Response to Reviewer Comments

Reviewer #1:

Dear Reviewer:

Thank you for your thoughtful and detailed review of our manuscript. We greatly appreciate the time and effort you dedicated to providing feedback. We have carefully considered all your comments and suggestions and revised our manuscript accordingly. All revisions are marked in red in the revised manuscript. Point-to-point responses to your comments are listed below:

1. This paper investigates precipitation space-time characteristics (from IMERG, presumably primarily from GPM and TRMM satellite missions) for 623 flood-causing precipitation (FCP) events over China during the period 2000-2023. Their primary conclusion is that "despite the increase in 3D characteristics of FCP events over the past two decades, flood disasters have shown a significant reduction, except for the direct economic losses". Unfortunately, they never say what they mean by "3D characteristics – the term appears only three times in the paper, twice in the abstract and once in the discussion -- but from Figure 3 one might conclude that these are centroid, magnitude, area, lifespan, moving distance, and moving speed. Importantly, these are all attributes of FCP; none have to do with flood characteristics themselves (e.g., inundation extent, depth, peak discharge, and so on).

Response: We appreciate your constructive comments and suggestions. In the revised manuscript, we have added a detailed description of 3D characteristics in Lines 15-16 as "***accumulated magnitude, accumulated affected area, centroid, lifespan, moving direction, and moving distance***". In addition, to investigate flood characteristics, we used surface runoff from ERA5 datasets and river discharge from GloFAS-ERA5 to represent land-surface runoff generation and river flood characteristics during the flood-causing precipitation (FCP) period. Detailed descriptions of GloFAS-ERA5 river discharge and ERA5 precipitation and surface runoff datasets are provided in Sections 2.1 and 2.2 of the revised manuscript, respectively. The spatial-temporal variations of surface runoff and river discharge during FCP periods are analyzed in Section 4.3 of the revised manuscript. To clarify the flood characteristics, we have added the following paragraph in Section 4.3 of the revised manuscript:

"**4.3 Spatial-temporal variation of surface runoff and discharge during the FCP event periods**

The spatial and temporal variations of hydrological processes during the FCP event periods are analysed (Fig. 7 and Fig. 8). It can be seen from Fig. 7 that FCP events associated with low surface runoff are found mainly in Northwestern China (NWC) and the Qinghai-Tibetan Plateau (TP). At the same time, FCP events with low surface runoff are distributed in the western parts of SC and NC. By contrast, FCP events with high surface runoff are predominantly observed in central SC and NC and northeastern NC. A comparison between TC and non-TC events reveals that the average surface runoff of non-TC FCP events is 30.81 $\times 10^3\,mm$, which is higher than that of TC FCP events with average value of 23.34 $\times 10^3\,mm$. Fig. 7b presents a similar spatial variation of river discharge. FCP events with high river discharge are primarily concentrated in the central of SC, NC, and northeastern parts of NC. These findings indicate that areas with large surface runoff and river discharge in the central SC and NC face a higher probability of flood occurrence..

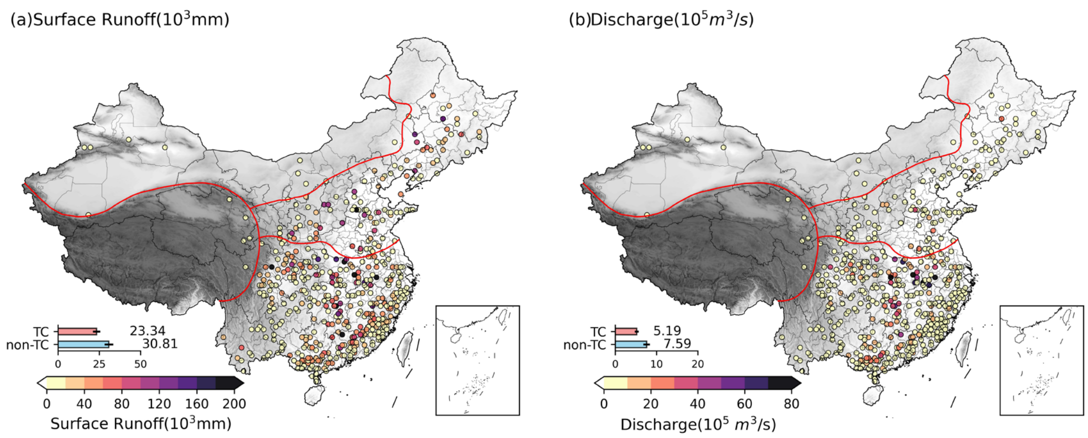

Figure 7. Spatial distribution of (a) surface runoff and (b) discharge during FCP event periods in China from 2000 to 2023. Bar chart illustrates the mean values of surface runoff and discharge of TC and non-TC FCP events. The shading indicates the terrain height.

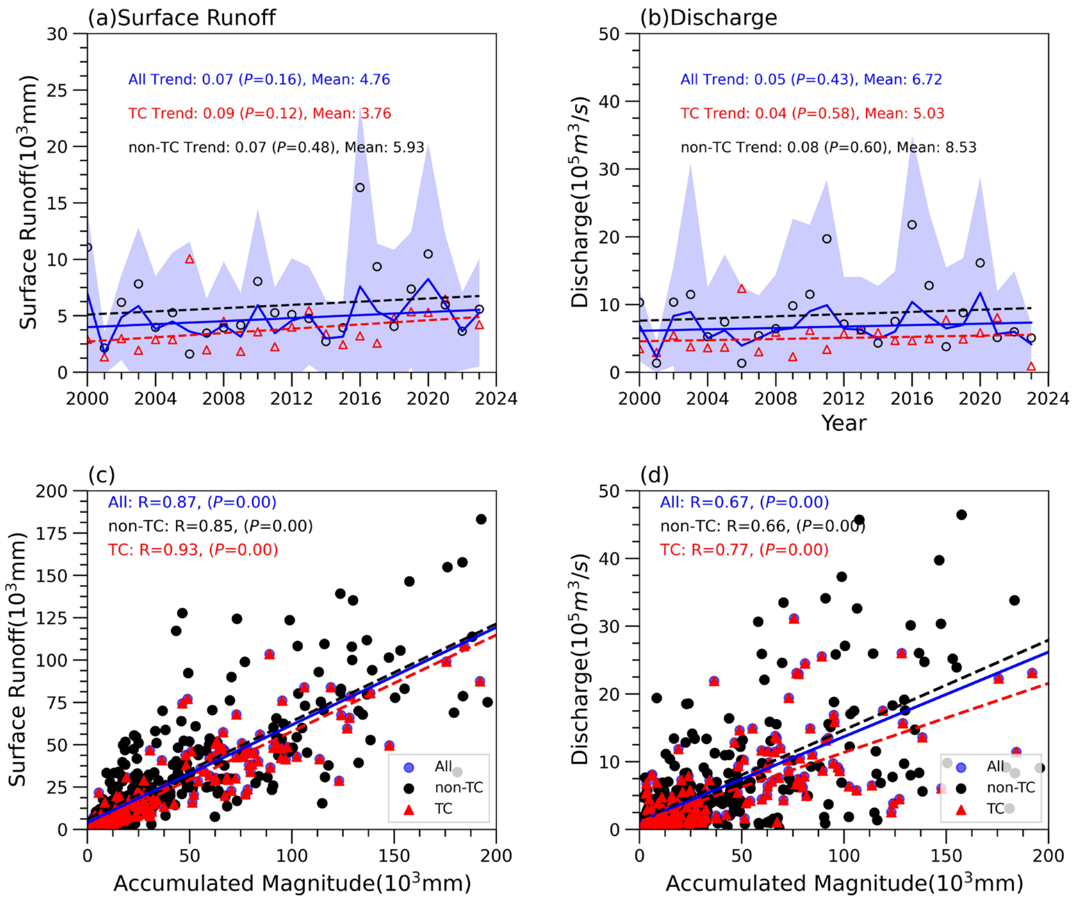

Figure 8. Time series of annual mean values of surface runoff (a) and discharge (b) during FCP periods in China from 2000 to 2023. The blue solid line and straight line indicate the time evolution and trend of mean values of surface runoff and discharge during 2000-2023, respectively. The blue shading indicates the ± standard deviation across the evolution of surface runoff and discharge during FCP events. The black dots and dashed line represent the annual mean values and trend of surface runoff and discharge during the non-TC FCP periods events from 2000 to 2023. The red triangles and dashed line represent the annually mean values and trend of surface runoff and discharge during the TC FCP periods events from 2000 to 2023. The relationships between surface

runoff and accumulated magnitude, and between discharge and accumulated magnitude are shown in (c) and (d), respectively. Black dots represent non-TC events, red triangles represent TC events, and the regression lines indicate the correlation trends (solid blue line for all events, dashed red line for TC events, and dashed black line for non-TC events). The Pearson correlation coefficient (R) and significance level (P) are provided for each category, showing significant positive correlations between the hydrological variables and accumulated magnitude at the 99% confidence level.

Figures 8a and 8b illustrate the temporal variations of surface runoff and river discharge during FCP event periods, respectively. Both surface runoff and river discharge show increasing trends, yet the trend is not significant at the 0.05 level. The mean surface runoff and river discharge for non-TC FCP events are higher than that of TC events. This finding can be attributed to increase of precipitation features in China, as shown in Fig. 5. According to the correlation analysis between the accumulated magnitude of FCP events, surface runoff, and river discharge, we find that surface runoff exhibits a significant correlation with accumulated magnitude (R=0.87, P<0.001). The correlation coefficients between the accumulated magnitude and surface runoff are 0.85 for non-TC and 0.93 for TC FCP events, both of which are statistically significant at the 0.01 level (Fig. 8c). By contrast, the correlation between accumulated magnitude and river discharge is relatively weaker, with the mean correlation coefficient greater than 0.67 and statistically significant at the 0.01 level. Consequently, enhanced 3D characteristics of FCP events across China drive increases in surface runoff and river discharge. Particularly, flood disasters are more prominent in central SC and NC."

2. Their primary source of flood information is something called the China Meteorological Disaster Yearbook. Exactly what is in this publication (or data base) I can't tell for sure as it's In Chinese, but it appears that it's only high-level attributes such as what one might find in NOAA's Billion Dollar Natural Disasters. So, they've managed to sidestep the entire field of flood hydrology, as well as what arguably is one of the current grand challenges facing the hydrologic community, specifically, if extreme precipitation is increasing, why aren't floods? (they do cite a 2018 WRR paper with that title). There in fact is reasonably conclusive observational evidence that extreme precipitation is increasing, and they cite some key papers along that line. But, they also note that "… despite the observed and projected increase in extreme precipitation, the flood magnitude and frequency exhibit mixed trend patterns. Several global scale flood trend detection studies have found that more stations exhibit significant decreasing trends in flood magnitude than increasing ones … These inconsistencies highlight the nonlinear relationship between precipitation intensity and flood disasters" What is widely acknowledged is that flood damages (but not necessarily deaths, especially in the developed world) have been increasing. Tanoue et al. (2016) have a pretty good paper on this, showing that increasing flood damages are strongly linked to increased development on flood plains. Surely this must be the case in China, especially during their study period. But that's hardly a new finding.

Response: Thank you for your note and suggestions. As you pointed out, flood disasters data used in this study is derived from the *China Meteorological Disaster Yearbook*, similar to NOAA's Disasters dataset. In this study, we systematically investigated the three-dimensional (3D) characteristics of FCP events, surface runoff, river discharge, and associated flood disasters from a 3D event-based perspective based on flood disaster data to improve our understanding of the characteristics and evolution process of rainstorms and floods. To further improve the analysis of flood processes, we introduced surface runoff (from ERA5) and river discharge (from

GloFAS-ERA5) in the revised manuscript. Our results show that evolution characteristics of FCP events have increased (not significant at the 0.05 level), and surface runoff and river discharge also show non-significant increasing trends. This finding indicates that the variations in rainstorms and floods in China are consistent, which is inconsistent with previous studies that found more stations exhibit significant decreasing trends in flood magnitude (e.g., Sharma et al. 2018). In addition, it is widely acknowledged that rising flood economic losses are closely linked to population growth and socioeconomic development in floodplains (Xie et al., 2018; Feng et al., 2023). In our study, we extracted and analyzed the 3D rainfall features, surface runoff, river discharge, and disaster impact of FCP events from 2000 to 2023 at the event-based scale. This event-oriented 3D framework effectively captures the spatiotemporal evolution of rainstorms and hazard impacts of flood disasters, providing more robust evidence for the relationships between flood hazards and changes in population and socioeconomic conditions, as illustrated in Figure 12 of the revised manuscript.

Reference:

Feng, J., Li, D., Li, Y., and Zhao, L.: Analysis of compound floods from storm surge and extreme precipitation in China. J. Hydrol. 627, 130402, https://doi.org/10.1016/j.jhydrol.2023.130402, 2023.

Sharma, A., Wasko, C., and Lettenmaier, D.P.: If precipitation extremes are increasing, why aren't floods? Water Resour. Res. 54, 8545-8551, https://doi.org/10.1029/2018WR023749, 2018.

Xie, Z., Du, Y., Zeng, Y., and Miao, Q.: Classification of yearly extreme precipitation events and associated flood risk in the Yangtze-Huaihe River Valley. Sci. China Earth Sci. 61, 1341-1356, https://doi.org/10.1007/s11430-017-9212-8, 2018.

3. Given the above, the contribution of this paper isn't clear to me. Certainly, "mining" the meteorological disaster yearbook, along with the precipitation data base, could yield some interesting insights, but I don't see how much that's very interesting could come from that without closely investigating the hydrological aspects of the floods. This clearly would involve some filtering to remove (or account for) the effects of flood regulation by dams and other means. There also is a question in my mind as to whether the length of the database (24 years) is sufficient, although perhaps they could make an argument for space for time substitution. In any event, the absence of any flood hydrology in the current version is, in my view, a fatal flaw, and I think the authors need to go back to the drawing board (and perhaps augment the author group with some flood hydrology expertise).

Response: We sincerely appreciate your valuable comments. In response to the core deficiencies in our manuscript, we have conducted in-depth reviews and improvements. We introduced river discharge reanalysis data from GloFAS-ERA5 to systematically evaluate the spatiotemporal variations of flood within regions affected by FCP events, thereby revealing the evolution of floods. Meanwhile, in order to be consistent with the GloFAS-ERA5 river discharge, we adopted ERA5 precipitation and surface runoff datasets that have the same source as GloFAS-ERA5, to systematically analyze the 3D spatiotemporal evolution of FCP and changes in land-surface runoff generation. Our results indicate that metrics of FCP events in China, including accumulated magnitude, accumulated affected area, centroid, lifespan, moving direction, and moving distance, all show increasing trends (insignificant at the 0.05 level). Correspondingly, surface runoff and river discharge also exhibit nonsignificant increasing trends.

Constrained by available datasets, this study cannot quantitatively assess the flood regulation effects of dams and other hydraulic projects. Nevertheless, based on the temporal and spatial distribution of dam construction in China shown in Fig. 1, the role of hydraulic projects in flood mitigation cannot be ignored. Although both flood-causing rainstorms and runoff display increasing trends, the hazard severity of floods in China have decreased. This implies that dams and hydraulic infrastructures play a critical role in national flood prevention and disaster reduction. Accordingly, we have explicitly acknowledged this limitation and discussed the impacts of hydraulic projects on rainstorm-flood hazards in the Discussion section (Lines 554-558 of the revised manuscript).

In addition, limited by the availability of historical disaster records, we have collected the most complete rainstorm-flood disaster data for this study, and we sincerely appreciate your understanding.

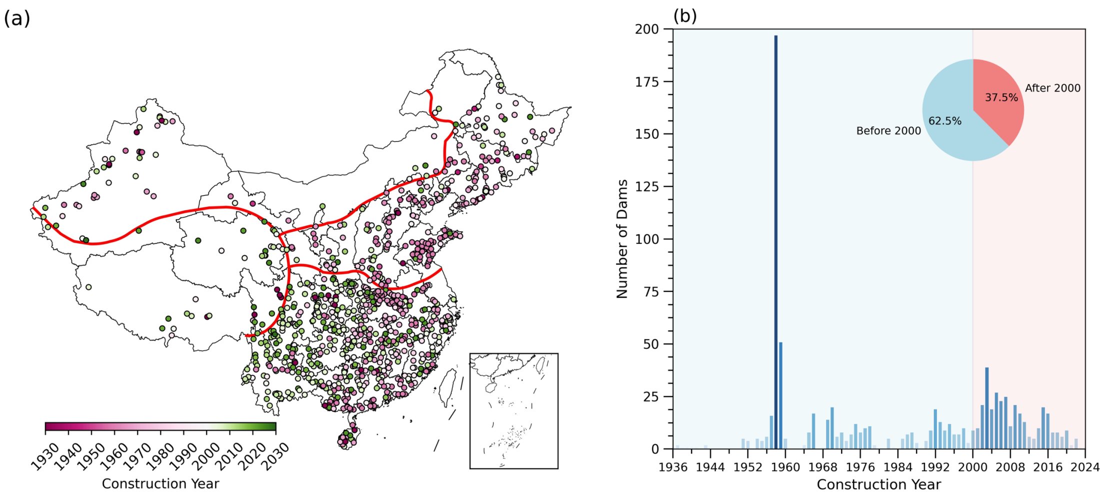

Fig. 1 (a) Spatial distribution of major dams and (b) the annual construction numbers of dams in China during 1930–2024

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 response to your comments is 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"

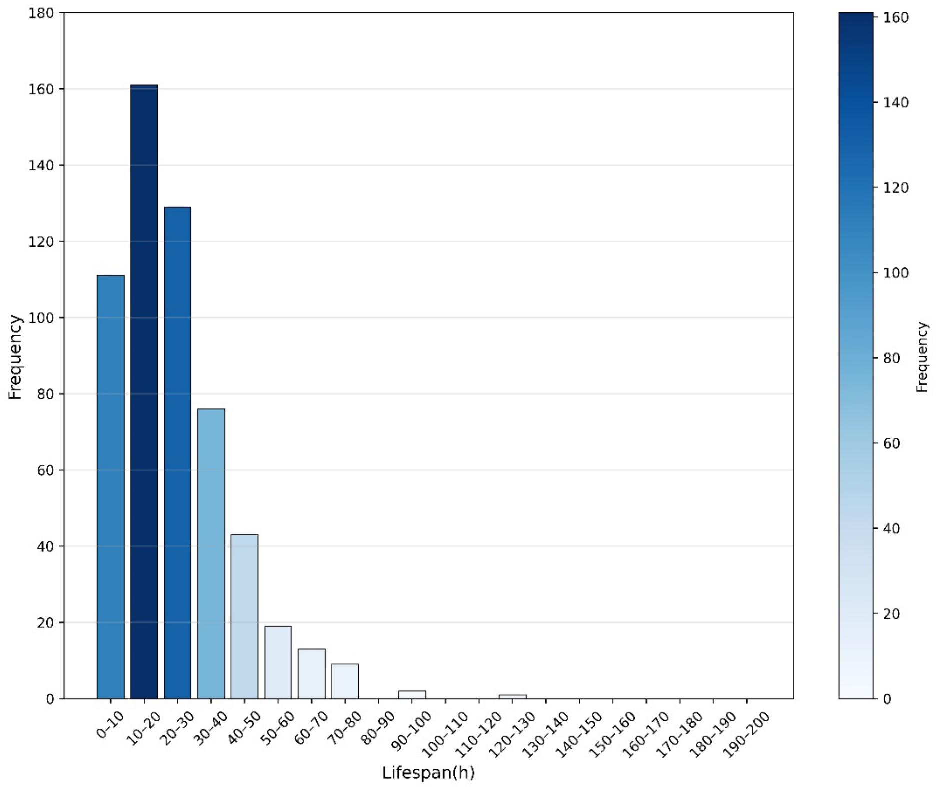

Fig. 1 The frequency of FCP lifespan from 0 to 200 hours with 10-hour intervals.

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)."

Response to Reviewer Comments

Reviewer #4:

Dear Reviewer:

Thank you for your thoughtful and detailed review of our manuscript. We greatly appreciate the time and effort you dedicated to providing 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. Point-to-point response to your comments is listed below:

1. The manuscript adopts a CC3D algorithm for FCP event identification, but it fails to clearly elaborate on the core innovations of this algorithm in the context of the study, for example, the rationale for optimizing the 95th percentile threshold for extreme precipitation or the criteria for judging event independence. Notably, the study solely uses the 95th percentile threshold without comparing it with the fixed threshold (e.g., 16 mm/h, as defined by the China Meteorological Administration) for validation. This omission makes it impossible to verify whether the selected threshold is universally applicable to FCP event identification across different regions (e.g., the arid northwest and humid southern China), potentially leading to under-detection or misdetection of events in specific areas.

Response: We sincerely appreciate this valuable and constructive comment. In the revised manuscript, we have added a detailed comparison of different precipitation thresholds. As shown in Fig. 1 and Fig. 2, we used two schemes to extract the three-dimensional (3D) properties of FCP events: (1) fixed intensity thresholds ranging from 1 to 16 mm h^{-1} (used in Fig. 1); (2) percentile-derived thresholds, defined as the 10th–90th percentiles of grid-scale 95th-percentile extreme precipitation thresholds across rainfall-affected areas (used in Fig. 2). We found that FCP events identified by the fixed 16 mm/h threshold fail to fully cover disaster-affected regions (Fig. 1). In contrast, FCP events extracted using the 10th–90th percentile thresholds derived from the 95th-percentile extreme precipitation can well capture the disaster-affected areas (Fig. 2). This confirms that the percentile-based threshold exhibits higher effectiveness and regional applicability for detecting the three-dimensional characteristics of FCP events across mainland China. We have established the threshold criteria for extracting the 3D properties of FCP events as suggested in the revised manuscript in Lines 195-196.

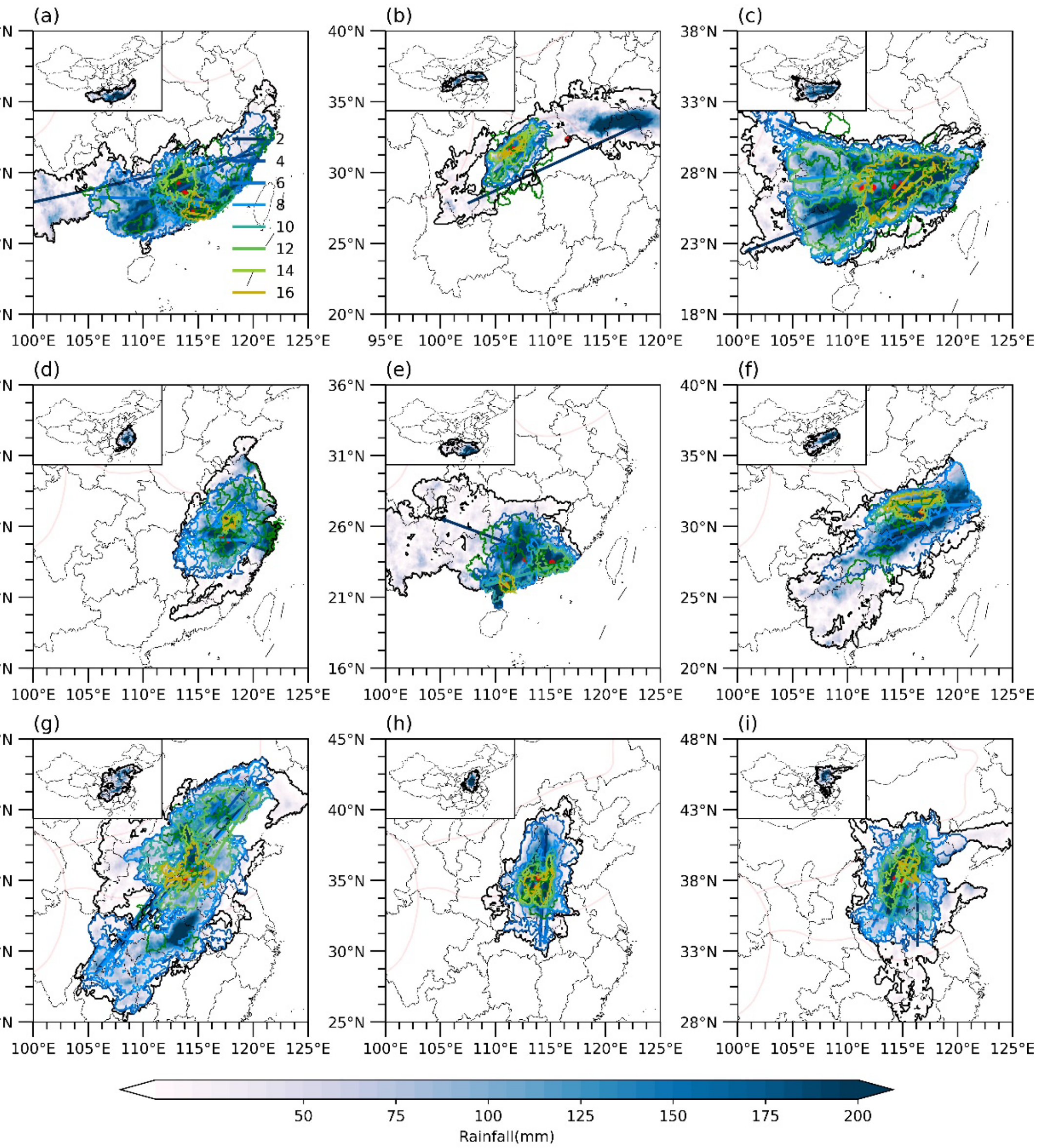

Fig. 1 The evaluation features of ten FCP events. The shading indicates the FCP accumulated area. The color polygons represent the precipitation extraction thresholds, ranging from 2 to 16 mm. The color arrows represent the movement of FCP event; the moving direction is from the tail to the head of the arrow; the length of arrow indicates moving distance.

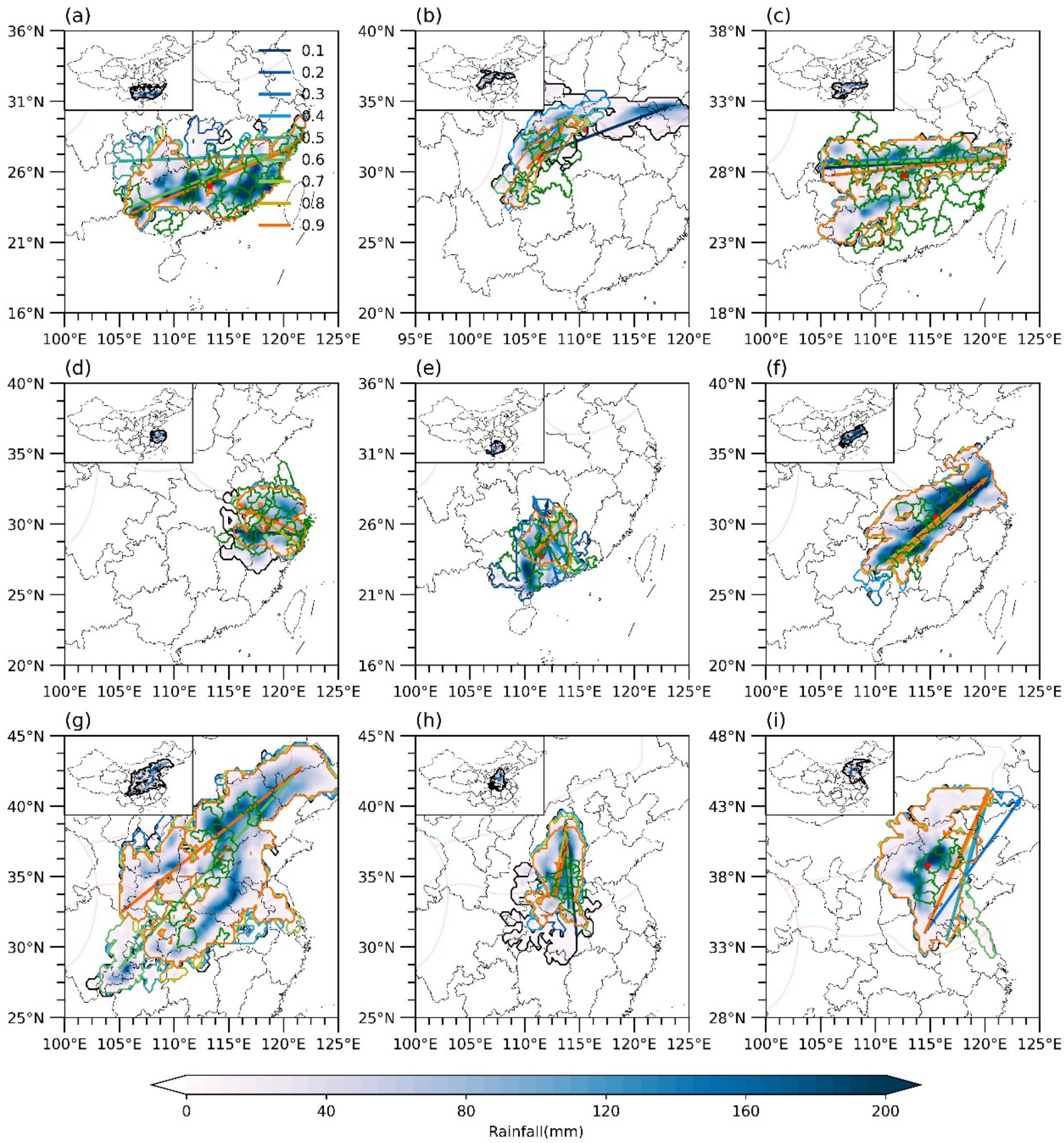

Fig. 2 The evaluation features of ten FCP events. The shading indicates the FCP accumulated area. The color polygons represent the precipitation extraction thresholds, which are derived from the 10th and 90th percentiles of the 95th percentile extreme precipitation thresholds over the precipitation affected areas. The color arrows represent the movement of FCP event; the moving direction is from the tail to the head of the arrow; the length of arrow indicates moving distance.

2. Population and GDP data use only two time points (2005 and 2020) to represent annual data for 2000–2010 and 2010–2020, respectively. This simplification ignores spatiotemporal heterogeneity in population migration and economic growth (e.g., rapid urbanization in the Yangtze River Delta), which could significantly distort the assessment of human activities' impact on flood disasters.

Response: We sincerely appreciate this constructive comment. We fully agree that using only two time points (2005 and 2020) to represent population and GDP data for 2000–2010 and 2010–2020 may oversimplify spatiotemporal variations and introduce uncertainties in assessing human impacts on floods. To address this issue, we have updated the population and GDP datasets for 2000–2020 at 5-year intervals from the website http://www.resdc.cn. The detailed data information is presented in Table 1 of the revised manuscript.

3. The manuscript acknowledges that hydraulic engineering (e.g., dams, reservoirs) is an important flood mitigation factor but excludes it from the driving factor analysis due to data limitations. However, large-scale hydraulic projects in China (e.g., the Three Gorges Dam) have significantly altered flood regimes, especially in SC and NC. Omitting these factors may limit the comprehensiveness of the driving factor analysis, and the manuscript should discuss how this omission impacts the interpretation of results.

Response: We sincerely appreciate this insightful comment. We fully recognize that large-scale hydraulic engineering (e.g., dams and reservoirs, particularly the Three Gorges Dam) exerts considerable influences on regional flood regimes in South China (SC) and North China (NC). Due to data availability constraints, we were unable to include hydraulic engineering variables in our quantitative driving-factor analysis in the current study. To improve the comprehensiveness of our results, we have supplemented a detailed discussion on the limitations caused by the exclusion of hydraulic engineering in the revised manuscript. We have added the following in Discussion (Lines 554-559) of the revised manuscript:

"This discrepancy might be caused by larger-scale hydraulic projects, such as dams and reservoirs. By the end of 2018, there are 98,822 reservoirs exist in China, with a total storage capacity of $8.95 \times 10^{12}\ m^3$ (Data are derived from China Water Statistical Yearbook 2018), which may significantly modulate the flood risks. Tang et al. (2023) studied the impact of dams on the flood in the Yangtze River, and found that dams and reservoirs mitigated the extreme flood by contributing to 94 % of the water level changes."

4. The manuscript reports that FCP 3D features (e.g., accumulated magnitude, lifespan) have increased, while most flood disaster metrics (except direct economic loss) have decreased. The explanation attributes this discrepancy to hydraulic engineering, but no quantitative evidence is provided to support this claim. For example, could the reduction in disaster impacts be quantified by the number or storage capacity of reservoirs built during the study period? Additionally, the increase in direct economic loss is linked to economic development, but a regression analysis or correlation between GDP growth and economic losses would strengthen this argument.

Response: Thank you for your comment. We fully agree that quantitative evidence is critical to validate the roles of hydraulic engineering and economic development. However, due to the lack of high-resolution and long-term spatial datasets on reservoir storage capacity at the national scale, we are unable to conduct reservoir-based quantitative attribution analysis in the current study. Accordingly, we have supplemented relevant published evidence and discussed the qualitative regulatory effects of hydraulic engineering on flood disasters in Lines 554-559 of the revised manuscript. For the relationship between GDP growth and direct economic losses, we have conducted corresponding correlation analysis. The results show that no significant correlation exists between them, with an R^2 value of only 0.228 (Fig. 3). Therefore, performing further regression or correlation analysis between GDP growth and economic losses would be of limited significance.

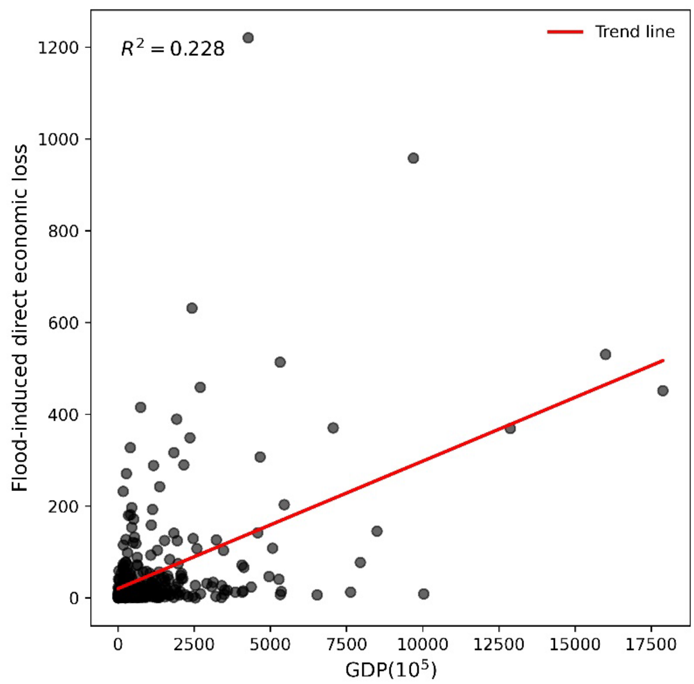

Fig. 3 Correlation analysis between flood-induced direct economic loss and GDP.

5. The finding of high death rates in the southeastern fringe of TP and SWC is attributed to the lack of flood mitigation infrastructure and flash floods triggered by landslides/debris flows. However, the manuscript does not provide data on infrastructure coverage (e.g., levee density, early warning systems) or the frequency of secondary disasters (landslides) in these regions. Incorporating such data or citing relevant studies would enhance the explanation of spatial loss patterns.

Response: Thank you for your comment. Given the difficulty in obtaining long-term, spatially explicit data on levee density and early-warning system coverage at the national scale, we are unable to carry out quantitative spatial analysis in this study. Accordingly, we have supplemented relevant published studies in the revised manuscript. These references confirm that the mountainous regions feature insufficient flood-mitigation infrastructure, inadequate early-warning capacity, and frequent flash floods triggered by landslides and debris flows, which collectively lead to higher flood-related mortality. Following your suggestion, we have added the above discussion in Lines 561–565 of the revised manuscript.

"The robustness of the findings is supported by existing studies, suggesting that numerous engineering measures around the world have improved flood control standards and mitigated the rising risks of flash floods. Lim et al. (2018) analysed the global benefits of existing flood-control projects and identified an 8 % reduction in the exposed population and 7 % GDP property exposure losses per year in flood-inundated areas from 1986 to 2005. Zhao et al. (2022) indicated that reservoirs can decrease housing losses caused by flash floods by 9.7-45.7 %."

6. What's 3D characteristic in Abstract?

Response: Thank you for your comment. We have added a detailed description of 3D characteristics at its first appearance in line 15, namely "**accumulated magnitude, accumulated affected area, centroid, lifespan, moving direction, and moving distance**".

7. Figure 3 (FCP identification algorithm flowchart) is poorly labeled: terms like '26 connectivity tracking' are not explained.

Response: Thank you for your comment. The detailed description of the FCP identification algorithm is provided in Section 3.2, which elaborates on the workflow shown in Fig. 3. We have supplemented a clear explanation of "26-connectivity tracking" in Section 3.2. We have added the following sentence in Lines 204–206 of the revised manuscript.

"The CC3D algorithm can move to a 3D 26-connected neighborhood, and searches for all 26-connected components in a 3D array along the dimensions of latitude, longitude, and time."

8. Table 1 (summarizing variables and data sources) is mentioned in the text (Section 2.3) but not included in the manuscript.

Response: Thanks for pointing this out. We have supplemented a table listing the data sources and cited it in Line 155 of the revised manuscript.

9. The term 'flood-causing precipitation (FCP)' is used throughout the manuscript but is not formally defined. It should be explicitly defined at the start of the Methods section to avoid confusion with 'extreme precipitation' or 'heavy rainfall'.

Response: Thank you for your comment. In our study, flood-causing precipitation (FCP) is defined as extreme precipitation events that trigger flood disasters at the regional scale. To avoid confusion with general extreme precipitation or heavy rainfall, we have provided an explicit formal definition of flood-causing precipitation (FCP) at the beginning of the Methods section (Lines 181-182) of the revised manuscript. We have added the following sentence in Lines 179-180 of the revised manuscript.

"It is an extreme precipitation event that trigger flood disasters at the regional scale"

10. The calculation method for 'accumulated affected area' (a 3D FCP indicator) is vague, whether it refers to horizontal projection area or curved surface area (critical for mountainous regions) is not specified.

Response: Thanks for pointing this out. The accumulated affected area in this study refers to the horizontal projected area of FCP events. We have clarified the definition of the accumulated affected area in Line 225 of the revised manuscript.

11. Page 7, Line 175: 'the 26-connectivity searching allows that a contiguous precipitation event occurring at a grid on the current hour can move to the adjacent grids in the following hour' is grammatically incorrect. It should be revised to 'the 26-connectivity search enables a contiguous precipitation event at a grid in the current hour to move to adjacent grids in the following hour.'

Response: Thanks for pointing this out. We amended as mentioned above.

12. Page 12, Line 295: 'the annually mean values and trend of TC FCP events' uses an incorrect adverb; it should be 'the annual mean values and trend of TC FCP events.'

Response: Thanks for pointing this out. We amended as mentioned above.

13. Page 15, Line 355: 'results in economic losses of USD 57.46 billion' lacks a clear time reference

(which flood event?)

Response: Thank you for your comment. This economic loss corresponds to the flood event that occurred in July 2016, and the relevant information has been supplemented in Lines 426–427 of the revised manuscript.

14. Figure 1's caption mentions a study period of 2000–2023, but the subplot label (a) 2024 is confusing.

Response: Thanks for pointing this out. We amended as mentioned above.

15. The abstract mentions "632 flood-causing precipitation (FCP) events" but does not specify how these events were derived from the 1,041 flood disaster records. A brief note on the event merging/classification process would improve clarity.

Response: Thank you for your comment. In Section 3.2 *Identification of flood-causing precipitation events*, we provide detailed description of the identification procedure for flood-causing precipitation events. We also explained how the 1,041 flood disaster records were processed by removing repeated events and ultimately classified into 632 FCP events.

16. The manuscript states that code is available upon request from the corresponding author, but making the code publicly available (e.g., on GitHub) would enhance reproducibility, which is increasingly important in environmental science research.

Response: Thank you very much for your valuable suggestion. The source code for identification of flood-causing precipitation events is available upon request from the corresponding author, as described in Line 636 of the revised manuscript. We will consider publicly sharing the code on GitHub in future research to improve the reproducibility of our work.