Response to Reviewer 1

This study investigates hydrological connectivity at the global scale using an index of runoff efficiency (RE), which combines the runoff coefficient (RC) and runoff intensity (RI). The authors identify distinct spatial patterns in RC, RI, and RE, including relatively high RC values in wet regions and high RI values in dry regions, and further suggest that these spatial variations are primarily controlled by climatic factors. The manuscript also shows that hydrological connectivity, as represented by RE, responds nonlinearly to precipitation intensity. This is a very interesting idea, as it attempts to represent the complex hydrological concept of connectivity with a simple integrated index. However, I am not fully convinced by the way the manuscript links RE to the definition of connectivity, nor by the physical interpretation given to changes in RE. In particular, while RE may be a useful response-based metric, its relationship to hydrological connectivity as a broader process concept is not yet sufficiently justified. Given these concerns, I recommend that the manuscript be considered for publication only after the issues detailed in the comments below have been adequately addressed.

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. In the review about concepts of hydrological connectivity, Bracken et. al. (2013,10.1016/j.earscirev.2013.02.001) highlight the broad and multi-dimensional nature of hydrological connectivity. I agree that the authors aim to use the combination of RC and RI to represent the ratio and rate of the transfer process. However, RE cannot fully represent the broader concept of connectivity. For example, hydrological connectivity may also be defined in terms of spatial soil-moisture patterns or the connection state of subsurface flow systems, and these aspects cannot be captured by RE alone. I therefore recommend that the authors explore the introduction more on concepts of connectivity and better understand why RE can be one of the proxies for representing the connectivity. At present, the Introduction places too much emphasis on the limitations of RC studies.

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. In addition, we added the concept and significance of runoff intensity (*RI*) in the last paragraph, and further explained that *RE* comprehensively represents the concept of connectivity in this runoff generation process:

"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)" (Lines 24-31)

"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*)." (Lines 80-86)

2. I do not fully understand the reason for including a hydrological model in the overall framework. The manuscript already derives quickflow through baseflow separation, which appears sufficient for the subsequent analyses. Although the authors state that the model is intended to represent interception and infiltration processes, these processes are not explicitly incorporated into the later analyses, nor are their effects quantified or discussed in a meaningful way. In addition, the event identification procedure does not seem to make use of the modeled rainfall–runoff relationship itself (e.g., the contribution of rainfall to the runoff in each step); instead, runoff events are first identified from the quickflow series and then matched to rainfall events based on timing. This makes the hydrological model useless in the framework, while introducing additional structural uncertainty.

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. To obtain the connectivity indicators for runoff generation, we first derive the quickflow through baseflow separation, and then the conceptual hydrological model is constructed to simulate the quickflow generation process (Lines 93-95). Specifically, the conceptual hydrological model can calculate the event runoff depth *R* and the corresponding runoff generation duration Δt_R (i.e., the net-rainfall duration), defined as the time during which $R > 0$ within an event, distinct from the event rainfall period (Lines 160-164). Only using derived quickflow through baseflow separation without hydrological simulation cannot calculate the transformation rate indicator *RI*, defined as $R/\Delta t_R$.

3. Furthermore, I think the model structure is not correct. In Formula 4, INF is proportional to SM. In other words, more wet soil leads to more infiltration. Is this correct? I therefore recommend that the authors either (1) use the quickflow estimated directly from baseflow separation and remove the model-based quickflow from the framework, or (2) improve the hydrological model and more fully justify the use of the model by explicitly identifying the events based on the model-derived rainfall–runoff process and by quantifying how interception and infiltration influence the results.

Response: Thanks for your kind question. We have corrected the INF formula as $\boldsymbol{INF = f_{max} * SM^{-b}}$. Similar to our previous reply, we first derive the quickflow through baseflow separation, and then the conceptual hydrological model is constructed to simulate the quickflow generation process. The conceptual hydrological model conceptually accounts for the effects of interception and infiltration in a simplified manner (Lines 107-110), aiming to calculate the event runoff depth *R* and the corresponding runoff generation duration Δt_R (i.e., the net-rainfall duration) (Lines 160-164). 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 (Lines 237-239). We also supplemented the shortcomings related to the model in the discussion section:

"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)" (Lines 464-469)

4. I do not agree with the way the authors link RE, connectivity, and flood risk in the manuscript. In particular, the term flood risk is not used precisely. Flood risk is generally understood as a function of hazard, exposure, and vulnerability, whereas RE cannot quantify all components of that relationship. Instead, I would suggest linking high RE to an increased likelihood of flood generation, rather than to flood risk itself.

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 (Lines 18, 170, 334, 335, 415, 419, 422, 504, 506).

5. I agree with the authors that RE reflects a trade-off between RC and RI at the long-term timescale. However, this also highlights a potential limitation of RE as a representation of connectivity. For example, do two regions with the same RE value—one characterized by very high RI and very low RC, and the other by moderate values of both RI and RC—actually exhibit the same hydrological connectivity? If not, it remains unclear how RE can serve as a robust proxy for connectivity.

Response: Thanks for your kind question. We have added the potential limitation of *RE* as a representation of connectivity in the discussion part:

"Moreover, it should be noted that the *RE* is an integrated connectivity indicator for runoff generation, and a given *RE* value can result from different combinations of *RC* and *RI*. For instance, a high *RE* may stem from a scenario of high *RC* and low *RI*, or, conversely, from a scenario of low *RC* paired with exceptionally high *RI*. This multiplicity of pathways highlights that *RE* is not determined by a single factor but emerges from the nonlinear integration of catchment-specific connectivity and infiltration processes. It is necessary to comprehensively use these indicators for characterising the connectivity of the runoff generation to improve our understanding of how the water cycle responds to the changing climate from a process perspective." (Lines 457-463)

6. I wonder how the authors manage the uneven distribution of data points across regions and climate zones. What is the influence of data availability on the analysis? Can it cause bias of the conclusion?

Response: Thanks for your kind question. Because the selected 6603 catchments are unevenly distributed across regions and climate zones, we used median values for group-level comparisons to reduce the influence of unequal sample sizes and outliers. Each IPCC region must have at least 30 available sites to ensure regional representativeness (Lines 246-248). We also clarified in the manuscript that data availability may still affect the representativeness of under-sampled regions and may introduce uncertainty in regional comparisons, although we do not expect it to change the main conclusions at the climate-zone level. We have provided relevant supplements to this point in the results and discussions:

"Given the uneven spatial distribution of catchments across regions and climate zones, median values are adopted for group-level comparisons to mitigate the influence of unequal sample sizes and outliers." (Lines 263-265)

"Second, the selected catchments exhibit uneven spatial distribution across regions and climate zones, a limitation that could undermine the representativeness of data-sparse areas. Although median-based summaries can reduce the effects of uneven spatial distribution, interpretation of the regional results from these underrepresented areas should be cautious. More data from the available hydrological stations would enable more refined and robust regional analyses." (Lines 469-473)

Specific comments:
7. Line 32: Ombadi eta al. (2023) does not state any findings about melting rate and snowpack dynamics

Response: Thanks for your kind question. We have deleted this literature and added references related to the content (Line 37).

8. Line 41: I don't think RC is a common indicator to quantify the process connectivity. For example, Phillips, et al. (2011, 10.1002/hyp.8123) shows distinct definitions of connectivity and runoff coefficient, although they are correlated.

Response: Thanks for your kind question. 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 (Lines 24-26). This study only focuses on the runoff generation process (*P*-*R*), distinguished from the channel routing process (Line 27). Thus, *RC* can serve as an indicator of the connectivity of the runoff generation process with respect to the transfer ratio (Lines 28-30), i.e., what fraction of precipitation becomes runoff (rather than being lost to evaporation or infiltration).
9. Line 76: add hypotheses or research questions in the last paragraph.

Response: Thanks for your kind question. We have added the research questions in the last paragraph.

"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? " (Lines 86-90)

10. Line 200: the explanation of event-to-event variability analysis is not clear; Why the authors used 10 mm/day as a criterion, rather than other rainfall intensity values.

Response: Thanks for your kind question. We have elaborated on the explanation of event-to-event variability analysis and provided the reason for 10mm/day:

"To analyze the event-to-event variability of process connectivity indicators, we first examine the variations of the indicators across events that are grouped by distinct discharge quantile intervals (0-20th, 20-40th, 40-60th, 60-80th, and 80-100th percentiles) for each catchment." (Lines 217-219)

"In alignment with standard engineering hydrology practice, where unit hydrographs are universally defined using 10 mm of effective rainfall, a unit precipitation of 10 mm is adopted (Lu et al., 2015; Singh et al., 2014)." (Lines 225-227)

11. Line 296: typo. Transformation ratio (i.e., runoff coefficient)

Response: Thanks for your kind question. We have corrected.

"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."(Lines 324-327)

12. Figure 4: I recommend including "slope" in the analysis. "Slope" has been widely recognized as an important factor in the concept of hydrological connectivity. In addition, I wonder why "area" was included in the random forest analysis, given that both RI and RC are already normalized by area.

Response: Thanks for your kind question. We apologize for the previous incorrect description of our variables. We include the slope variable as the "slp_dg_sav" for analysis in the revised version. In addition, we have removed the area variable in the revised version. Figure 4 and related descriptions have been revised (Lines 296-297; 301).

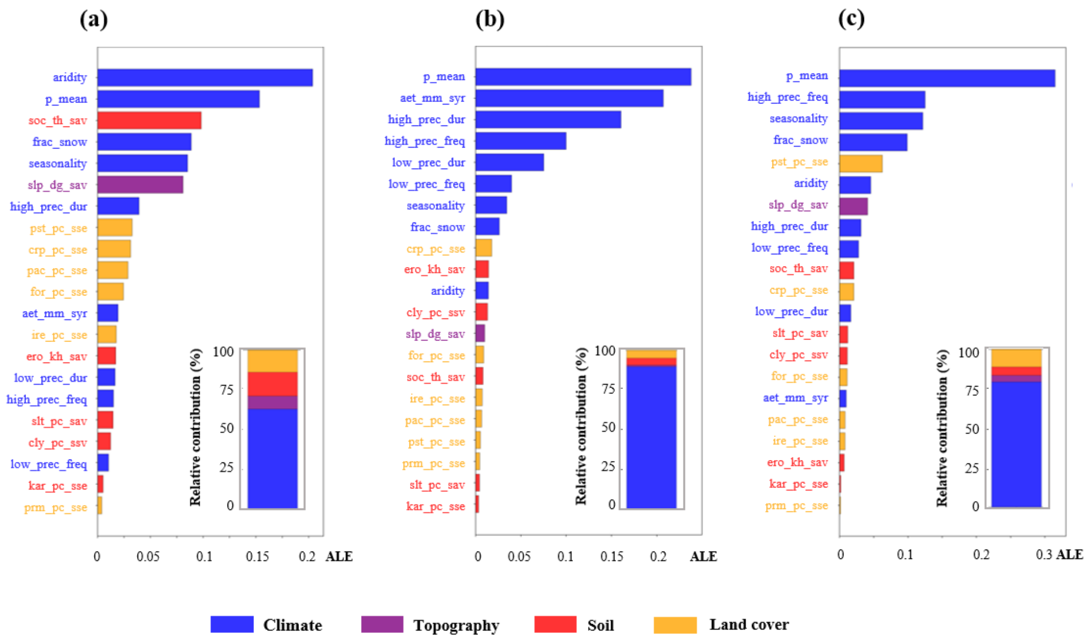

Figure 4. The Influence of catchment attributes on process connectivity indicators based on the interpretable machine learning approach (RF-ALE). (**a**) runoff coefficient. (**b**) runoff intensity. (**c**) runoff efficiency. Blue, purple, red, and yellow correspond to the categories of catchment attributes related to climate, topography, soil properties, and land cover, respectively. The proportional contribution of each category is illustrated by the bar height in the lower-right corner.

13. Figure 5: modify the y axis. Now this scale makes it hard to find the difference between the values.

Response: Thanks for your kind question. We have modified the scale size of Figure 5.

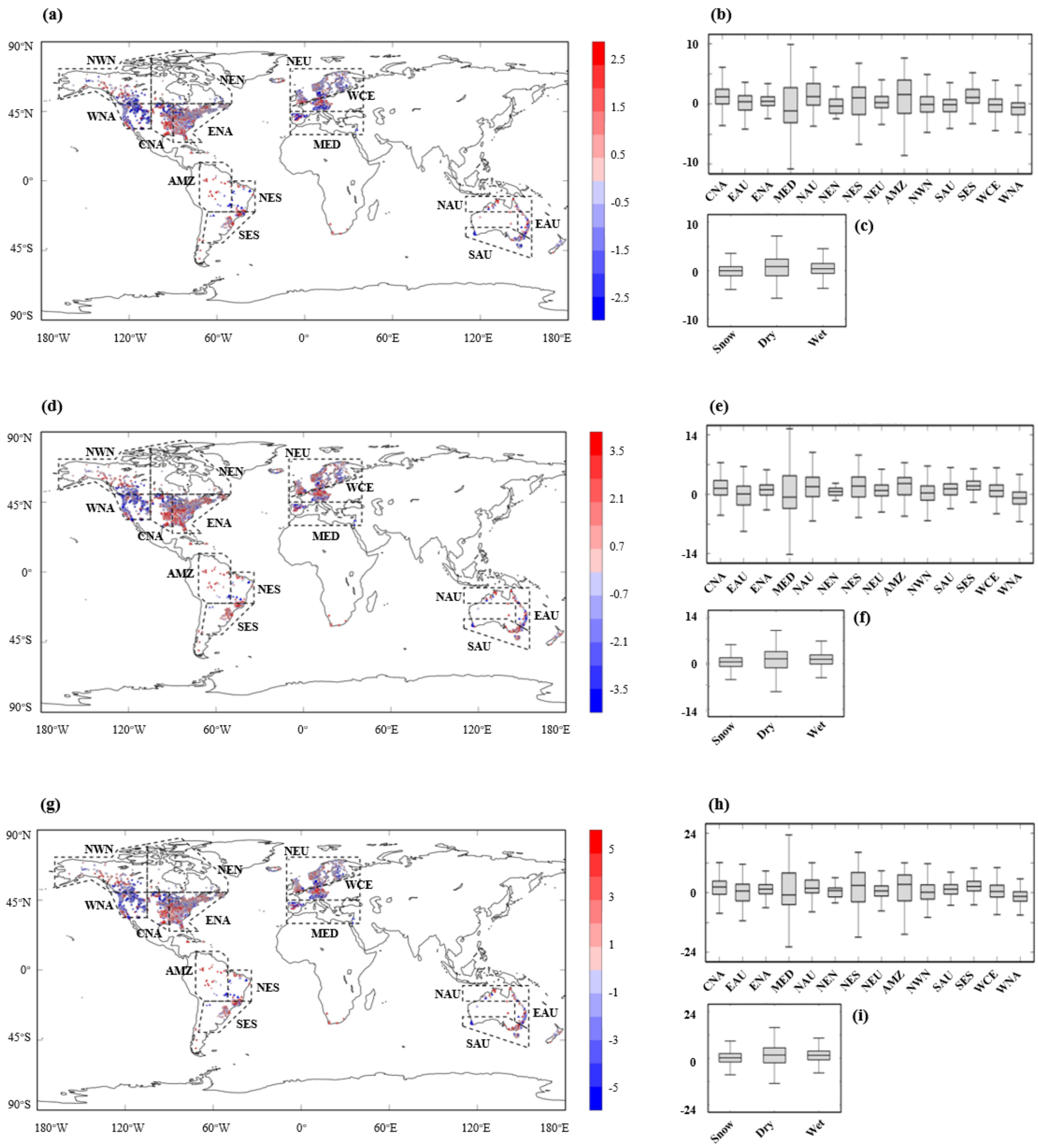

Figure 5. The long-term trends of the process connectivity indicators over 1950-2020. (**a-c**) for the runoff coefficient. (**d-f**) for the runoff intensity. (**g-i**) for the runoff efficiency

14. Line 417: There is no clear connection between the sentences before and after "However." The high sensitivity of RE to rainfall intensity is expected because both RC and RI are sensitive to rainfall intensity, and RE is the product of these two variables. However, this does not resolve the issue with RE arising from the trade-off between RC and RI.

Response: Thanks for your kind question. What we want to explain is that, in terms of long-term average spatial variability, *RE* shows *RC* dominance in wet areas and *RI* dominance in arid areas. For a specific catchment, the time variability of *RE* at the event scale exhibits a nonlinear response with precipitation intensity, which may lead to both high *RC* and high *RI*, resulting in a synergistic effect. We have revised the relevant statement (Lines 445-452):

"Besides, at the event scale, *RE* exhibits a strongly nonlinear response to meteorological forcing within a given catchment, particularly marked by a pronounced amplification with increasing precipitation intensity. Specifically, our analysis reveals that *RE* increases nonlinearly with the intensity of individual precipitation events, where high-intensity storms produce substantially greater *RE* values compared with low-intensity events (Fig. 7). Such behaviour is difficult to detect in long-term averages, where the effects of individual events with varying intensities are smoothed out over time**.** This nonlinear amplification indicates that, during heavy storms, **both the ratio and the rate of precipitation to runoff transformation increase simultaneously and substantially**. "

15. In addition to the influence of rainfall intensity on RE, total rainfall depth may also affect connectivity or RE. It is recommended to discuss whether saturation-excess runoff in wet catchments could influence connectivity, as well.

Response: Thanks for your kind question. We have added discussions on the effect of total rainfall depth on connectivity:

"Finally, the empirical power-law relationship developed here does not exactly account for event total precipitation depth and antecedent soil moisture, which can influence runoff-generation connectivity by governing storage filling and the expansion of saturated contributing areas, particularly in wet catchments where saturation-excess runoff is more prevalent. " (Lines 481-484)

Response to Reviewer 2

Liang et al. assess rainfall-runoff relationships at the global scale by introducing a composite metric "runoff efficiency" (RE), defined as the product of runoff coefficient (RC) and runoff intensity (RI). They find that while the three indicators differ in magnitude across different regions, they are primarily controlled by climate attributes at the global scale. In addition, the authors implement a power law relation between RE and precipitation intensity, with its parameters varying for different climates. While the proposed approach is quite interesting, I would like to raise some critical points and general comments for the authors to consider before proceeding with the manuscript's publication process.

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.

Major comments

1. I do not fully understand the reason for setting up a hydrological model as described in section 3.1.1., especially since the simulations obtained with the model are not used later on in the analysis? The parametrization of the model introduces additional uncertainty, and I do not believe that its use can be justified only to exclude catchments with a KGE < 0.5. The data described in section 3 has additionally been quality-checked as indicated by the authors, so why not focus on these data and, if necessary, interpolate between the gaps (maybe set a lower threshold of, e.g., 5 days to reduce interpolation time span)

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. To obtain the connectivity indicators for runoff generation, we first derive the quickflow through baseflow separation, and then the conceptual hydrological model is constructed to simulate the quickflow generation process (Lines 93-95). Specifically, the conceptual hydrological model can calculate the event runoff depth R and the corresponding runoff generation duration Δt_R (i.e., the net-rainfall duration), defined as the time during which $R > 0$ within an event, distinct from the event rainfall period (Lines 160-164). Only using derived quickflow through baseflow separation without hydrological simulation cannot calculate the transformation rate indicator RI, defined as $R/\Delta t_R$.

Besides, 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 (Line 239). The setting of a maximum missing measurement threshold of 10 days instead of a lower threshold (such as 5 days) is to utilize as many catchments as possible for sample size analysis. The 10-day threshold can also be found in previous large sample research (Han et al., 2020). (Lines 235-237)

2. While the idea of introducing a metric “RE” that reflects runoff intensity (RI) and transformation depth (RC) is interesting, I do not agree with the implications the authors attribute to RE. As far as I understand, a higher RE does not automatically imply “a larger fraction that is transformed to runoff with a faster rate for a given precipitation input” (L153). RC can be large while RI can be small, and the other way around, both resulting in the same RE. In the revised version of the manuscript, I would encourage the authors to explicitly explain these characteristics (and thus possible implications) of RE.

Response: Thanks for your kind question. We agree that a higher *RE* does not automatically imply “a larger fraction that is transformed to runoff with a faster rate for a given precipitation input". We use *RE* as a comprehensive indicator of the connectivity for the runoff generation process. The spatial variability of *RE* at the multi-year mean scale is reflected in the competition between *RC* and *RI*, with *RE* dominating in wet areas and *RI* dominating in dry areas (Lines 441-445). However, for the temporal variability of *RE*, the *RC* and *RI* show synergy, meaning that regions with a higher transformation ratio may simultaneously mean a faster transformation rate under climate change (Lines 445-452).

We further added relevant discussions on the characteristics of *RE* in the discussion:

" Moreover, it should be noted that the *RE* is an integrated connectivity indicator for runoff generation, and a given *RE* value can result from different combinations of *RC* and *RI*. For instance, a high *RE* may stem from a scenario of high *RC* and low *RI,* or, conversely, from a scenario of low *RC* paired with exceptionally high *RI*. This multiplicity of pathways highlights that *RE* is not determined by a single factor but emerges from the nonlinear integration of catchment-specific connectivity and infiltration processes. It is necessary to comprehensively use these indicators for characterising the connectivity of the runoff generation to improve our understanding of how the water cycle responds to the changing climate from a process perspective." (Lines 457-463).

3. Based on their analysis of catchment attributes influencing the above-mentioned metrics of RC, RI, and RE, the authors find that climate attributes exert strong influence on all metrics. Given the large, inherent climate gradients in global datasets, these gradients may overwrite differences in physical catchment properties, e.g., in terms of soil types or geology. This is especially relevant since many field-based studies emphasize the importance of catchment properties in runoff processes (e.g., Tromp-van Meerveld & McDonnell, 2006). I would recommend to at least discuss this issue in the revised version of the manuscript, including appropriate references of both large-scale and field-based studies.

Response: Thanks for your kind question. We have added this issue to the discussion part:

" 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). It is also important to note that the strong climate gradients inherent in global datasets may mask subtler (yet process-relevant) controls from soils and geology characteristics that are frequently emphasized in field-based studies on the connectivity of the runoff generation process (Tromp-Van Meerveld and Mcdonnell, 2006). " (Lines 399-407)

4. In my view, the authors usages of the terms "process connectivity" and "flood risk" may be misleading. With regard to the first term, "connectivity" can occur at different spatial scales. At the catchment scale, it may refer to the hillslope-riparian connectivity of different flow paths leading to the catchment's outlet. In that sense, I do not see how the authors' suggested metrics reflect hydrological connectivity; for example, a large RC does not automatically imply fully established connectivity within a catchment - one would need additional information (e.g., spatially distributed soil moisture measurement) to support this hypothesis. With regard to the second term, I do not see how "flood risk" can be quantified by simply looking at the runoff metrics. The authors are encouraged to revise (or omit) the use of the two terms in the revised manuscript.

Response: Thanks for your kind questions. We have 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. Thus, RC can serve as an indicator of the connectivity of the runoff generation process with respect to the transfer ratio, i.e., what fraction of precipitation becomes runoff (rather than being lost to evaporation or infiltration)：

" 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)" (Lines 24-31)

For the second question, we agree that the term "flood risk" may be misleading. The higher RE value may imply a larger proportion of precipitation is transformed into runoff at a faster rate within an event. It is typically associated with a larger event runoff volume and higher peak discharge, and thus a greater potential for flood generation (Lines 169-171). Thus, we change it into "the potential for flood generation" (Lines 18, 170, 334, 335, 415, 419, 422, 504, 506). Thanks again for your questions.

5. While results obtained in snow-dominated regions are still described in the results section, they are almost entirely omitted in the discussion section. For a complete picture, it would be beneficial

to include these results into the discussion as well. On the other hand, other parts of the discussion (e.g., L 414-431) are excessively long and may be shortened.

Response: Thanks for your kind question. We have added discussions on snow-dominated regions and shortened other parts.
" It is worth highlighting that snow-dominated catchments exhibit the highest multi-year mean *RC*, which is likely attributed to the generally lower evaporative losses and the reduced infiltration capacity in frozen or near-saturated soils (Lundberg et al., 2016). This finding is further supported by the importance of snow fraction in explaining spatial *RC* variations (Fig. 4a)." (Lines 391-394)

Line by line comments

6. L 15-21: I would recommend to start with a summary of both long-term and event-based analysis for the different regions (wet, dry, snow), followed by the implications of the findings to conclude the abstract.

Response: Thanks for your kind question. The order in which we explain the spatiotemporal variations of connectivity indicators is (1) the spatial patterns of the multi-year average and the influencing factors, (2) the long-term temporal changes, and (3) the event-scale variability. This order is in our methods and results.

We first examined the spatial patterns of the multi-year average, and found a relatively high *RC* and *RI* in wet and dry areas, respectively. Interpretable machine learning further reveals that climatic attributes primarily control the process connectivity globally. We then analyzed the long-term temporal changes and highlighted the hotspot IPCC regions. We finally analyzed the effect of precipitation intensity on *RE* at the event scale, and found a high sensitivity in dry climate zones. (Lines 12-19)

7. L 34-37: The authors may want to consider deleting this sentence, as I do not see how this is relevant to the present study.

Response: Thanks for your kind question. We have deleted these sentences.

8. L 44-46: Runoff coefficients have been analyzed on larger scales as well, e.g., Merz & Blöschl, 2009, Tarasova et al., 2018, Zheng et al., 2023

Response: Thanks for your kind question. We have corrected our expression to "Many previous studies concentrate on small scales" (Line 45), and supplemented the above references (Lines 62, 65).

9. L 60-62: Merge sentences

Response: Thanks for your kind question. We have merged sentences:

" In contrast, other large-sample studies conducted in the United Kingdom and Germany revealed that geological conditions and soil properties are key driving factors for the spatial variability of *RC* (Zheng et al., 2023b; Tarasova et al., 2018a) " (Lines 64-66)

10. L 75: This sentence is rather unspecific. In the previous sentences, the authors describe their analysis steps, but the aim(s) of the paper need to be stated more specifically.

Response: Thanks for your kind question. We have added the aim of the paper:

" **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*). " (Lines 79-86)

11. L 86: Should be "2.1 Quantification […]"?

Response: Thanks for your kind question. We have corrected the order number of the section. (Line 102)

12. L 96: Specifying that the model is applicable to snow-dominated catchments seems unnecessary.

Response: Thanks for your kind question. We have removed the relevant statements. (Lines 107-110)

13. L 134: Is the threshold of 0.1 mm d-1 set for all catchments globally? If so, it should be indicated somewhere.

Response: Thanks for your kind question. We have added the statement for the threshold of 0.1 mm d-1 set for all catchments:

" We then match each identified runoff event with contributing rainfall (including snowmelt) events. Rainfall (or snowmelt) events are defined as periods of rainfall that are separated by no-rainfall periods, with a distinguished threshold of 0.1 mm d^{-1} **for all catchments** to remove trace or inconsequential events (Wu et al., 2021). "(Lines 147-149)

14. L 207: In the data section, the temporal resolution of the data should be indicated.

Response: Thanks for your kind question. We have added the daily temporal resolution of the data. (Lines 230-233)

" The hydrological and meteorological data come from the Caravan large sample dataset (Färber et al., 2025; Kratzert et al., 2023), a comprehensive repository that systematically compiles **daily** time series and key catchment attribute information for more than 20,000 catchments across the globe. Specifically, **daily** observed discharge (*Q*) is sourced from gauge stations, while **daily** precipitation (*P*), temperature (*T*), soil moisture (*SM*), and snow water equivalent (*SWE*) are sourced from the ERA5-Land reanalysis dataset. "

15. L 288: Are the trends described in this section statistically significant? This information should be added somewhere, either in the text or in Figure 5.

Response: Thanks for your kind question. We only explored the long-term trends of all catchments from 1950 to 2020 based on the relative Sen slope, without conducting a separate significance analysis. (Line 314)

16. L 295- 298: The terms related to the "transformation rate" seem to have been mixed up here? Please check again.

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. "(Lines 324-327)

17. L 329-330: Here, it would be good to shortly repeat the meaning of parameter m in a more physically interpretable context (e.g., move sentence from L 335).

Response: Thanks for your kind question. We have moved the sentence from L 335 and shortly repeated the meaning of parameter *m*.

" The spatial distributions of the two fitted parameters RE_{10}, defined as the runoff efficiency under a unit precipitation intensity of 10mm/day, and *m*, representing the sensitivity of runoff efficiency to changes in precipitation intensity, are illustrated in Fig. 7. The regional statistical summaries for these parameters are provided in Table 2. For the parameter RE_{10} (Figs. 7a-c). "(Lines 360-363)

18. L 360-361: I do not fully understand this sentence. What exactly does "transfer of the temporal characteristics of precipitation" mean?

Response: Thanks for your kind question. We have rewritten this sentence.

" For the runoff intensity (*RI*), the dominant factors are the average duration and frequency of high-precipitation events, suggesting that shorter and/or more frequent intense precipitation events tend to generate more temporally concentrated runoff events with shorter Δt_R and consequently higher *RI* values." (Lines 394-396)

19. L 402-408: These sentences rather read like the first sentences of a conclusion. The authors may want to consider removing this part.

Response: Thanks for your kind question. We have removed this part.

20. L 447: The conclusions section rather reads like a summary of the results. What do the authors actually conclude based on their findings?

Response: Thanks for your kind question. We have added our conclusions based on the findings.

" According to the long-term average values of the metrics, we find a relatively high RC and RI in wet and dry areas, respectively, **highlighting a compensatory balance between the transformation ratio and rate across climates**. "(Lines 497-499)

"The analysis of long-term trends reveals a synergy of transformation ratio and rate, ……, **suggesting a larger event runoff volume and higher peak discharge, and thus a higher potential for flood generation**. "(Lines 501-504)

" We further establish an empirical power-law relationship between precipitation intensity and *RE* and find a high sensitivity under dry climates, **indicating the nonlinear amplification effect of runoff generation in water-limited regions during intense storm events**. Overall, **our proposed process-connectivity framework,** integrated both the **transformation ratio and rate** from precipitation to runoff, **offers a novel and multi-dimensional perspective to understand spatiotemporal variations in the runoff generation process.** And the framework allows for extension to other critical processes in the global hydrological cycle, including precipitation recycling and runoff routing dynamic processes. "(Lines 508-514)

Technical comments

21. The font sizes in almost all figures are too small and hard to read, especially the ones showing the global maps. It would be beneficial to adapt this in the revised version of the manuscript.

Response: Thanks for your kind question. The size of the global maps in Figures 3, 5, 6, and 7 has been enlarged.

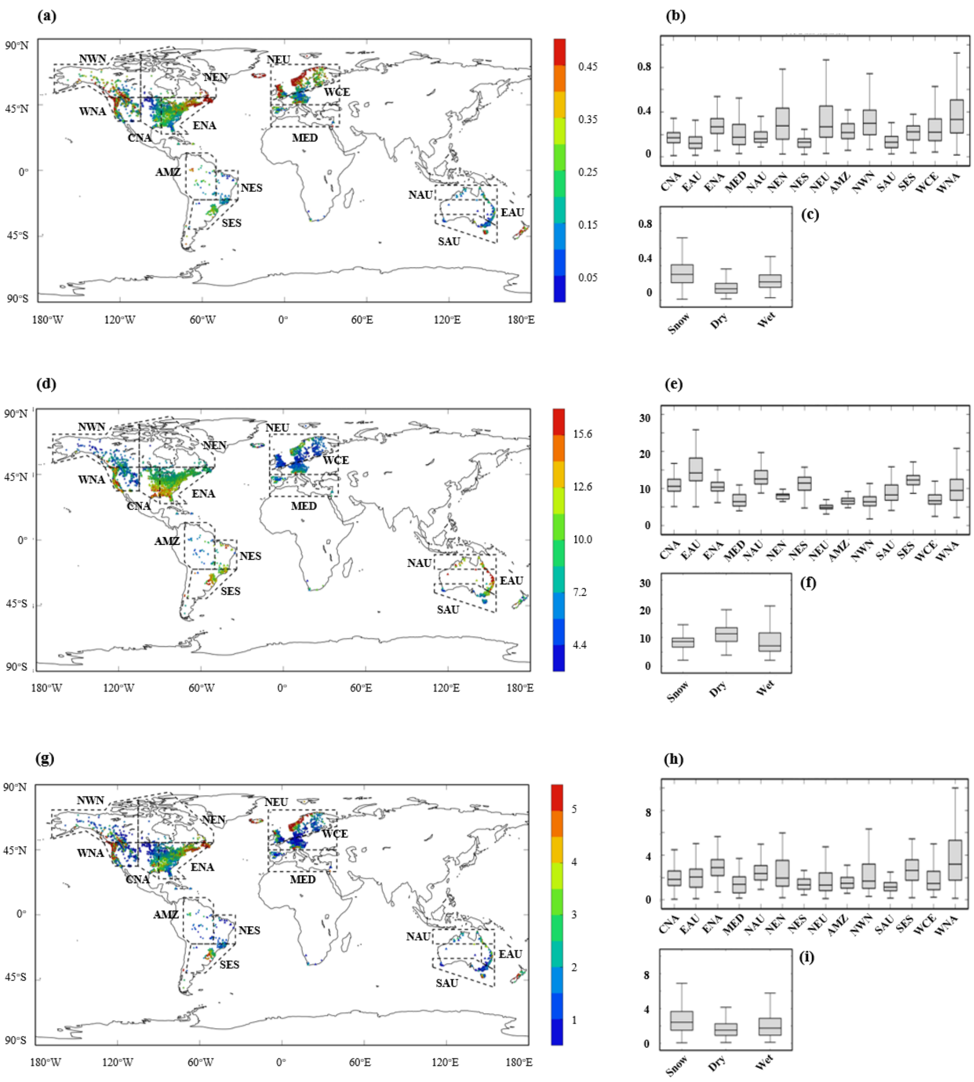

Figure 3. The spatial pattern for the multi-year average of the process connectivity indicators across the globe. (**a-c**) for the runoff coefficient. (**d-f**) for the runoff intensity. (**g-i**) for the runoff efficiency

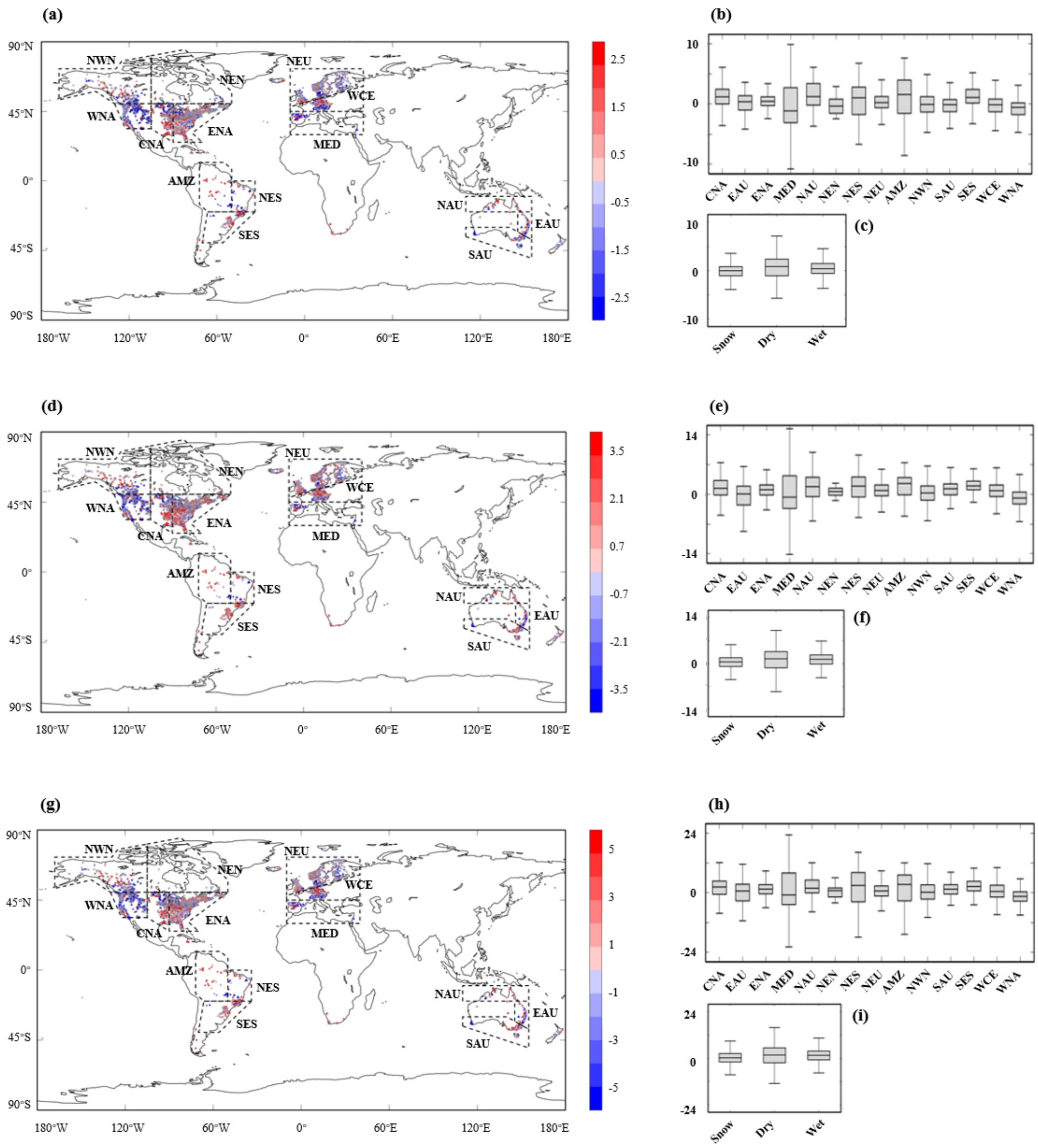

Figure 5. The long-term trends of the process connectivity indicators over 1950-2020. (**a-c**) for the runoff coefficient. (**d-f**) for the runoff intensity. (**g-i**) for the runoff efficiency.

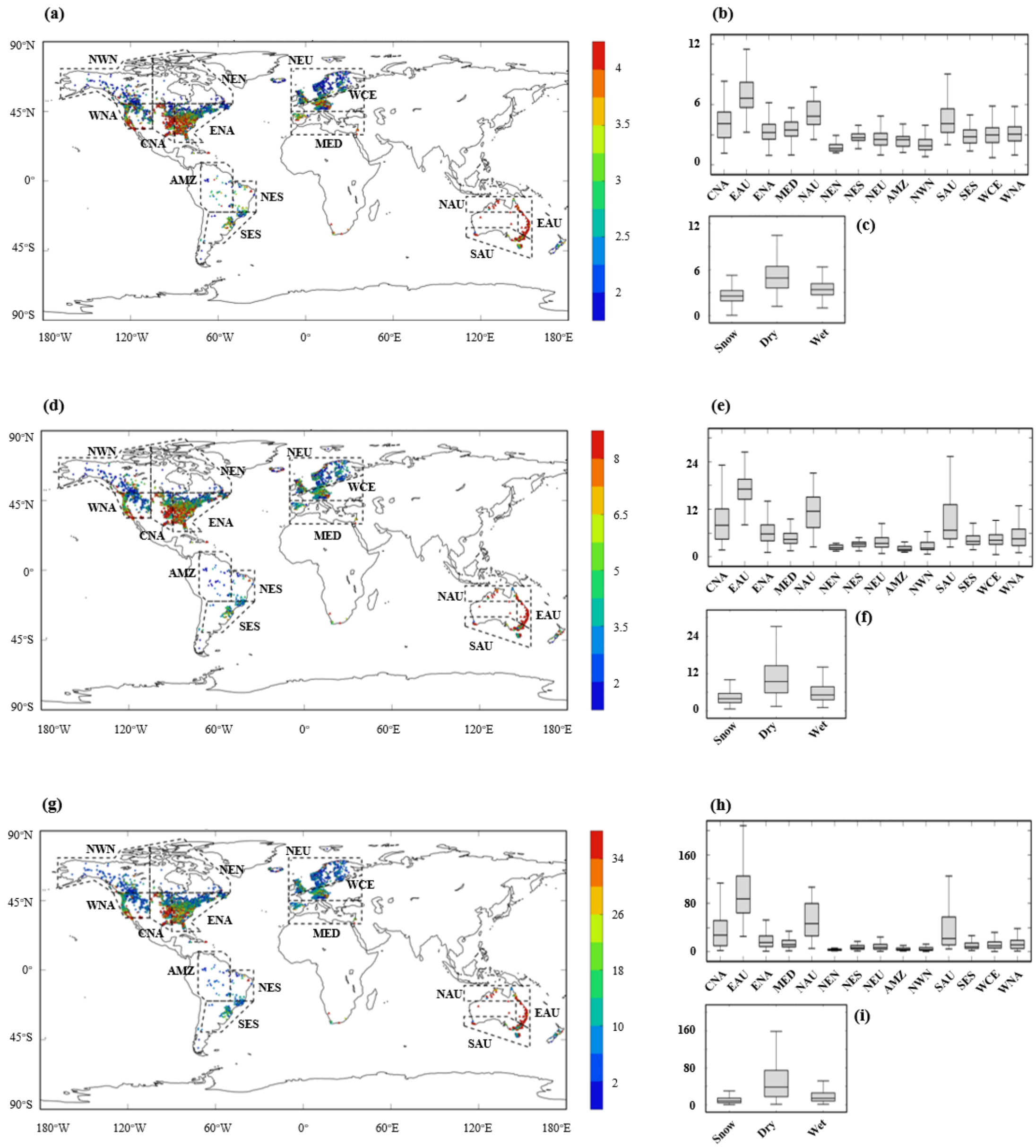

Figure 6. The fold-change in the connectivity indicators from the highest to the lowest peak-discharge quantile ranges, i.e., (80–100th percentile)/ (0–20th percentile). (**a-c**) for the runoff coefficient. (**d-f**) for the runoff intensity. (**g-i**) for the runoff efficiency.

22. Table 2: It would be interesting to transform this table into a figure (for the supplement) of, e.g., boxplots per regions, where each catchment can actually be represented as a point.

Response: Thanks for your kind question. Fig.7b,7e, and S10b are the boxplots per regions corresponding to Table 2.

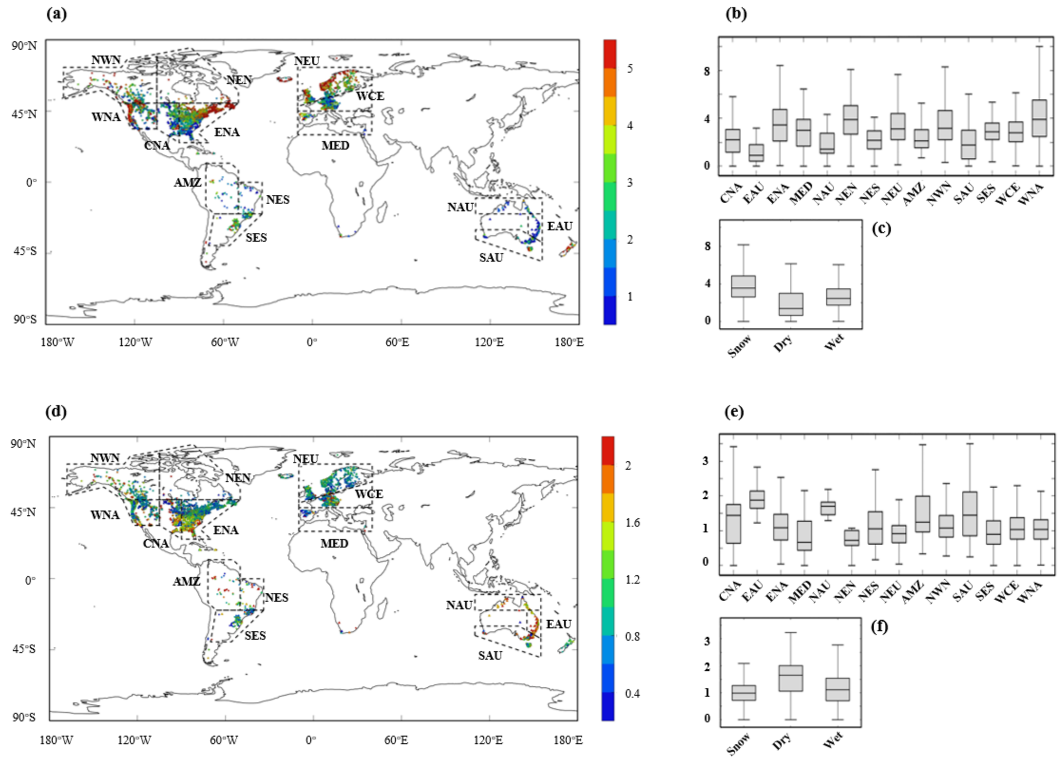

Figure 7. The spatial pattern of parameters of the power-law relationships between precipitation intensity and runoff efficiency. (**a-c**) for the parameter RE_{10}. (**d-f**) for the parameter *m*.

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.** " (Lines 24-41)

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)" (Lines 45-49)

"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." (Lines 67-74)

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?** "(Lines 78-90)

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 (Line 239). 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 (Lines 464-469):

"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 quikflow 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 (Lines 93-95):

" 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." (Lines 473-481)

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 (Line 149). 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 (Lines 262-263; 481). Moreover, our regional analysis based on the median values of each group could further minimize the impact of extreme values (Lines 263-265).

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 (Line 239), which minimizes the interference of reservoirs.

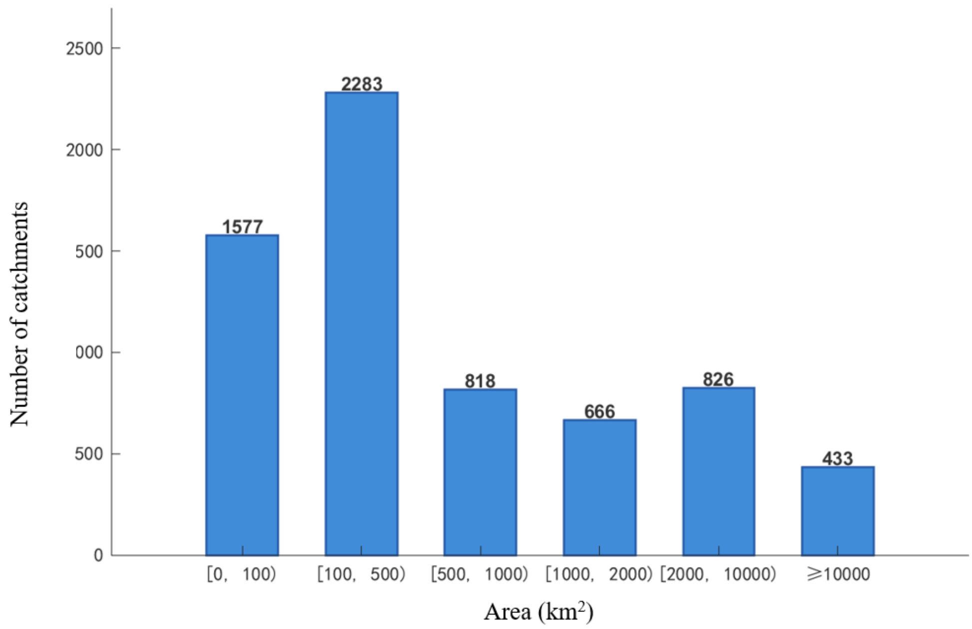

Figure S1. Distribution of the area of 6603 catchments for analysis.

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. "(Lines 324-327)

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.

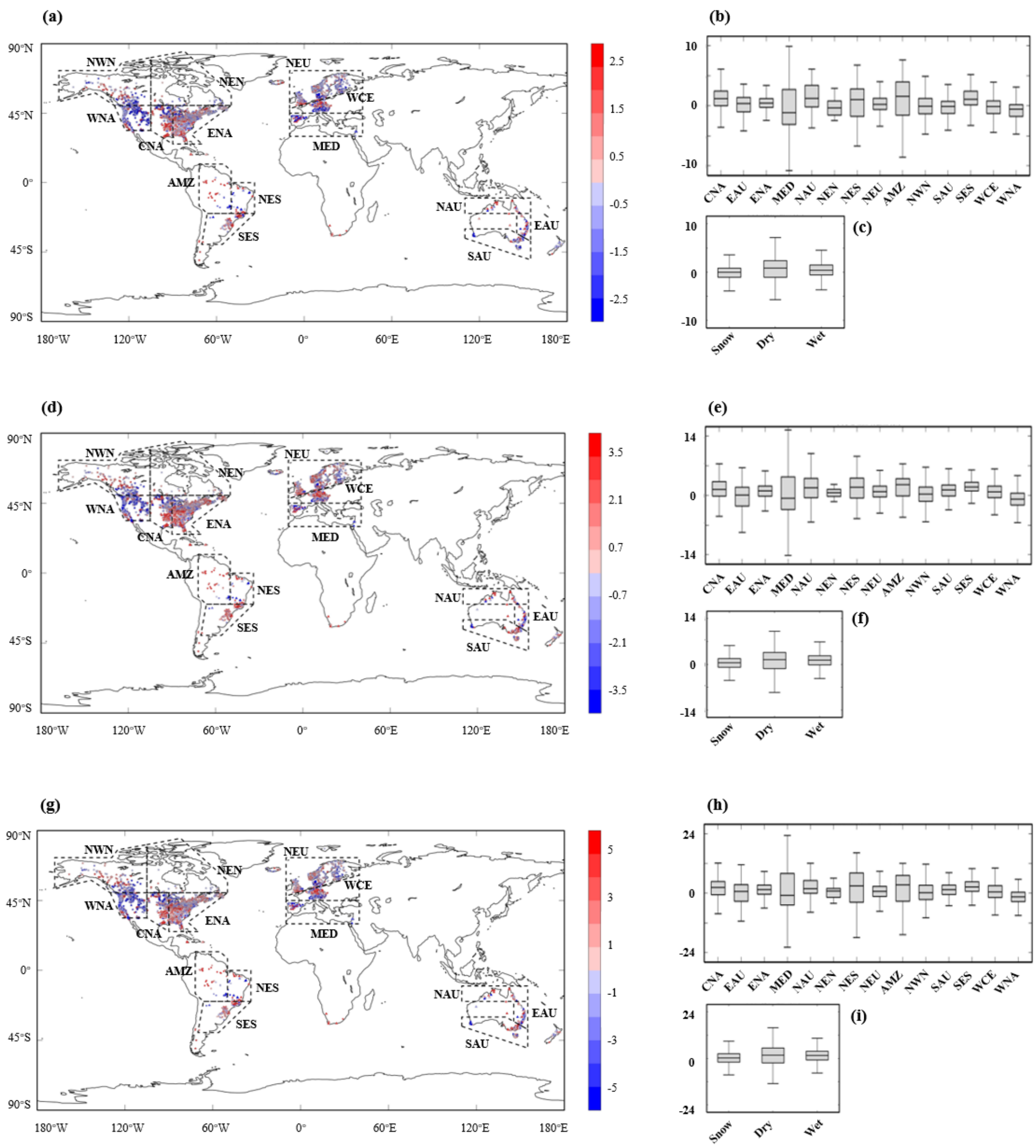

Figure 5. The long-term trends of the process connectivity indicators over 1950-2020. (**a-c**) for the runoff coefficient. (**d-f**) for the runoff intensity. (**g-i**) for the runoff efficiency.

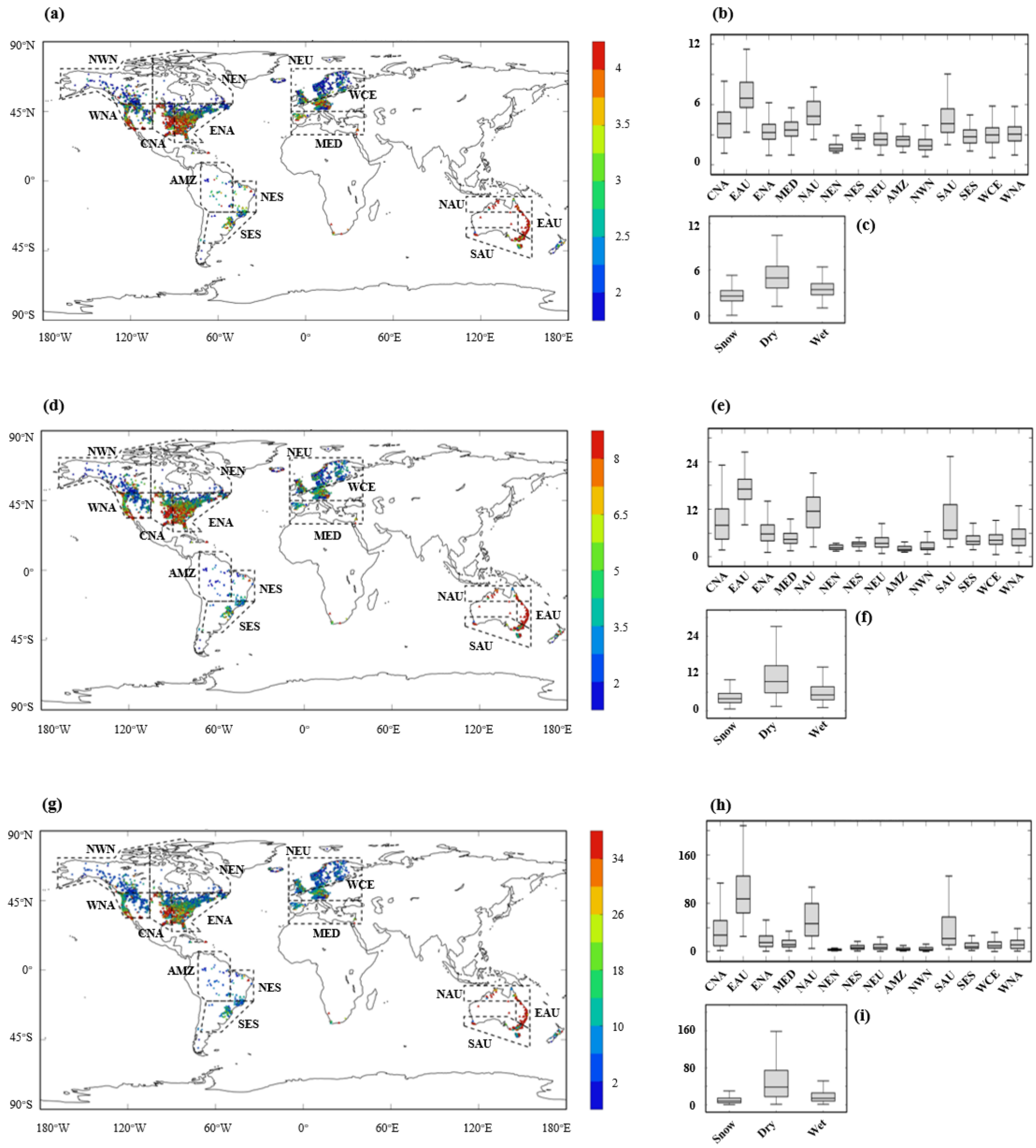

Figure 6. The fold-change in the connectivity indicators from the highest to the lowest peak-discharge quantile ranges, i.e., (80–100th percentile)/ (0–20th percentile). (**a-c**) for the runoff coefficient. (**d-f**) for the runoff intensity. (**g-i**) for the runoff efficiency.

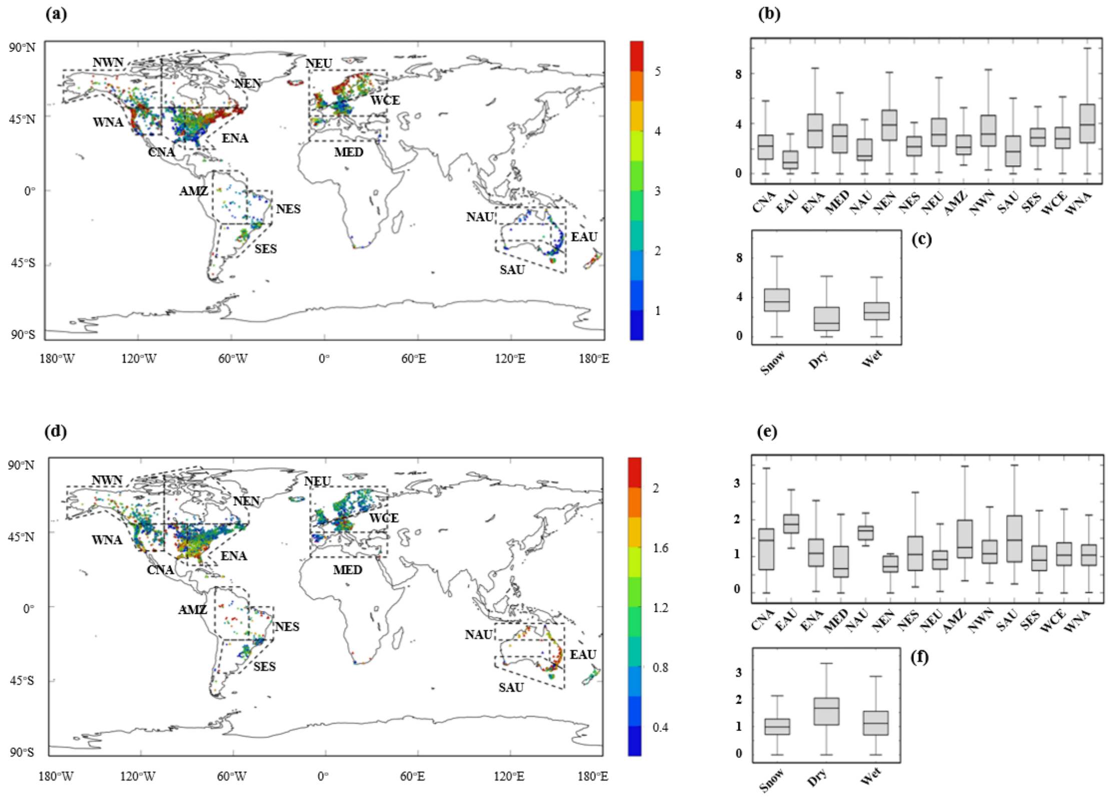

Figure 7. The spatial pattern of parameters of the power-law relationships between precipitation intensity and runoff efficiency. (**a-c**) for the parameter RE_{10}. (**d-f**) for the parameter *m*.

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 (Lines 399-404):

" 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 (Lines 408-419).

" 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.**"