

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. 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. 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. 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).

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. 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.

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."

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). "

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)."

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. Thus, we change it into "the potential for flood generation." 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)."

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.

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" , and supplemented the above references.

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). "

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*). "

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

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

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.

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). "

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.

" 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.

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. "

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). "

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."

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.** "

"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.** "

" 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. "

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.

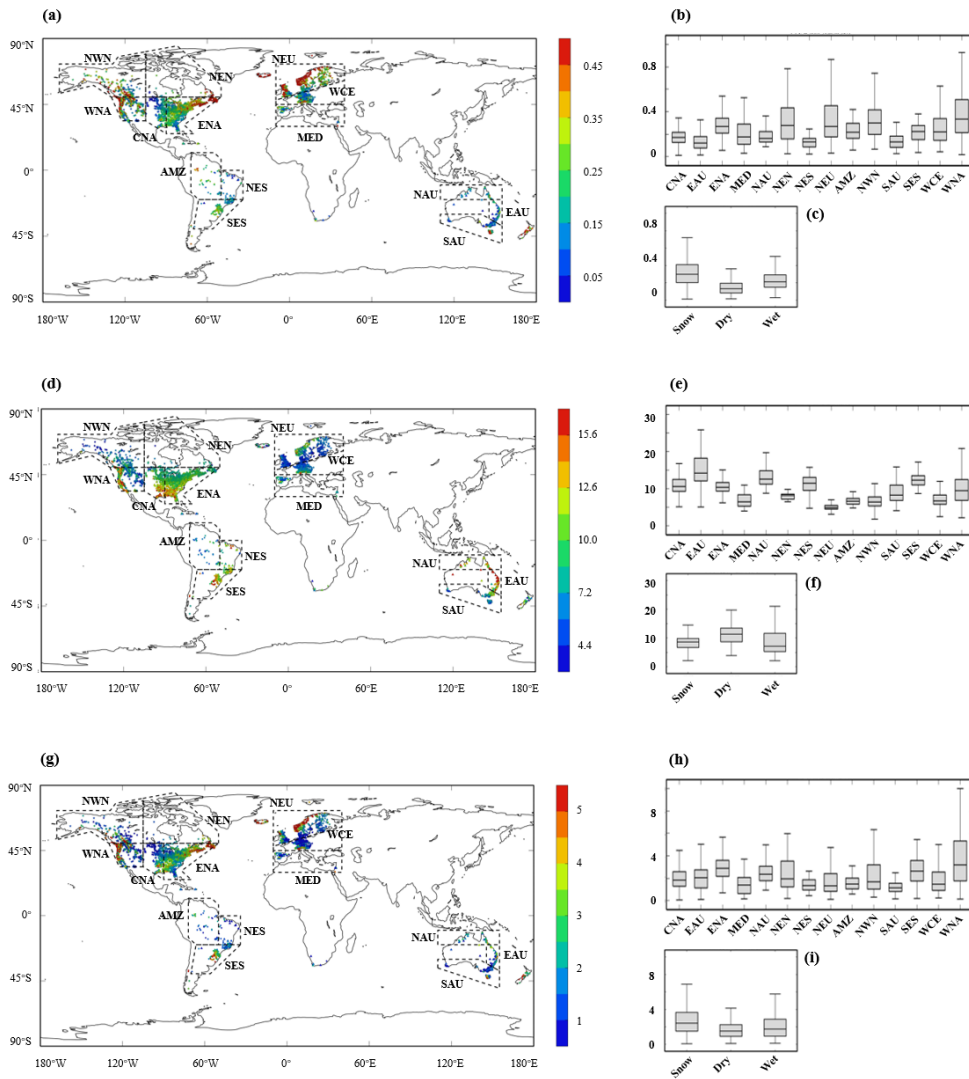


Figure 3. The spatial pattern for the multi-year average of the process connectivity indicators across the globe. (a-c) for the runoff coefficient. (d-f) for the runoff intensity. (g-i) for the runoff efficiency

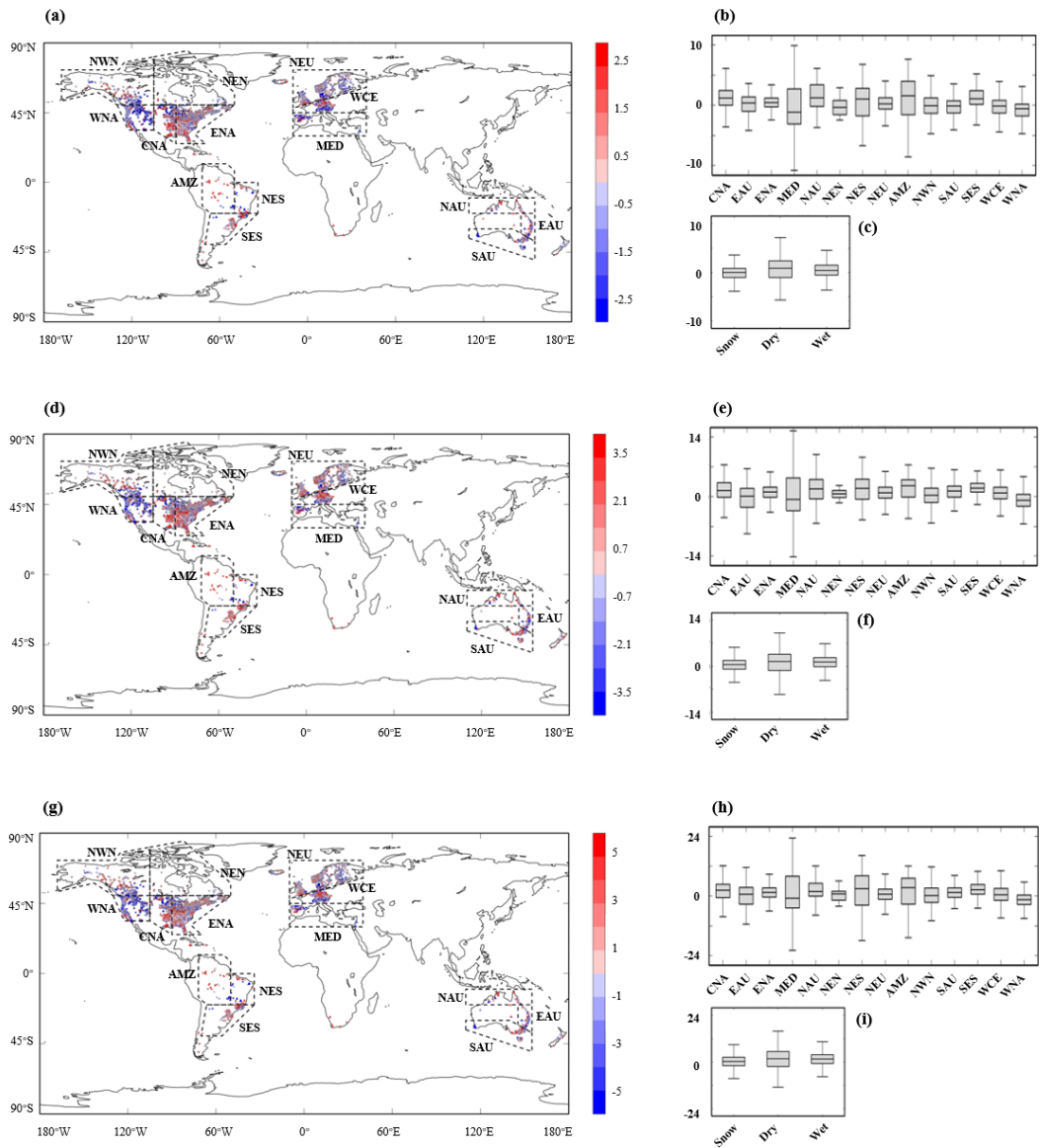


Figure 5. The long-term trends of the process connectivity indicators over 1950-2020. (a-c) for the runoff coefficient. (d-f) for the runoff intensity. (g-i) for the runoff efficiency.

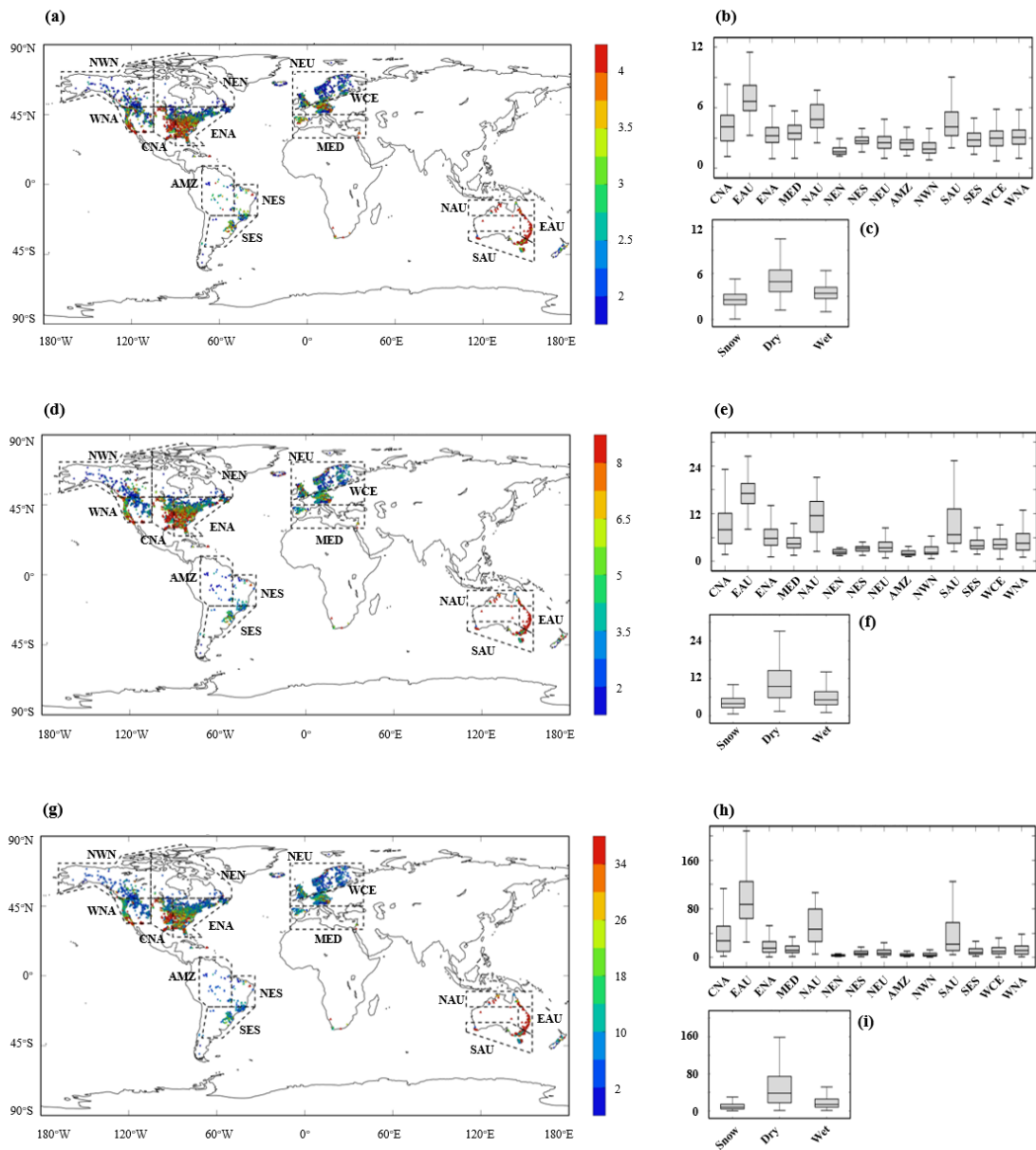


Figure 6. The fold-change in the connectivity indicators from the highest to the lowest peak-discharge quantile ranges, i.e., (80–100th percentile)/(0–20th percentile). (a-c) for the runoff coefficient. (d-f) for the runoff intensity. (g-i) for the runoff efficiency.

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.

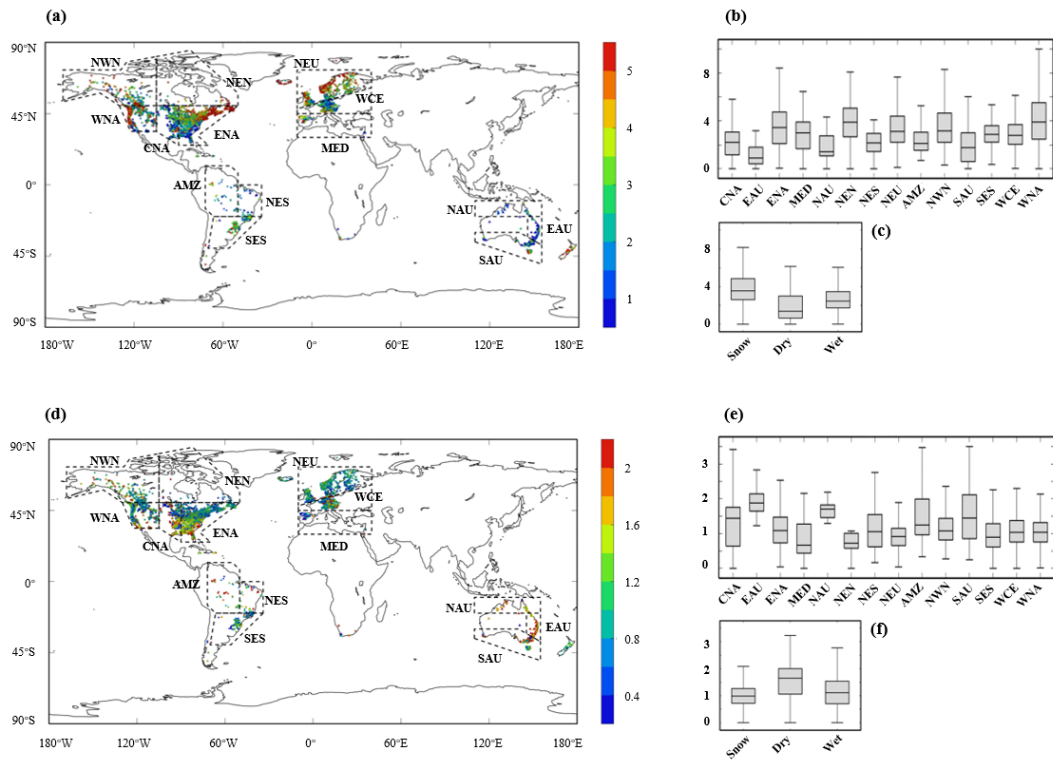


Figure 7. The spatial pattern of parameters of the power-law relationships between precipitation intensity and runoff efficiency. (a-c) for the parameter RE_{10} . (d-f) for the parameter m .