

Response to Reviewer 3

Beyond Runoff Coefficient: Revealing Global Patterns of Process Connectivity in Runoff Generation through Intensity Integration (Liang et al.,) The manuscript Liang et al., discusses the connectivity processes describing runoff generation. Authors propose a new composite runoff efficiency integrating runoff coefficient and runoff intensity and have examined more than 6000 catchment globally over 1950-2020 to quantify the spatial-temporal patterns and characteristics. A machine learning based analysis has also been incorporated which reveals that climate attributes primarily control the runoff processes. Further hotspots of process connectivity has been identified with their further implications. The study is timely and comprehensive and can be crucial in providing new insights into global runoff generation process and can be utilised in relevant applications of the same. However, there are several avenues where authors need to clarify and possibly modify before publication.

Response: We appreciate the reviewer's comments and recognition of the relevance of our study. We will respond and make revisions to each of the questions you have raised.

1. The authors need to built up on the foundation of why process connectivity is relevant for the arguments provided in paragraph one in the introduction section. The authors have mentioned hydrological connectivity L 25-28, and then process connectivity in L 39. however, more clarity and connection on why this is important need to be provided.

Response: Thanks for your kind question. We added a broader concept of hydrological connectivity in the first paragraph, while also introducing the focus of our manuscript on the connectivity of the runoff generation process (*P-R*), distinguished from the channel routing process. We further elaborated on the importance of understanding the connectivity of the runoff generation process based on several real cases.

" Hydrological connectivity, defined as the water transfer within or between components of the hydrologic cycle, is characterised by both the ratio and rate of the transfer process (Bracken et al., 2013). This broad concept manifests across various hydrological processes such as runoff generation, channel routing, and groundwater recharge (Van Tiel et al., 2024; Wang et al., 2025; Gou et al., 2025; Phillips et al., 2011). **Among these, the process connectivity of runoff generation—the transformation from precipitation to runoff—is of particular importance because it determines what fraction of precipitation actually becomes available for streamflow (rather than being lost to evaporation or infiltration) and how rapidly this transformation occurs before the subsequent routing process (Bronstert et al., 2002; Shen et al., 2020). Over the past decades, climate change has profoundly altered this connectivity by modifying both rainfall characteristics and snow-related processes (Richter and Marty, 2026; Zhang et al., 2024).** For example, warming has intensified precipitation extremes, leading to more frequent and intense

heavy rainfall events (Yin et al., 2018; Zhang et al., 2023). Such changes can generate flash floods with higher peaks and larger volumes, thereby increasing flood hazards and socioeconomic risks (Blöschl, 2022; Miller and Hess, 2017). Moreover, global warming significantly reshapes snowpack dynamics by decreasing the proportion of precipitation being stored as snowpack, along with a faster melting rate (Li and Fan, 2025; Guan et al., 2022). This shifts the seasonal runoff pattern, triggering earlier and more pronounced spring flow peaks followed by the diminished summer baseflow, which exacerbates agricultural drought and water scarcity in downstream regions (Han et al., 2024). **Therefore, a comprehensive understanding of the process connectivity in runoff generation is critical to enhancing climate adaptation and mitigating water-related hazards. "**

2. In the literature review, it has been mentioned that majority of existing research concentrates on small scale catchments and some examples of UK, Austria and Italy etc have been cited. Reasoning behind the focus on small scale catchments and limitations related to attempting diverse regions globally need to be discussed in further details (not just limiting to L64-66).

Response: Thanks for your kind question. We have added reasoning behind the focus on small-scale catchments and limitations related to attempting diverse regions:

" Many previous studies concentrate on small scales, such as agricultural irrigation plots (Badoux et al., 2006; Taye et al., 2013; Sumner et al., 1996; Nyssen et al., 2010) and hillslopes (Kinnell, 2014; Gomi et al., 2008b; Penna et al., 2011; Gomi et al., 2008a), partly due to the advantages of dense instrumentation and process experiments (e.g., soil moisture networks, tracers) that are often infeasible at larger scales, thereby supporting hypothesis testing and mechanistic understanding of thresholds and connectivity (Bishop et al., 2024; Wu et al., 2025)"

"Despite these valuable regional findings, existing studies are inherently limited in their spatial scope and covariate diversity. Within constrained hydroclimatic and physiographic domains, the limited variability among controlling factors gives rise to significant multicollinearity, posing a substantial challenge to disentangling their independent contributions and quantifying their relative importance at broader spatial scales (Do Nascimento et al., 2025; Clerc-Schwarzenbach et al., 2024). Consequently, the extrapolation of region-specific findings to ungauged or hydroclimatically divergent catchments is inherently associated with high levels of uncertainty. A global-scale analysis encompassing a more diverse covariate space is therefore essential to disentangle these confounding controls and advance toward a more generalized understanding of runoff generation."

3. Relating to previous comment ··RC for diverse global regions is itself sensitive to many factors, given runoff intensity has also been added, the authors really need to clarify 1. Why runoff intensity is crucial here? 2. Why this is important in a global context in terms of both hydrological processes and implications,3. L75 outlines very vaguely about how the proposed framework is helpful. Authors need to elaborate here.

Response: Thanks for your kind question. We have added the importance and hydrological implications of *RI*, and the how the proposed framework is helpful, in the last paragraph of the introduction.

" To address this limitation, we propose a systematic analytical framework for assessing process connectivity in runoff generation through intensity integration. **The aim is to understand spatiotemporal variations in the runoff generation process from the perspective of two-dimensional connectivity (i.e., transformation ratio and rate).** Specifically, the *RC* reflects the transformation ratio of precipitation into runoff. **The runoff intensity (*RI*), defined as the ratio of runoff depth to net rainfall duration, can directly indicate the transformation rate. This indicator is closely related to the surface runoff generation rate and the magnitude of peak discharge** (Bronstert et al., 2023; Léonard et al., 2006), **providing critical insights into the dynamic response of catchments to precipitation events.** To achieve a more holistic characterization of the runoff generation process connectivity, runoff efficiency (*RE*) is further developed to encapsulate both the volumetric ratio of precipitation transformed into runoff (captured by *RC*) and the temporal rate of this transformation process (reflected by *RI*). Applying this framework in 6,603 catchments worldwide over 1950–2020, we answer the following critical questions: **(a) What are the global spatial patterns of the process connectivity indicators, and to what extent do climate and landscape attributes drive their spatial heterogeneity? (b) What are the temporal dynamics of process connectivity indicators across multiple temporal scales, including long-term trends and event-to-event variability? "**

4. Overall methodology seems to be fragmented and proper explanations are needed behind selection of the approaches and later combining them. For e.g. a very simplistic representation of rainfall-runoff model has been considered (Fig1b), this is fine for a small scale study, however for such large number of diverse catchments, I wonder what limitations might arise because of this and if they need to be clarified or discussed. Some sort of sensitivity/uncertainty analysis is highly recommended at least demonstrating these.

Response: Thanks for your kind question. We propose an integrated framework for assessing process connectivity for runoff generation that jointly considers both the transformation ratio and rate from precipitation to runoff. The conceptual hydrological model aims to calculate the event runoff depth *R* and the corresponding runoff generation duration Δt_R (i.e., the net-rainfall duration), and further obtain the process connectivity indicators for the transformation ratio and rate. We simulated the runoff generation process with the simulation accuracy *KGE* in catchments greater than 0.5 to maximize the rationality of the model simulation. We acknowledge the limitations/uncertainties of the hydrological model structure, and choose a single hydrological model mainly for the consistency of indicators across regions, avoiding differences in the results of different hydrological models calculating runoff processes (such as *R* and Δt_R). We have added relevant discussions for the limitations of a single hydrological model in the manuscript.

"First, our analysis only relies on a single conceptual rainfall–runoff model with its own assumptions and simplifications, which may not be universally applicable across the diverse range of global

catchments and introduces structural uncertainty (Parasuraman and Elshorbagy, 2008). Although parameter calibration and performance screening have already secured a reasonable level of accuracy, future work could be done for ensembling hydrological models to better capture runoff-generation processes and to enhance the robustness of the results (Solanki et al., 2025). "

5. Authors also need to elaborate the methodology described in Fig1. There are several steps, for e.g. derived quickflow from insitu streamflow vs quickflow simulation from other hydro-met data, pugging into hydrological model?

Response: Thanks for your kind question. We have elaborated the methodology described in Fig. 1:

" To quantify the runoff generation connectivity indicators, the quickflow is first derived from the in situ streamflow observations. Subsequently, a conceptual hydrological model is developed to simulate the quickflow generation process forced by other hydro-meteorological data, and the rainfall-runoff events are further identified. "

6. In Section 3.1.2. there are several points which need more explanations and disclaimers, e.g. to what extent , presence of noise has been addressed in order to define a runoff event, the quickflow might not be reaching 0 in humid catchments or in the cases where model/data's structural influences overtake. This might lead of splitting or separation of one event into multiple and vice-versa. Similar comment can be made for the threshold of 0.1 mm/day. Further, since the response of rainfall to runoff is not linear therefore, the centroid might not fall withing the lag window as suggested, for e.g. for long rainfall events...what impact such events can lead to, needs to be discussed.

Response: Thanks for your kind question. We have added discussions on uncertainties of identification and matching of rainfall–runoff events.

" Third, uncertainties also exist in the identification and matching of rainfall–runoff events. Runoff events are currently defined to end when simulated quickflow returns to zero, yet in humid catchments, slow recession and structural biases from baseflow separation and model simulation may prevent strict zero-flow conditions, potentially causing event splitting or merging. In addition, the 0.1 mm d⁻¹ threshold employed to delineate rainfall events is an empirical truncation criterion that may alter event boundaries, especially under hydroclimatic extremes. Moreover, rainfall–runoff matching relies on the DCMA-based lag window and the assumption that the rainfall-event centroid falls within that window; this assumption may be violated by nonlinear responses, particularly for long-duration and low-intensity events, thereby introducing matching errors. These uncertainties potentially affect event-scale identification and matching to some degree, but are expected to be partially mitigated in our analysis of multi-event averages and large-scale spatial patterns."

7. Direct multiplication of RC*RI might be sensitive to very small values of t_R and P, what precautions have been taken to address these?

Response: Thanks for your kind question. Δt_R is measured on a daily scale and is therefore bounded by the temporal resolution ($\Delta t_R \geq 1$ day for identified events), and trace precipitation days are filtered out using the 0.1 mm d^{-1} threshold during rainfall-event definition. Besides, the sensitivity of very small values of Δt_R and P can further be smoothed in our analysis of multi-event averages and large-scale spatial patterns. Moreover, our regional analysis based on the median values of each group could further minimize the impact of extreme values.

8. L218 The catchments have been selected into wet, dry and snow. Maybe, the authors can also display the distribution of catchments according to sizes. Maybe a histogram will help, later dependence of results on the size of catchments can also be checked. Did the authors also check the presence of reservoirs, dams, or such structures in the catchments, they can be critical in influencing the results.

Response: Thanks for your kind question. We have added the size of catchments in a histogram as shown in Fig.S1. Considering that this study mainly focuses on the process of runoff generation, the related impact of the catchment area will not be further explored here. Besides, due to the fact that this study is based on the conceptual hydrological model simulation results, the KGE of all selected catchments is greater than 0.5, which minimizes the interference of reservoirs.

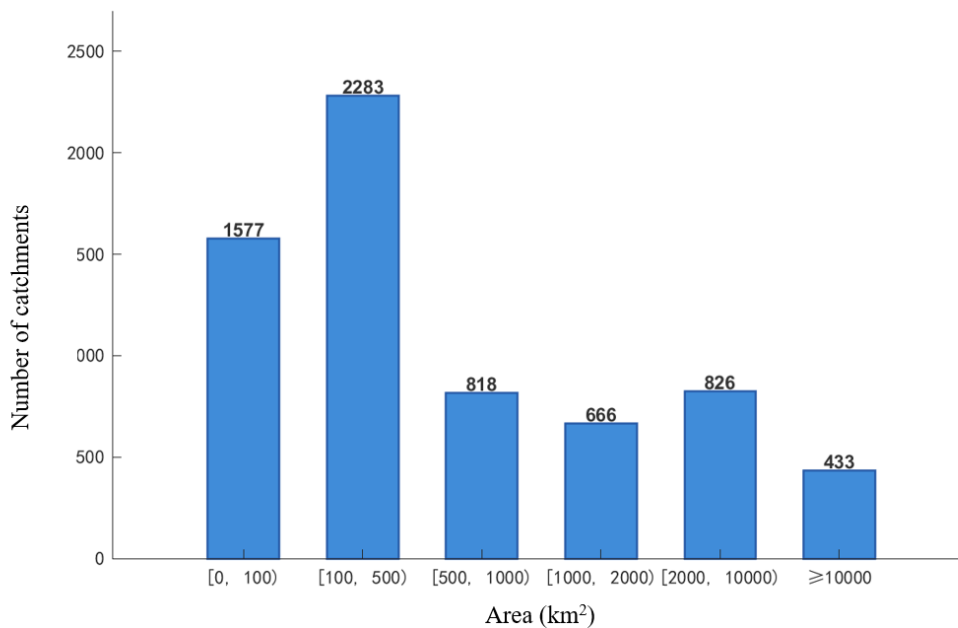


Figure S1. Distribution of the area of 6603 catchments for analysis.

9. L295 confusing statement: “trends of the transformation rate (i.e., runoff coefficient) and the transformation rate (i.e., runoff intensity) ...” please rephrase.

Response: Thanks for your kind question. We have corrected the confusing description:

" This indicates that long-term trends of the transformation ratio (i.e., runoff coefficient) and the transformation rate (i.e., runoff intensity) from precipitation to runoff show great synergy, meaning that regions with a higher transformation ratio may simultaneously experience a faster transformation rate under climate change. "

10. Figure 5,6,7 are too small to be analysed. Please resize/reorganize in the revised version.

Response: Thanks for your kind question. The size of the global maps in 5, 6, and 7 has been enlarged in the revised version.

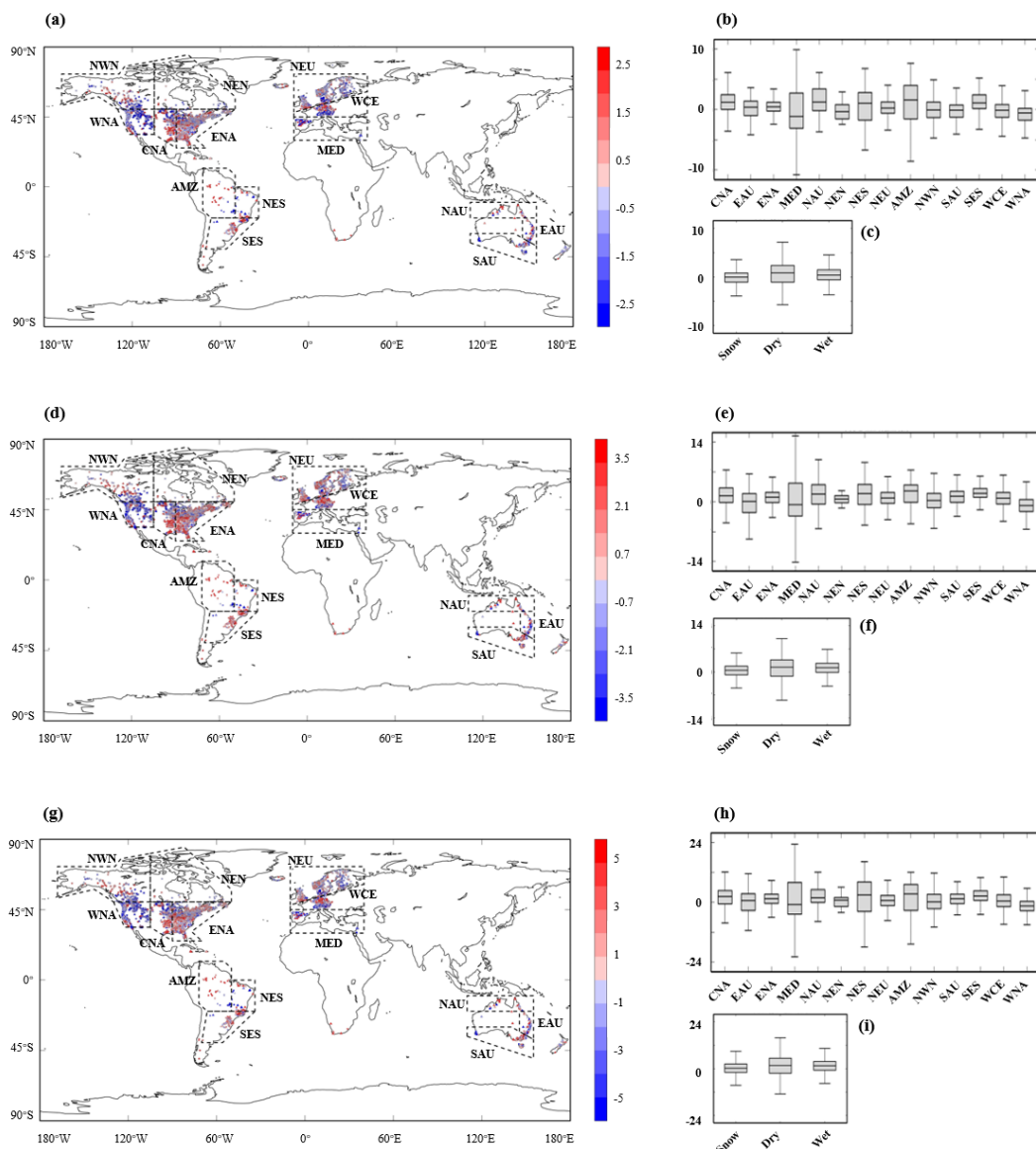


Figure 5. The long-term trends of the process connectivity indicators over 1950-2020. (a-c) for the runoff coefficient. (d-f) for the runoff intensity. (g-i) for the runoff efficiency.

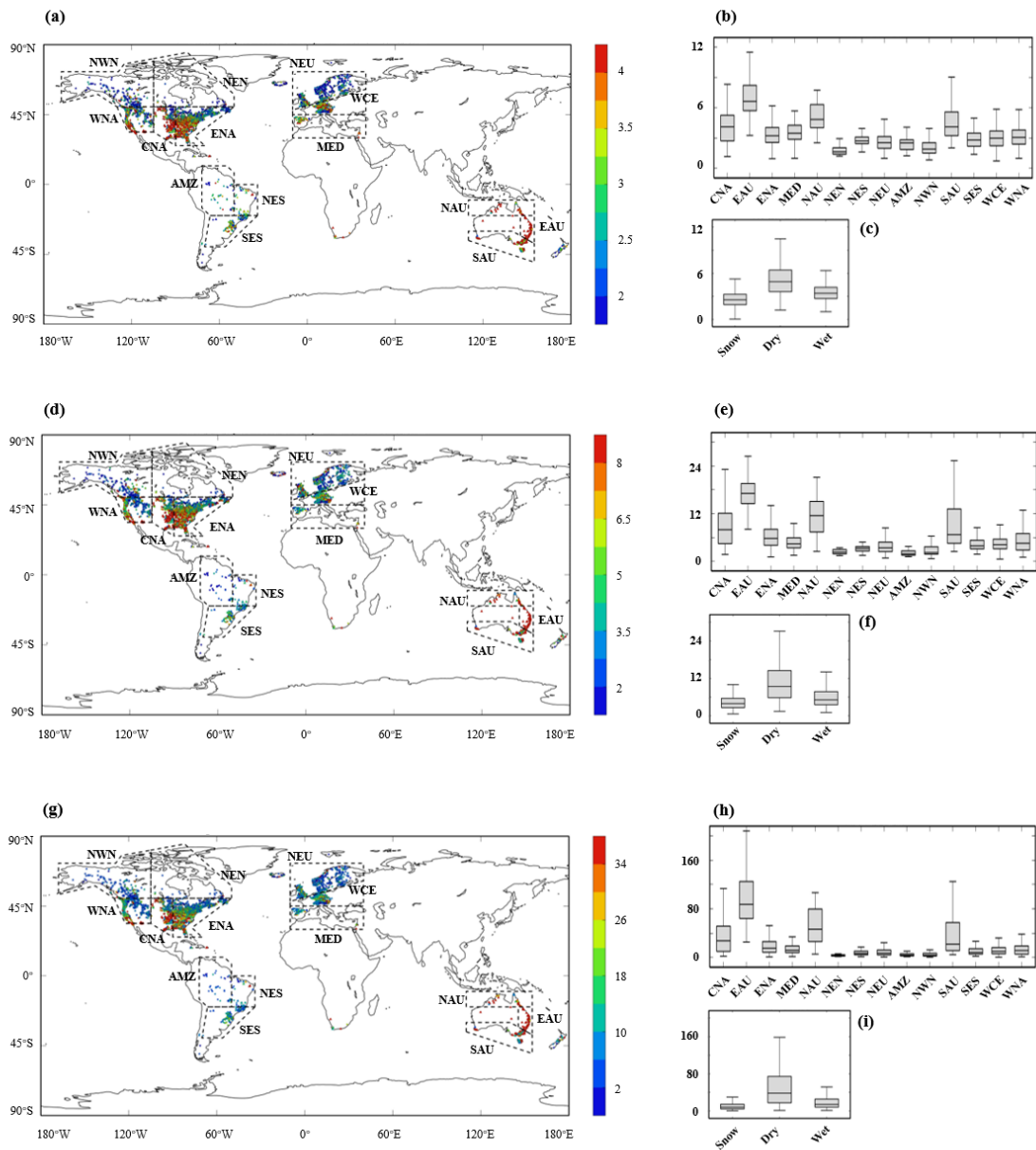


Figure 6. The fold-change in the connectivity indicators from the highest to the lowest peak-discharge quantile ranges, i.e., (80–100th percentile)/(0–20th percentile). (a-c) for the runoff coefficient. (d-f) for the runoff intensity. (g-i) for the runoff efficiency.

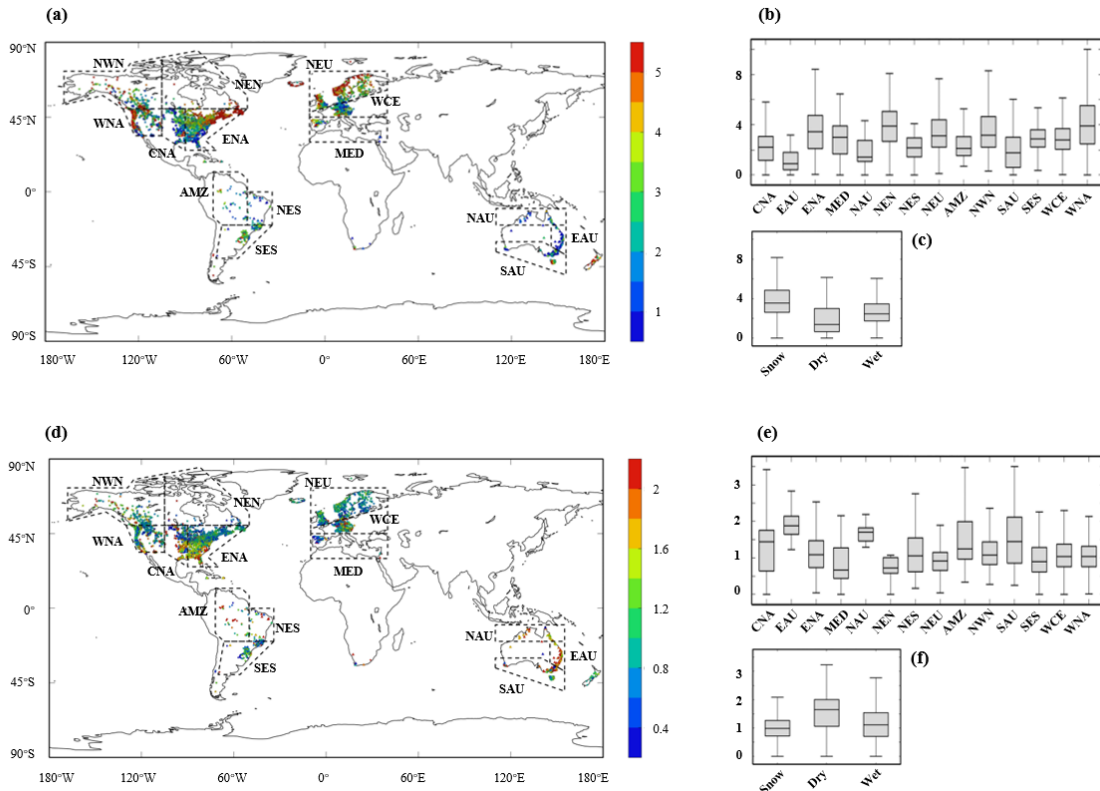


Figure 7. The spatial pattern of parameters of the power-law relationships between precipitation intensity and runoff efficiency. (a-c) for the parameter RE_{10} . (d-f) for the parameter m .

11. L365“...climatic indicators control the process connectivity at global scale...”, although authors mention some results Fig 5. and arguments . I feel this is too broad statement to be made here. A more suitable approach would be to discuss in detail, how the factors were selected and how they sufficiently represent climatic controls. May be a region-wise characterisation would help.

Response: Thanks for your kind question. We have corrected the previous representation. We mainly want to discuss the impacts of attributes of different types (climate and landscape) on the connectivity of the runoff generation process:

" In terms of categorical attributions, the explainable machine learning reveals that climate-related attributes account for a substantial portion of the cross-catchment variability in RC , RI and RE , suggesting that climatic water - energy availability acts as a first-order constraint on long-term runoff-generation connectivity at the global scale, while landscape characteristics (e.g., topography, soils and land cover) exert potentially region-specific regulatory effects. This finding is consistent with previous large-sample research on the dominant role of climate attributes in runoff generation processes (Jehn et al., 2020). "

12. Similarly, L370, the jump to flood risk is not understood. Please clarify what is meant by floods and flood risks here... for e.g. an overflowing river in amazon might be called flooded but does it also necessarily represent risk?

Response: Thanks for your kind question. We agree that the flood risk is inappropriate, and have changed the meaning of *RE* to the potential for flood generation:

"By analysing long-term trends of the runoff generation connectivity indicators for runoff generation over 1950–2020, we identified several hotspots (Fig. 5). The increasing connectivity brings larger event runoff volumes and higher peak discharges, and thus causes a greater **potential for flood generation**. In contrast, the decreasing trends in runoff generation connectivity are found in western North America and the Mediterranean, which might be attributed to the reduction of total precipitation and enhanced evaporation. Thus, there are drier soils, lower runoff coefficients, and weaker runoff intensity, and consequently a reduction in average **potential for flood generation**."