Author Response to Reviews of

Glacial runoff buffers droughts through the 21st century

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Earth System Dynamics Discussions

RC: ***Reviewer Comment***, AR: *Author Response*, ☐ Manuscript text

We thank the reviewers for their consideration throughout this process. Only one reviewer requested changes on the most recent version of the manuscript. We respond to each suggestion directly below, where necessary quoting excerpts of revised text. A revised manuscript with changes highlighted is attached

1. Anonymous Reviewer 1

Reviewer 1 did not participate in this round of review.

2. Reviewer 2, Caroline Clason

2.1. General comments

RC: ***No suggestions for revision - I would accept as it is.***

AR: *We thank the reviewer for her consideration.*

3. Reviewer 3, Sarah Hanus

3.1. Overview

RC: ***Thank you for submitting the revised version of your manuscript. All my minor comments were well addressed. However, some clarifications regarding my comments referring to the methodological limitations / uncertainties are still needed.***

3.2. Basin-averaged precipitation

RC: ***The authors explain that they perform an area-weighted sum of the variables from each GCM over the grid cells in the basin and thus the previous assumption "Our modified SPEI calculation assumes that both precipitation and glacial runoff are distributed evenly across the drainage basin..." does not hold anymore. Can you clarify this? Does an area-weighted sum mean that you weighted the precipitation output of each GCM grid cell in the respective basin by the area of the corresponding grid cell? And the sum gives the mean precipitation of a basin? However, in Equation 1 a fraction of the total precipitation in the basin is replaced by the glacier runoff from Huss and Hock (2018). If I understood your explanation correctly, my first comment remains: There is the possibility of an increased moisture source term in the modified SPEI that does not stem from glacier runoff but from the methodological limitation. This might be the case if glaciers are located in a rather wet part of the basin, e.g. Amu Darya basin (see the toy example in the previous comment). If you would want to circumvent this limitation, you would have to subtract the glacier area fraction from the precipitation amounts of the actual grid cells where glaciers are located and not from the basin-averaged precipitation.***

I do not expect you to change this methodology, as this might only very slightly impact the results, but I expect some discussion of this potential limitation similar to the discussion of the precipitation correction factor. An example quantification of whether this methodological limitation affects the main results of your study would be helpful to understand it. This quantification could be combined with the following comment as both methodological limitations likely lead to an increased moisture source term in the modified SPEI which does not relate to glacier runoff itself and could potentially affect the results regarding buffering of droughts by glacier runoff.

AR: *Thank you for clarifying this comment further. We agree that our method might overestimate the moisture source when glaciers are concentrated in the wettest parts of the basin, and we have conducted the sensitivity test of moisture overestimation in SPEI as suggested.*

We should mention that the area-weighted sum of GCM-derived variables gives the ***total*** *(not the mean) of each variable over the basin. The area-weighting multiplies the value at each grid cell by the percent of that grid cell that falls within the basin boundary. For example, consider a basin that covers 5 grid cells: one grid cell in the center is covered entirely, and the basin boundaries cross four adjacent grid cells such that only a portion of each is covered. Say the four adjacent cells are 40%, 30%, 20%, and 10% covered, respectively. Then the area-weighted sum of precipitation would be:*

$$P_{total} = P_1 + 0.4P_2 + 0.3P_3 + 0.2P_4 + 0.1P_5$$

and the corrected moisture source term would be:

$$\tilde{P} = \frac{A - A_g}{A} P_{total} + R$$

Because the area-weighting in the computation of P_{total} is per fraction of grid cell covered, rather than per fraction of basin covered, the arithmetic of assigning glacial runoff to a specific grid cell is less direct than the *toy model originally proposed. After puzzling about this for a while, though, we are convinced the reviewer is correct in saying that our method could still overestimate moisture. Please see new section B2.1. We have also added specific mention to the main text Discussion:*

> *Our offline computation method also comes with the caveat that it is likely to capture effects that are not strictly glacial. For example, in Equation 1, we scale the basin-total precipitation by the total non-glaciated area rather than scaling down precipitation from the specific GCM grid cells where glaciers are found. This methodological choice may tend to overestimate the moisture source term when glaciers are found in comparatively wet parts of a basin (see Section B2.1). Further, ...*

3.3. Precipitation correction factor

RC: ***The added paragraph to the discussion is well written and explains concisely and honestly the potential limitations. Thanks a lot! It also shows for one example basin how much the precipitation would increase assuming a default precipitation factor. What would still be needed to understand the implications of this limitation is the connection between the increase in precipitation and the changes in SPEI. The effect of an increase in precipitation on SPEI is not straightforward. The higher the potential evaporation, the larger the effect of increased precipitation on Di values (Eq. B1). Therefore, the effect will be larger in summer and if the basin is located in lower latitudes/altitudes, I assume. Then, to calculate the SPEI, the values are compared to the standardization set of SPEI. It is not clear to me how much the SPEI and your results would change if there would be a % increase in precipitation in the Cooper basin. I agree that it makes no sense to implement a precipitation correction for all basins in the manuscript. However, it is important to know that the methodological limitations have no significant effect on the results. Therefore, I suggest the authors follow their calculations of the results for two basins, given no glacier melt but an increase in precipitation. One good example would be the basin with the largest glaciation as suggested by the authors already, where the increase in precipitation would be largest. Another example could be a basin with high potential evapotranspiration, e.g. Indus basin (see Fig. 2 in Laghari et al, 2012) where a change in the moisture source term leads to larger Di values. It would be valuable to see if this increase in precipitation changes the SPEI and the amount of droughts / frequency of droughts or whether the results are robust to these methodological limitations.***

AR: *Thank you very much for this detailed suggestion. We have added extended discussion of both the precipitation correction and basin-total moisture overestimation in section B2.1 "Non-glacial effects deriving from our processing". We computed a new version of SPEI with a uniform scaling-up of precipitation by a factor of 1.5 in glaciated areas, which we have called "SPEI$_{PS}$". We compare SPEI$_{PS}$ to SPEI$_N$ and SPEI$_G$ in the new Figure B2 (ensemble mean SPEI over time) and Table B1 (buffering statistics).*

The suggested sensitivity test showed that SPEI$_{PS}$ did overlap with SPEI$_G$ in the Copper basin, and it did have fewer and less severe droughts than SPEI$_N$. However, the effect was readily distinguishable from the glacial drought buffering by difference in magnitude and temporal pattern. In the Rhone, Tarim, and Majes basins, the SPEI$_{PS}$ ensemble means were closer to SPEI$_N$ than to SPEI$_G$. In addition to the description in section B2.1, we have added the following to the main text Discussion:

> *A sensitivity analysis (Section B2.1; Table B1) indicates that non-glacial enhancement of the moisture source term in SPEI can produce strong drought buffering, but the effect is distinct from the drought buffering calculated from glacial runoff. More detailed analyses to partition the two effects will improve future forecasts of glacial drought buffering.*