Paper Review: Glacial runoff buffers droughts through the 21st century (Ultee et al.)

Overview

This paper investigates drought buffering by glacier runoff in the 21st century in 56 major river basins worldwide. Glacier runoff can be an important buffer to interannual variability in runoff. However, dynamic glacier runoffs are not included in GCMs and thus also neglected when calculating drought indices (e.g. SPEI). The authors modify the SPEI to consider glacier runoff as part of water accumulation. Using the SPEI, they calculate number and severity of drought events from 1980-2100 using 8 GCMS and RCP 4.5 and RCP 8.5. They compare differences of the modified SPEI including glacier runoff to normal SPEI. Moreover, they perform a correlation and clustering analysis to identify the explanatory variables for drought buffering by glacier runoff. The results suggest an increased water supply and a buffering of drought frequency and severity when accounting for glacier runoff. A large glaciated fraction and low historical precipitation lead to high drought buffering by glaciers as identified by the clustering analysis.

General comments

This is a very well-written paper focusing on the relevance of glacier runoff for future hydrological droughts worldwide. I enjoyed reading it because it is well structured, concisely written with self-explanatory headers, and it provides a novel analysis of importance of glaciers. I also appreciate the code and data availability including a Jupyter Notebook to reproduce the results.

Specific Comments

Methodological Limitations / Uncertainties

- In line 115 you mentioned an important assumption of your approach and claim that you will address this simplification below. However, I did not find where this assumption was further addressed in the discussion or elsewhere. Precipitation in mountain areas (where glaciers are located) tend to be larger than in the rest of the basin due to orographic precipitation, especially in basins, which are considerable arid further downstream (e.g. Amu Darya) (Immerzeel et al., 2020, Extended Data Fig.3a). Assuming an equal distribution of precipitation when calculating the modified moisture source term leads most likely to an overestimation of total precipitation in the basin. Thus, the moisture source term in SPEI will be increased, however this increase is an artefact of the method used and not due to including glacier melt. I miss a discussion about this limitation and how it might have influenced the results and conclusions. I would expect that the influence is larger in basins that are considerable drier in the lowlands than in the mountains.

  Below is a simplified example to illustrate my point using arbitrary values:

    Precipitation in Mountains (20% of catchment): 3000mm

    Precipitation in Lowlands (80% of catchment) 500mm

    Glacier Area 4%

    Total precipitation: 0.2*3000 + 0.8*500 = 1000 mm

    In the modification of your precipitation input this would result in a total precipitation of

    1000*0.96 + 0.04*3000= 1080mm

- In the model of Huss and Hock (2015) which is used to generate the glacier runoff in Huss and Hock (2018) a precipitation correction factor and a precipitation lapse rate is applied to the input precipitation data under the assumption that precipitation in high elevations is likely underestimated in data sets. The precipitation correction factor is used as calibration parameter for the glacier model. Therefore, precipitation as output from the glacier model is different from the original precipitation data set. So, the runoff from glacier area in form of snowmelt and rain will be higher than the precipitation of the original GCM data on this area. This also leads to an increase in the moisture source term of SPEI that does not directly stem from glacier melt itself. Although glacier area is shrinking, the precipitation input of the glacier model is still used for the initial glacier area. I would appreciate a discussion about the possible limitation: How does the usage of total glacier runoff data fixed to the initial glacier area instead of using only glacier melt data impact your results? As an idea, you could increase the moisture source term of $SPEI_N$ by increasing the precipitation over the glacier area by a default factor (e.g. 1.5 as this is the default factor for precipitation correction in GloGEM (Huss and Hock, 2015)) and look if this impacts your results (Fig. 3)

$$P_{SPEI_N} = \frac{(A - A_G)}{A} \cdot P + \frac{A_G}{A} \cdot 1.5 \ \cdot P$$

- In general, I missed a bit more in depth discussion about limitations and uncertainties of the study. It was touched upon (l.249- 257) but this is only related to possible feedbacks of glacier retreat that are not captured in the GCMs, but I think there would be more uncertainties to discuss, for example how informative it is to average hydro-climatic variables over the whole basins, and to discuss the possible limitations stated above.
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Basins without drought buffering of glaciers?

- Figure 3: The figure contains a lot of data points. Therefore, it is difficult to grasp, how many basins experience more/less/equal buffering in future and how many basins do not experience a buffering at all in the past and the future (black dots on the zero line). I would suggest to either add these numbers in the figure or in the text describing the figure. In the abstract you claim that accounting for glacier runoff tends to increase drought buffering even in basins with little glacier cover. Looking at Figure 3, I see also a lot of basins without difference especially for small glaciers (black dots close to the zero line). How do you explain this?

- How do you explain that there are quite a lot of basins where you do not see drought buffering in 1980-2010 in Figure 3, although you use the same standardization set for $SPEI_w$ and $SPEI_N$ as explained in l.305-312. I would argue that this should lead to higher $SPEI_w$ values than $SPEI_N$ values in the past and thus maybe to a reduced number and severity of droughts for $SPEI_w$ compared to $SPEI_{N.}$

Minor Comments

Abstract

- L.4 I would specify “hydrological drought conditions”.
- L.7 can you quantify more what “relatively little” glacier cover means?

- I would appreciate some more quantification of the results, e.g. for how many basins did the inclusion of glacier runoff buffer droughts?

Methodology

- L.95: A list of used GCMs in the appendix would be useful for the reader (now you have to search for it until you find it in Figure B3)
- L 137: A short explanation of the definition of aridity index you use would be helpful. I assume you use ratio of precipitation to evaporation such that high values mean wetter conditions? (compare l.201, l.235)

Results

- Figure 1 and Figure A1: I think adding the percentage of glacier coverage next to the name of each basin would give the reader a better overview of the glaciation of the basin and make it easier to interpret the results of the figure
- In Figure 3, Table 1 and Figure 4 I miss the description of whether RCP 4.5 or RCP 8.5 was used.
- Figure 3: no units for the severity are given as axis labels.
- Table 1: AI: abbreviation not mentioned before

Appendix

- L.368: “The only notable difference between the two sample sets is in the magnitude of glacial runoff.” This statement is not clear to me, I do not see it in Figure B4. I rather see differences in precipitation between the upper and lower row.
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Techincal corrections

- L. 339 $SPEI_G$ should be $SPEI_W$

References

Huss, M., & Hock, R. (2015). A new model for global glacier change and sea-level rise. *Frontiers in Earth Science*, *3*, 54.

Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, *8*(2), 135-140.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., ... & Baillie, J. E. M. (2020). Importance and vulnerability of the world’s water towers. *Nature*, *577*(7790), 364-369.