Response to Reviewer Comments

Reviewer #2:

Dear Reviewer:

Thank you for your thoughtful and detail review of our manuscript. We greatly appreciate the time and effort you dedicated to providing your feedback. We have carefully considered all your comments and suggestions and revised our manuscript accordingly, and changes to our manuscript are highlighted within the document by using red colored text. We hope that the integration of the reviewer's feedback has improved the quality of the manuscript. Point-to-point responses to your comments are listed below:

1. Lines 40–47: I encourage the authors to expand the discussion on changes in extreme precipitation under climate change, with a particular focus on Clausius–Clapeyron scaling and the worst-case scenario of precipitation. Scaling rates (i.e., % K^{-1}) have been reported to increase with precipitation magnitude, and incorporating this background would enhance the importance of the present study, which focuses on extreme precipitation. Please refer to the studies listed below.
https://doi.org/10.1016/j.jhydrol.2025.133724
https://doi.org/10.5194/hess-28-1251-2024

Response: Thank you very much for your comment and valuable suggestion to improve the quality of our manuscript. According to your suggestion, we have expanded the discussion regarding the changes in extreme precipitation under climate change, with a specific focus on Clausius–Clapeyron (CC) scaling and the worst-case scenarios of extreme precipitation. As highlighted in the recommended literature (Hiraga et al., 2025; Wasko et al, 2024), the scaling rate (expressed as % K^{-1}) generally increases with precipitation magnitude—rarer and more extreme events exhibit stronger intensification rates, often exceeding the theoretical CC scaling of 6-7 %/°C. This background strongly reinforces the scientific importance of focusing on flood-causing extreme precipitation events, as these high-impact events are most sensitive to warming and show the largest projected increment. We have added corresponding discussions and citations of the revised manuscript to highlight the physical mechanism. We added the following sentences in Lines 39-55 of the revised manuscript:

"Extensive research has examined the changes of extreme precipitation at regional and global scales using a range of indices and detection methodologies (Westra et al., 2013; Asadieh and Krakauer, 2015; Ban et al., 2015; Wu et al., 2019; Chinita et al., 2021). These studies reported that the frequency and intensity of heavy precipitation have increased. Some research using rain gauge observations suggests that sub-daily heavy precipitation may have increased more than daily heavy precipitation (Chinita et al., 2021). The concerns about such super-adiabatic increase have further been raised by modeling simulation, which projected further to increase between 2 % and 10 % by 2100 under a high-emissions scenario (Kharin et al., 2013). Notably, the heaviest and rarest precipitation events are projected to have the largest increase in frequency and intensity (Thackeray et al., 2022). The dominant driving factor of increment of extreme precipitation is the thermodynamic increase due to a 6-7 %/℃ increase in the saturation vapor pressure of the atmosphere, which was dictated by the Clausius-Clapeyron (CC) relationship (Trenberth et al., 2003). Hiraga et al. (2025) suggested that probable maximum precipitation magnitude events become more frequent with annual exceedance probability increasing by about $10^1 \sim 10^2$ from the historical to +4K climatic conditions. Meanwhile, moisture and buoyancy increase associated with temperatures increase can trigger extreme precipitation intensification exceeding the CC scaling rate (i.e., super-CC scaling) (Fowler et al., 2021). In addition, dynamical drivers linked to shifts in global circulation modify extreme rainfall occurrence by altering the storm tracks and propagation speeds (Chan et al., 2023; Wasko et al., 2024)."

2. Line 61: Please include references to support the statement "Most previous studies".

Response: We sincerely appreciate your suggestion. Yes, we have added several references on Line 72 in the introduction section of the revised manuscript.

3. Lines 86–94: Although the performance of IMERG has been extensively evaluated at the global scale, it can be dependent on region and precipitation system. Furthermore, a spatial resolution of 0.1° is sometimes insufficient to represent extreme precipitation associated with localized convective systems. I encourage the authors to strengthen the justification for the use of IMERG, specifically by addressing its performance in China and for extreme precipitation. The authors are welcome to perform additional analyses in this context; if not, please expand the discussion based on previous studies.

Response: Thanks for your comment and valuable suggestion. According to the comments from Reviewer 1, our study analyzed river discharge during the FCP period based on the GloFAS-ERA5 dataset, which addresses the insufficient understanding of flood characteristics identified in previous studies. In order to be consistent with the GloFAS-ERA5 river discharge, our study selected the precipitation and surface runoff fields from ERA5 to analyse the spatiotemporal evolution patterns of rainstorm events and runoff generation processes over mainland China. As one of the latest high-resolution climate reanalysis datasets, ERA5 is a global atmospheric reanalysis product developed by ECMWF using the 4D-Var data assimilation techniques (Hersbach et al., 2020). Compared with other reanalysis datasets, such as MERRA-2, NCEP/NCAR, and JRA55, the ERA5 outperforms them for precipitation and extreme precipitation over China, although its performance is not as good as satellite-based data (i.e., Integrated Multi-satellite Retrievals for Global Precipitation Measurement (GPM) (IMERG) precipitation product) (Jiang et al., 2023). Thus, our study employs the ERA5 dataset to investigate the rainfall, surface runoff, and flood characteristics of 632 flood-causing precipitation (FCP) events. Please see the details below and Lines 104-117 of the revised manuscript.

"The GloFAS-ERA5 river discharge reanalysis is produced by coupling the land surface model runoff component of the ECMWF ERA5 global reanalysis with the LISFLOOD hydrological and channel routing model (Harrigan et al., 2020). The LISFLOOD model is forced with daily HTESSEL surface and subsurface runoff from ERA5. In order to be consistent with the GloFAS-ERA5 river discharge, the precipitation and surface runoff fields from ERA5 were selected to analyze the spatiotemporal evolution patterns of rainstorm events and runoff generation processes over mainland China with high spatial (0.25°) and temporal (1 h) resolution covering the period 2000 to 2023. As one of the latest high-resolution climate reanalysis datasets, ERA5 is a global atmospheric reanalysis product developed by ECMWF using the 4D-Var data assimilation technique (Hersbach et al., 2020). Compared with other reanalysis datasets, such as MERRA2, NCEP/NCAR, and JRA55, the ERA5 performs better for precipitation and extreme precipitation over China, although its performance is not as good as that of satellite-based data (e.g., the Integrated Multi-satellite Retrievals for Global Precipitation Measurement (GPM) (IMERG) precipitation product) (Jiang et al., 2023). Note that ERA5 underestimates the frequency of occurrence and interannual variability of mesoscale convective systems (MCSs) (Alpizar et al., 2026). The ERA5 reanalysis precipitation product used in this study is accessible in C3S Climate Data Store (https://cds.climate.copernicus.eu/datasets, last access: 10 May 2026)."

Reference:

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., ... & Thépaut, J. N.:The ERA5 global reanalysis. Q. J. R. Meteorolog. Soc. 146(730), 1999-2049, https://doi.org/10.1002/qj.3803, 2020.

Jiang, S.H., Wei, L.Y., Ren, L.L., Zhang, L.Q., Wang, M.H. and Cui, H.: Evaluation of IMERG, TMPA, ERA5, and CPC precipitation products over mainland China: Spatiotemporal patterns and extremes. Water Sci. Eng. 16(1): 45-56, https://doi.org/10.1016/j.wse.2022.05.001, 2023.

4. Lines 100–102: What about the consistency between the datasets used before and after 2020? I believe that the datasets (e.g., the Meteorological Disaster Yearbook and newspaper-based records) may differ substantially in several aspects. Combining two different datasets in a temporally consecutive manner may affect trend analyses and related results. Could the authors provide justification for combining these datasets and discuss the potential impacts on the conclusions?

Response: Thank you for your comment and valuable suggestion. All the supplemented flood disaster data are derived from officially released records, which ensures their authenticity and reliability. Note that, although the flood disaster records are obtained from multiple sources (i.e., the Meteorological Disaster Yearbook and newspaper-based records), they are all standardized official statistics that adhere to the same disaster classification criteria and recording standards, ensuring the consistency of core information across different data sources. We added the following sentences in Lines 124-128 of the revised manuscript:

"we supplemented flood disaster data from 2020 to 2023 using news reports and government sources by searching for the keywords 'flood' and 'inundation' online. All supplemented flood disaster data are derived from official released records, which guarantees their authenticity. Notably, although rainstorm flood records were collected from multiple sources, they represent authentic and valid disaster records and can accurately reflect the impacts caused by flood disasters."

5. Caption of Figure 2 Please explain panel (c).

Response: Thank you for your comment. We have revised the caption of Figure 2 to clarify the interpretation of panel (c) in Lines 175-176 of the revised manuscript.

6. Line 160: Did you test the sensitivity of this selected period to your results? I encourage the authors to examine the sensitivity in order to evaluate the robustness of the conclusions.

Response: Thank you for your comment. In general, the lifespan of an FCP event is not greater than 3 days, and it is rare for such events to last more than 7 days (Wang et al., 2022a). As shown in Fig. 1, we found that the lifespan for 632 FCP events analyzed in this study was shorter than 200 hours, with most events concentrated within 0-80 hours. Thus, we extract the FCP identification period for the 5 days before and after the event occurrence time is reasonable, which can fully capture the complete precipitation process of FCP. We have added the following sentences to Lines 186-189 to clarify why we selected 5 days window before and after the event occurrence in the revised manuscript.

"Based on the previous research findings, the lifetime of an FCP event is generally no longer than 3 days, and it is rare for such events to last more than 7 days (Wang et al., 2022). Thus, in order to detect all potentially associated persistent FCP events, we extract the FCP identification period for the 5 days before and after event occurrence"

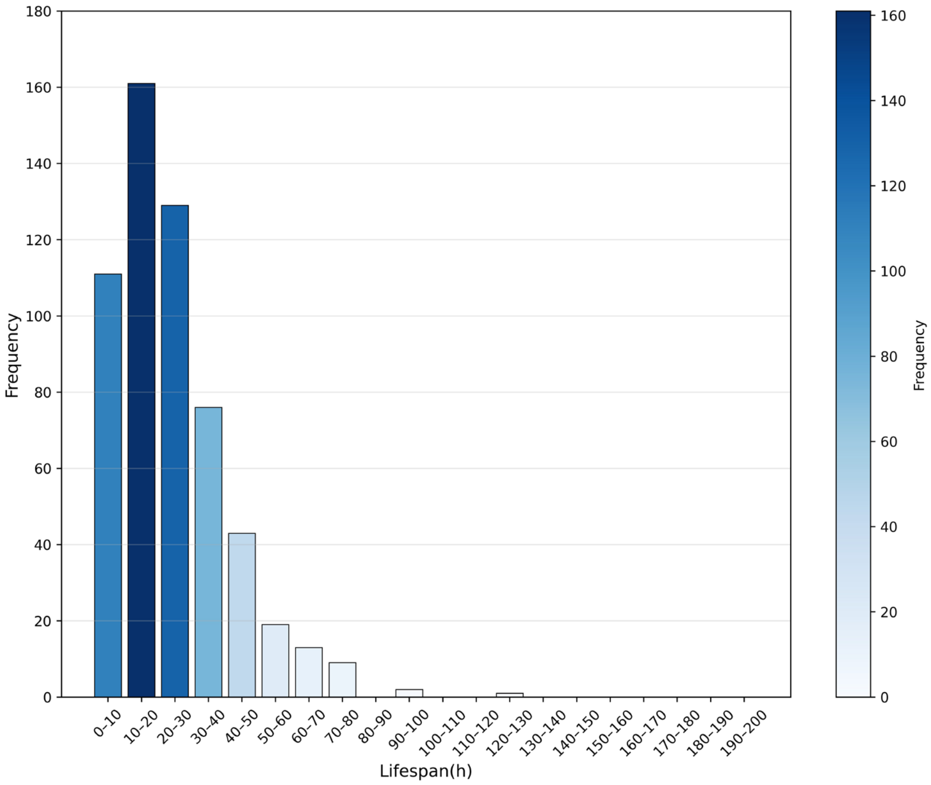

Fig. 1 The frequency of FCP lifespan from 0 to 200 hours with 10-hour intervals.

Reference:

Wang, X., Luo, M., Wu, S., Ning, G., Liu, Z., Wang, S., Wang, P., Zhang, H., and Li, X.: Spatiotemporal evolution patterns of contiguous extreme precipitation events across China from a 3D perspective. Geophys. Res. Lett. 49, e2022GL098840, https://doi.org/10.1029/2022GL098840, 2022.

7. Lines 185–189: It is unclear how the FCP was classified into TC-related and non-TC-related precipitation. Please provide a detailed explanation and justification for this classification.

Response: Thank you for your comment. The flood disasters induced by TC-related and non-TC heavy rainfall are classified in the Meteorological Disaster Yearbook. For the supplemented flood disaster data from 2020 to 2023, we categorized FCP events into TC and non-TC based on the official disaster bulletins and authoritative news reports, ensuring consistent classification criteria throughout the study period. We added the following in Lines 216-218 of the revised manuscript to make it clearer:

“The China Meteorological Disaster Yearbook (MDY) labels these two categories for 2000–2020, while the supplementary 2020–2023 flood disaster data are categorized into TC and non-TC based on the official disaster bulletins and authoritative news reports”

8. Lines 282–283: Here, the analysis could be expanded based on the Clausius–Clapeyron scaling rate discussed in my earlier comments. It would be of broad interest if the trends shown in Figure 6 could be interpreted in terms of temperature-dependent scaling rates.

Response: We appreciate your constructive comment. Following your suggestion, we have added the following statements to lines 322-326 of the revised manuscript to interpret the results derived from Figure 6 based on the Clausius–Clapeyron scaling rate.

“The intensification of extreme precipitation is primarily governed by the thermodynamic effects constrained by the Clausius-Clapeyron (CC) relationship. As atmospheric temperature increases, saturation vapor pressure increases at a theoretical rate of 6–7% $°C^{-1}$, providing the fundamental physical mechanism for enhanced extreme precipitation events (Trenberth et al., 2003; Allan et al., 2022).”

9. Lines 366–369: “Accumulated magnitude and lifespan demonstrate higher CC values than accumulated area and moving distance, indicating that precipitation events with large accumulated magnitude and longer lifespan are more susceptible to flood disasters.”
I believe that such conclusions regarding the relative importance of the considered factors cannot be drawn based solely on direct comparisons of correlation coefficients because of potential multicollinearity. Please clarify this point.

Response: We sincerely appreciate this comment. We fully agree that the relative importance of factors cannot be simply determined by comparing Pearson correlation coefficients, because multicollinearity among explanatory variables may distort the real contribution of each factor. In our study, the four three-dimensional (3D) precipitation characteristics (accumulated magnitude, accumulated area, lifespan, moving distance) are significantly correlated with each other, so direct comparison of correlation coefficients is not rigorous enough. Therefore, we have carefully revised the statement in lines 446-450 of the revised manuscript to make it more accurate, as follows:

“Among the precipitation factors, accumulated magnitude and lifespan show higher CC values with flood disasters, indicating that precipitation events with larger accumulated magnitude and longer lifespan tend to trigger severe disaster impacts.”

10. Lines 445–449: I encourage the authors to further elaborate the discussion on changes in extreme precipitation under climate change, with greater emphasis on scaling rates with rainfall magnitude. Recent studies suggest that scaling rates can depend on rainfall mechanisms (e.g., tropical cyclones versus non-TC events), which may provide additional support for the present findings.

Response: We sincerely appreciate this valuable and constructive comment. Following your suggestion, we have further elaborated the discussion on changes in extreme precipitation under climate change in Lines 536–544 of the revised manuscript, with greater emphasis on the scaling rates of rainfall magnitude. We have also supplemented and discussed recent studies indicating that scaling rates can differ between rainfall mechanisms. This additional discussion provides stronger support to our main findings and improves the depth of the manuscript. The relevant content has been carefully revised and updated of the revised manuscript. We added the following sentences in Lines 536–544 of the revised manuscript:

"These patterns are closely linked to the increase of the moisture-holding capacity of the atmosphere with higher temperature at approximately 7%/℃ (Trenberth et al., 2003). Under global warming context, the increasing atmospheric moisture and buoyancy not only elevate the frequency of extreme precipitation events but also can lead to intensification rates that exceed the Clausius–Clapeyron (CC) scaling, exhibiting super-CC scaling (Fowler et al., 2021). Under a +4 K warming scenario, probable maximum precipitation (PMP) events are projected to become substantially more frequent, with their annual exceedance probability rising by approximately $10^1 \sim 10^2$ (Hiraga et al., 2025). Besides thermodynamic controls, dynamic factors associated with large-scale circulation changes also modulate the frequency and propagation of extreme rainfall by shifting storm trajectories and movement speeds (Chan et al., 2023; Wasko et al., 2024)."