainfall event occurs within a 7-day window following a heatwave event. However, the rationale for selecting this specific window length is not provided. Furthermore, the term "random probability" may be misleading and could be reconsidered or more clearly defined.

Response: Following the approach of You et al., we set the time window to 7 days in this study. You et al. tested time windows of 1, 3, and 7 days, and their findings indicated that the choice of time window has little impact on the overall conclusions. In this study, we selected a 7-day window for two main reasons: (1) to accommodate the physical linkage between heatwaves and extreme precipitation, and (2) to obtain a sufficient sample size of CHWEP events, thereby ensuring the robustness of our analysis. Furthermore, we have replaced the term "random probability" with "coincidence probability." Event coincidence analysis (ECA) assumes that the lagged occurrences between heatwaves and heavy rainfall are randomly distributed. By comparing the observed probability of CHWEPs against this coincidence probability, we can highlight the underlying physical connection driving extreme precipitation following heatwaves. The revisions have been highlighted in red in the manuscript for your review. We sincerely thank the reviewer for the valuable comments and suggestions, which have helped us improve the accuracy and readability of this study.

(You and Wang, 2021)

You, J. and Wang, S.: Higher Probability of Occurrence of Hotter and Shorter Heat Waves Followed by Heavy Rainfall, Geophys. Res. Lett., 48, https://doi.org/10.1029/2021gl094831, 2021.

Reviewer 2 also noted the absence of reported p-values associated with the Wilcoxon Rank Sum Test. Additionally, the bar plots used to illustrate the proportion of grid cells with positive or negative significant/non-significant WRST results are difficult to interpret, as the color scheme is inconsistent with that used in the corresponding spatial maps.

Considering these remaining concerns, I believe the manuscript would require major revisions before it can be considered for publication. Addressing the points above would substantially improve the clarity, robustness, and interpretability of the study.

Response: We have appropriately revised the relevant sections. The spatial distribution of the p-values from the WRST is shown in the figure below (Fig. S6). In the main figure, we applied stippling to the significant areas (at the 5% significance level), which allows for a clear visualization of the regions where the median exhibits a significant increase or decrease. Furthermore, we calculated the proportions of areas showing an increase (NSP), a significant increase (SP), a decrease (NSN), and a significant decrease (SN), which are represented by orange, dark red, light blue, and dark blue, respectively. This effectively reflects the different categories of change and maintains consistency with the increasing and decreasing color tones in the colormap. The revisions have been highlighted in red in the manuscript for your review. We thank the reviewer for pointing out these issues, which have helped us continuously improve and enhance this study.

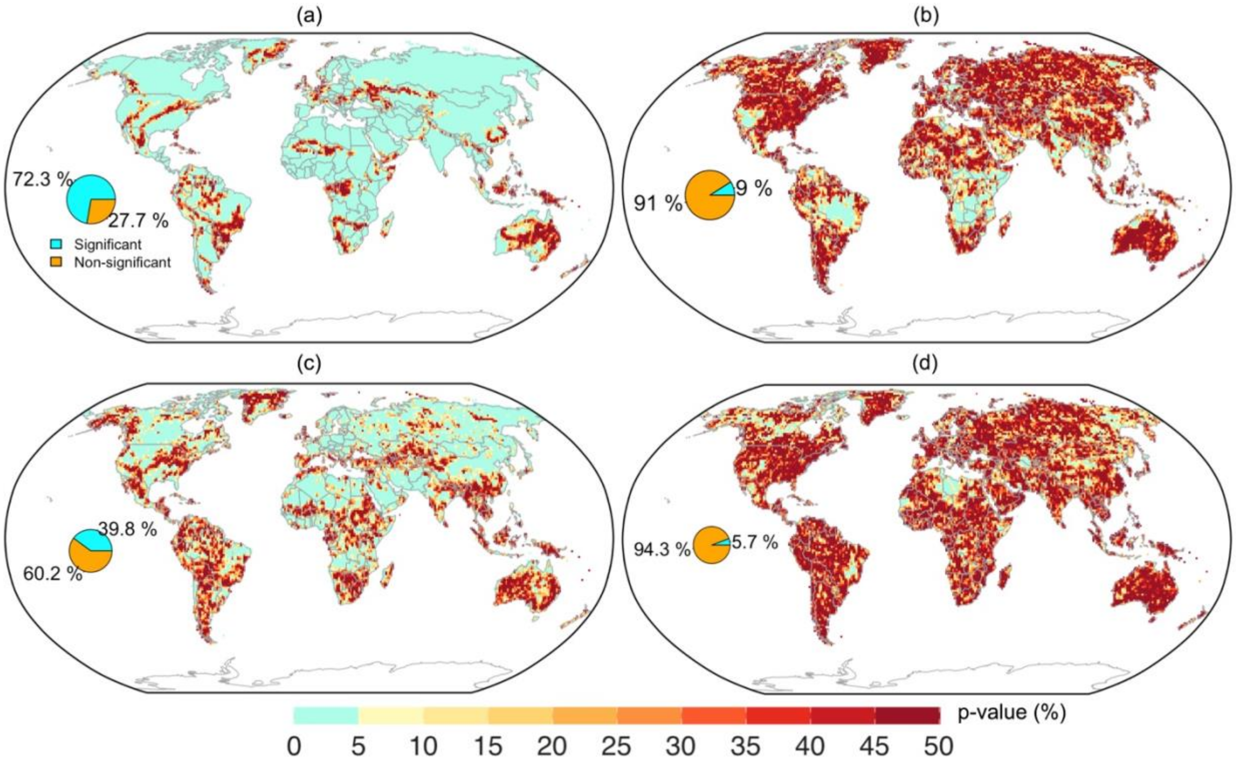

Figure S6. Spatial distribution of the p-value of median differences between CHWEP and single extreme events in frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) from 1980 to 2024 based on WRST test.

Response to the Reviewer

Dear Reviewer,

We sincerely thank the reviewer for your thorough evaluation and constructive feedback. Your insightful comments have been instrumental in strengthening the quality and clarity of this manuscript. We have carefully revised the text in accordance with your suggestions, addressing each point in detail. All modifications are highlighted in red for your convenience, and our point-by-point responses are provided below.

Thank you again for your time and kind assistance.

Best regards,
The Authors

Compared with the preprint, the revised manuscript has incorporated several changes, and the overall quality of the manuscript has improved to some extent. The authors' responses to the reviewers were relatively conscientious. However, some issues raised by the editor and previous reviewers have still not been fully justified. Therefore, I think substantial revisions are still needed before this manuscript can be considered for publication in HESS.

1. The bias-correction section is still not fully convincing. The authors did not follow the editor's suggestion to provide preliminary validation. In addition, it is not common to use the mean of three reanalysis datasets as the observational reference, and they also did not quantify between-member variability as suggested by editor. Although the authors added a new paragraph introducing quantile delta mapping (QDM), they did not provide a sufficiently comprehensive discussion of how this method has been used in previous studies or whether it is appropriate for their specific case. There are many important papers in this field that were not cited.

Response: We have incorporated an analysis of CHWEP and individual extreme events derived from CMIP6 model outputs for 1980-2024, with the 2015-2024 period based on the SSP2-4.5 scenario. Comparison with reanalysis data reveals strong consistency between the CMIP6 simulations and observations, particularly in the spatial distribution of events and the correlations among their attributes (Fig. S3 and S4). Notably, the CMIP6 models robustly capture the spatial variability of key characteristics for both CHWEP and standalone extremes (Fig. S7). Quantile Delta Mapping (QDM) is a trend-preserving bias correction method developed from traditional Quantile Mapping (QM). It has been widely applied to correct temperature and precipitation outputs from General Circulation Models (GCMs) and Regional Climate Models (RCMs), particularly CMIP5/CMIP6 datasets, with the goal of reducing systematic biases while preserving projected climate change signals. By explicitly adding (for temperature) or scaling (for precipitation) the model-inherent change signal in quantile space, QDM effectively retains the projected change across all quantile levels. For CMIP6 daily precipitation, QDM has proven highly effective at mitigating mid-to-high quantile biases and improving extreme indices, making it a standard choice for basin- and national-scale studies. For CMIP6 daily maximum and minimum temperatures, QDM substantially reduces mean and distributional biases, bringing model outputs into closer agreement with reanalysis and observational datasets. Given its robust performance and widespread adoption in climate data correction, this study employs QDM to correct CMIP6 precipitation and daily maximum temperature data. All corresponding revisions have been highlighted in red in the manuscript for your review. We sincerely thank the reviewer for these constructive comments, which have been instrumental in refining and strengthening this work.

(Dai et al., 2022; Kim et al., 2020; Qin and Dai, 2022)

Dai, C., Qin, X. S., Zhang, X. L., and Liu, B. J.: Study of climate change impact on hydro-climatic extremes in the Hanjiang River basin, China, using CORDEX-EAS data, Weather Clim. Extrem., 38, 100509, https://doi.org/https://doi.org/10.1016/j.wace.2022.100509, 2022.
Kim, S., Joo, K., Kim, H., Shin, J.-Y., and Heo, J.-H.: Regional quantile delta mapping method using regional frequency analysis for regional climate model precipitation, J. Hydrol., 125685, https://doi.org/https://doi.org/10.1016/j.jhydrol.2020.125685, 2020.
Qin, X. and Dai, C.: Comparison of different quantile delta mapping schemes in frequency analysis of precipitation extremes over mainland Southeast Asia under climate change, J. Hydrol., 606, 127421, https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.127421, 2022.

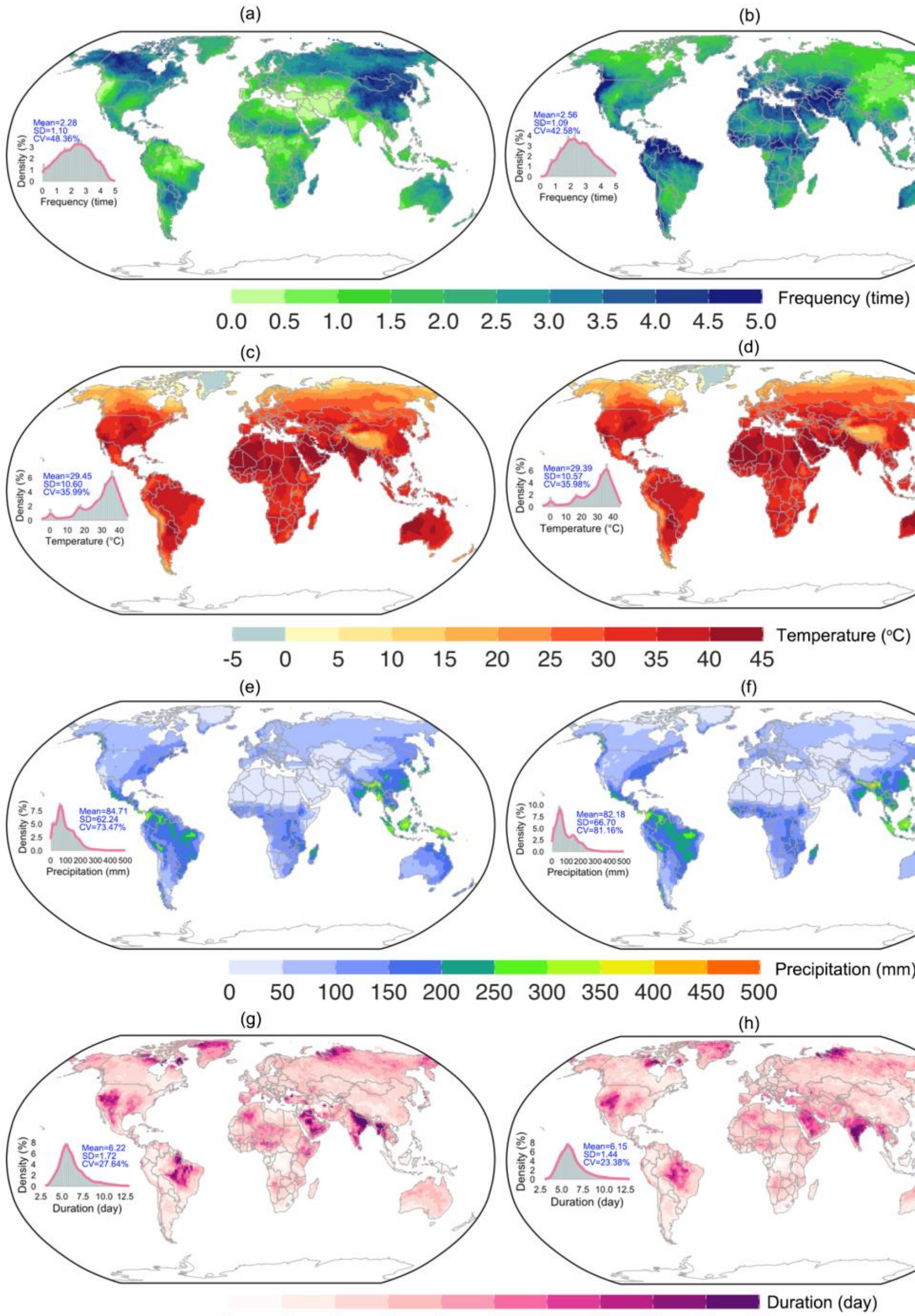

Figure S3. Spatial distribution of the mean values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 1980 to 2024 based on CMIP6 historical data.

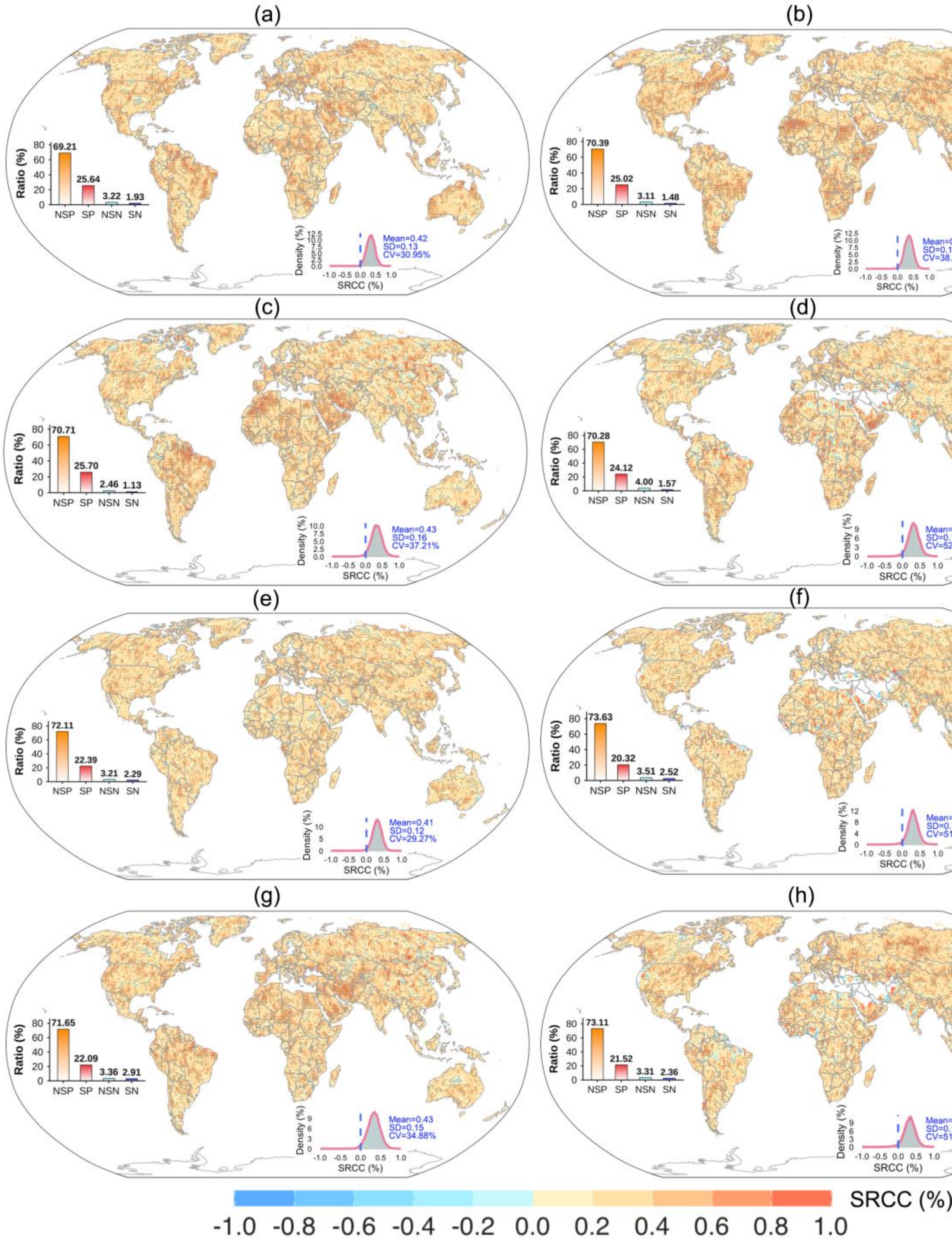

Figure S4. Spatial distribution of the SRCC values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 1980 to 2024 between reanalysis data and CMIP6 historical data.

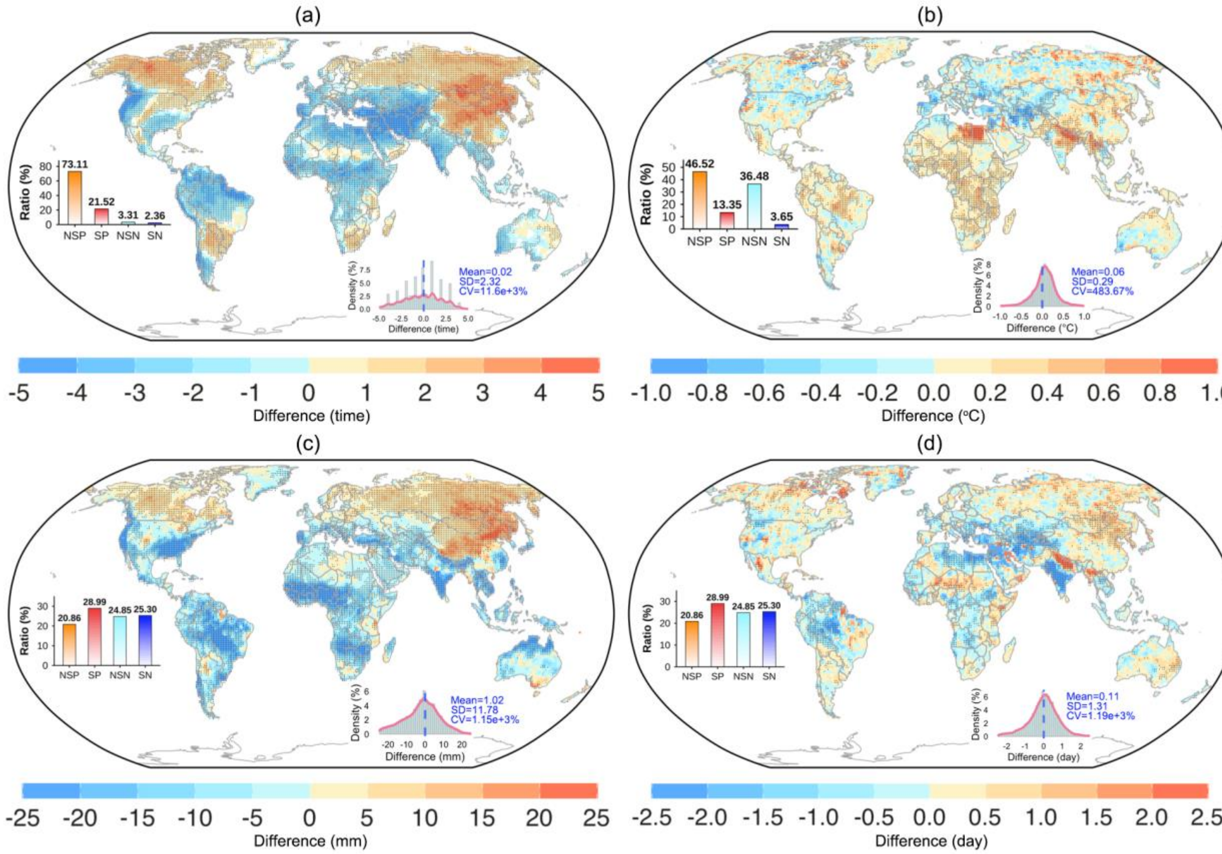

Figure S7. Spatial distribution of median differences between CHWEP and single extreme events in frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) from 1980 to 2024 based on CMIP6 data. (Note: In the left bar chart, NSP denotes Non-Significant Positive, SP denotes Significant Positive, NSN denotes Non-Significant Negative, and SN denotes Significant Negative. The same abbreviations apply hereinafter.)

2. The new explanations added by the authors for the Wilcoxon rank-sum test (WRST) and the climate model selection are still not convincing, and there are also some factual mistakes. The authors state that only a few models provide daily tasmax output and that the four selected GCMs offer relatively high spatial resolution. However, daily tasmax output is available for many more GCMs than suggested. In addition, the spatial resolutions reported in Table S1 do not appear to fully match the native atmospheric resolutions of the listed models, and there are other models with higher spatial resolution.

Response: To assess differences in event characteristics between CHWEP and single extremes, we employed the Wilcoxon rank-sum test (WRST). Unlike the parametric Student's t-test, which assumes normality and homoscedasticity, the WRST is a non-parametric, rank-based method that makes no assumptions about the underlying data distribution. This renders it particularly robust for extreme climate metrics, which frequently exhibit skewness, heavy tails, and outliers. While sensitivity analyses using the t-test yielded consistent qualitative conclusions, the WRST provides a more statistically rigorous framework for our data. Regarding spatial processing, the native horizontal resolutions of the selected GCMs are summarized in Table S1. To ensure consistency across models and with the reanalysis reference dataset, all outputs were regridded to a common

1° × 1° latitude-longitude grid. A multi-model ensemble mean was subsequently computed to reduce structural uncertainty and mitigate inter-model systematic biases. All corresponding revisions have been highlighted in red in the manuscript. We sincerely thank the reviewer for these constructive suggestions, which have substantially strengthened the methodological transparency and overall rigor of this study.

3. The editor suggested that "Adding quantitative metrics, regional analysis and deeper interpretation in the results and discussion would enhance your manuscript.", but the authors did not address this point very well. Although some additional discussion has been added, most of it remains rather superficial and mainly attempts to convey a simple message: CHWEP is more severe than a single event. This point has already been discussed many times and is, to some extent, already well recognized in the current literature (see: https://www.nature.com/articles/s41612-024-00579-4). Therefore, I do not think this paper currently provides enough new or sufficiently useful scientific insight to the field.

Response: We have comprehensively revised the Discussion section to better contextualize the study's background, synthesize the key findings, and elucidate the physical mechanisms underlying the spatial disparities between CHWEPs and single extreme events. A major addition is a mechanistic analysis that disentangles the thermodynamic and dynamic drivers of regional extreme event amplification. In equatorial and tropical regions, the pronounced increases in CHWEP frequency and precipitation intensity are predominantly thermodynamically controlled. Consistent with the Clausius-Clapeyron relationship, atmospheric moisture-holding capacity increases exponentially with warming (~7% K^{-1}), intensifying the hydrological cycle and elevating the likelihood of extreme convective precipitation following heatwave onset. Conversely, the amplified temperature intensity in the Northern Hemisphere mid- to high-latitudes is largely governed by dynamic atmospheric processes. Arctic amplification reduces the meridional temperature gradient, leading to a slower and more meandering mid-latitude jet stream. This dynamical shift promotes the persistence of blocking anticyclones, which extend heatwave duration and induce subsidence-driven clear-sky conditions that further amplify radiative surface heating. Integrating this mechanistic framework substantially deepens the interpretive value of our results and outlines clear pathways for future process-based research.

Building upon previous research, this study makes significant advancements by comprehensively and systematically analyzing the spatiotemporal patterns and differences between CHWEPs and single extreme events. Crucially, we emphasize how CHWEPs are more intense than single extreme events and why they exert greater impacts. This represents a distinct improvement over the study by Zhou et al., which primarily focused on the spatiotemporal variations of CHWEPs alone, we have cited the study by Zhou et al. in the appropriate section of the manuscript. Furthermore, we introduced event coincidence analysis (ECA) to statistically reveal a specific linkage between heatwave and extreme precipitation events, demonstrating that extreme precipitation is more likely to be triggered following a heatwave event. All revisions are highlighted in red in the manuscript. We sincerely thank the reviewer for these insightful suggestions, which have significantly strengthened the scientific depth and structural coherence of this work.

(Zhou et al., 2024)

Zhou, Z., Zhang, L., Zhang, Q., Hu, C., Wang, G., She, D., and Chen, J.: Global increase in future compound heat stress-heavy precipitation hazards and associated socio-ecosystem risks, npj Clim. Atmos. Sci., 7, 33, https://doi.org/10.1038/s41612-024-00579-4, 2024.