Glacial runoff modulates 21st century basin aridity, but models disagree on the details

Lizz Ultee[1], Sloan Coats[2]

[1]Massachusetts Institute of Technology, Dept. of Earth, Atmospheric, and Planetary Sciences
[2]University of Hawaii at Manoa, Dept. of Earth Sciences

Key Points:

- We compute the effect of glacial runoff on the Standardized Precipitation-Evapotranspiration Index for 56 glaciated basins.
- In general, accounting for glacial runoff increases mean SPEI and decreases variance.
- Projected 21st-century changes in basin hydroclimate both with and without glacial runoff show wide variation across models.

Corresponding author: Lizz Ultee, `ehultee@umich.edu`

Abstract

Global climate model projections suggest that 21st century climate change will bring significant drying in the midlatitudes. Recent glacier modeling suggests that runoff from glaciers will continue to provide substantial freshwater in many basins, though the supply will generally diminish throughout the century. In the absence of dynamic glacier ice within global climate models, a comprehensive picture of future basin-scale water supply has been elusive. Here, we leverage the results of existing global climate and global glacier models to compute the effect of glacial runoff on the Standardized Precipitation-Evapotranspiration Index, an indicator of basin-scale aridity. We find that glacial runoff tends to decrease anomalous aridity and reduce interannual variability in water supply, even in basins with relatively little glacier cover. However, in many basins we find inter-model spread as large as the hydroclimate signal, which suggests considerable structural uncertainty.

Plain Language Summary

Every year, glaciers accumulate some water from precipitation and release some water from melting and surface runoff. The seasonal pattern of freshwater release from glaciers makes them an important source of freshwater for mountainous regions around the world. Computer simulations have shown that the supply of freshwater from glaciers is likely to change as the climate changes during coming decades. Separately, global climate model simulations suggest that many basins will experience more drought in the coming decades due to changes in the global water cycle. To understand what consequences those changes could have for on-the-ground water availability, we analysed existing simulations of glaciers together with global climate model simulations. We calculated a metric called the Standardized Precipitation-Evapotranspiration Index, which describes drought conditions, for 56 river basins that have glaciers upstream. We found that including glacial meltwater and runoff in the calculation can reduce estimated drought during the 21st century in most basins. However, the glacial effect becomes weaker as glaciers shrink due to climate change, and the strength of the effect over time varies from one global climate model to another. We identify priority areas for model development to build a more consistent understanding of the glacial water effect on drought.

1 Introduction

Global climate model projections suggest that on large scales the terrestrial midlatitudes will experience significant drying over the coming century (Cook et al., 2014), although there are uncertainties related to the choice of hydroclimate metric (Milly & Dunne, 2016; Swann et al., 2016; Scheff et al., 2017; Mankin et al., 2018; Yang et al., 2019; Mankin et al., 2019). While ongoing model development has improved the treatment of key hydroclimate processes, a number of factors important at regional scale remain difficult to capture. In particular, current global climate models struggle to account for changing glacier volume and extent, with important consequences for projections of future water availability in glaciated regions (Barnett et al., 2005). Runoff from mountain glaciers accounts for up to 40% of dry-season water supply in arid regions (Soruco et al., 2015; Pritchard, 2019) and responds nonlinearly to changing climate (Huss & Hock, 2018). Future glacier runoff depends on glacier dynamics that cannot be simulated directly in global-scale models and are not easily extrapolated. Moreover, the importance of glacial runoff for water supply differs with regional climate (Kaser et al., 2010; Immerzeel et al., 2010; Rowan et al., 2018), emphasising the need for a holistic view of glaciated-basin hydroclimate change.

The use of global climate models (GCMs) to project hydroclimate change is appealing because the simulated changes are consistent with climate physics on the global-to-regional scale. Nevertheless, the climate physics simulated by an individual model are an uncertain approximation of those in the real world. Intercomparisons of multiple global climate models allow for a quantification of the range of projections that result from this uncertainty—so called structural uncertainty. These quantifications are hindered, however, by the incomparability of inherent (those simulated directly by the model) hydroclimate metrics across models. For instance, the land components of global climate models range widely in complexity, most notably with different numbers of soil levels with inconsistent corresponding depths. The resulting difficulty in comparing soil moisture across models has lead to the widespread use of offline soil moisture models when quantifying hydroclimate change, specifically in the form of standardized drought indices that facilitate like-for-like intercomparison.

The analysis of such indices depends on reliable model simulation of hydroclimate. In many cases, global climate models are not equipped to handle the hydrology of glaciated basins on the century scale. The MATSIRO land surface model (Takata et al., 2003) used in MIROC-ESM, for example, handles water routing through snowpack, but not multiannual storage in glacier ice. The land surface scheme of CNRM-CM6 allows limited water storage in snow and ice and includes a “permanent snow/ice” land tile classification (Decharme et al., 2019), but cannot resolve changes in ice cover over time. GCMs including CCSM and NorESM use the Community Land Model (CLM) to simulate land-surface dynamics and hydrology. CLM includes glacier ice among its land-cover types, but does not account for glacier dynamics or change over time (Lawrence et al., 2018). Further, the spatial resolution of current GCMs leaves them poorly equipped to handle precipitation gradients in high-relief areas (Flato et al., 2013), where mid-latitude glaciers are most likely to be found. Global glacier models have demonstrated that glacier coverage worldwide cannot be assumed static over the coming century (Huss & Hock, 2018; Marzeion et al., 2018); thus, surface hydrology schemes that do not account for changing glacial water storage over time risk under- or over-estimating the true basin-level water availability (van de Wal & Wild, 2001).

There have been substantial recent efforts to quantify 21st-century changes in glacial water runoff at global (Bliss et al., 2014; Huss & Hock, 2018; Marzeion et al., 2018) and regional scales (Juen et al., 2007; Immerzeel et al., 2012; Schaefli et al., 2019). To understand how these changes translate to changing basin-scale water availability, however, requires the added context of regional hydroclimate variability and change (Kaser et al., 2010). Here, we quantify the glacial effect on basin-level drought at the global scale. Our approach combines hydroclimate output of eight general circulation models with offline simulated glacial runoff (Huss & Hock, 2018) forced by boundary conditions from the same models. Together these are used to calculate the Standardized Precipitation Evapotranspiration Index (SPEI) with and without a glacial runoff component for 56 basins. We compare how the 30-year mean and variance of SPEI changes when glacial runoff is considered.

2 Methods

Only eight models of the set of 12 analyzed in Huss and Hock (2018) are used herein, as the variables necessary to calculate SPEI were not available for four of the models. In each case the same associated historical and representative concentration pathway (RCP) 4.5 and 8.5 simulations (Taylor et al. 2008) that were used in Huss and Hock (2018) are also used herein. For each model and simulation and each of the 56 hydrological basins we extract atmospheric surface temperature, surface pressure, total precipitation, surface specific humidity, and surface net radiation. Specifically, we identify all latitude-longitude grid points from the native model grid that fall within the spatial boundary of the hydrological basin, using basin definitions from the Global Runoff Data Centre, and then average the associated variables to produce a single timeseries for each hydrological basin and variable. Because some model grids have low spatial resolution, there are models and basins where no data is available (15% of the total). Nevertheless, at least one model for each hydrological basin has data.

Using the input data described above, we calculate a single SPEI timeseries for each model and basin. SPEI is a drought index based on normalized accumulations of precipitation minus potential evapotranspiration (PET). To calculate SPEI, we first use surface temperature, surface pressure, surface specific humidity, and surface net radiation as inputs to the Allen et al. (1998) formulation of the Penman-Monteith method for estimating PET (see also Cook et al., 2014). Total precipitation and PET are then used to calculate SPEI following Vicente-Serrano et al. (2009). Because SPEI includes a user-defined timescale of integration, we calculate SPEI for a range of timescales from 3-27 months to test the sensitivity of our results. Only the results for 15-month integration timescale are shown herein.

To test the role of glacial runoff in drought we calculate an additional version of SPEI where we replace the total precipitation input to the SPEI calculation by

$$\tilde{p} = \frac{A - A_g}{A} p + \frac{A_g}{A} r, \tag{1}$$

where $\tilde{p}$ is the modified moisture source term, p is the initial moisture source term with no glacial component, A_g is the glaciated area of the basin, A is the total basin area, and r is the basin glacial runoff from Huss and Hock (2018) forced with each general circulation model.

For each model and hydrological basin SPEI time series, we then compute and compare the 30-year running mean and variance of SPEI with and without glacial runoff. We also take the difference of SPEI with and without glacial runoff and compute running means of this difference for each basin. Finally, we compare model-by-model changes in SPEI mean and variance at the end of the 21st century (2070-2100) for RCP 4.5 and 8.5.

3 Results

3.1 Glaciers tend to reduce aridity

Almost universally, the effect of accounting for glacial runoff is an increase in mean SPEI. That is, glacial runoff tends to reduce drought. More specifically, there is unanimous model agreement that glacial runoff increases mean SPEI (i.e. reduces anomalous dryness) in the late 21st century for 35 of the 56 basins tested. However, there is great variation among basins in the temporal trends of SPEI. In some basins, different models project very different future SPEI, both with and without glacial runoff.

Figure 1 shows the 30-year running-mean SPEI for four basins. In the Copper River basin of Alaska, all eight models project an increase in SPEI throughout the 21st century, with even more pronounced increases when glacial runoff is taken into account. In the Rhone basin of central Europe, most models project decreasing SPEI throughout the century to be slightly mitigated by glacial runoff. The four models available for the Majes basin of Peru (see Section 2) disagree about the temporal trend in SPEI, but none are much changed by the inclusion of glacial runoff. Most interesting is the Tarim basin of central Asia. When glacial runoff is not considered, all eight models project SPEI to decrease throughout the 21st century, becoming negative on average after 2050. However, with glacial runoff included, models show an initial increase in SPEI around the year 2000, generally remaining positive (though decreasing) through the end of the century. This suggests that in the Tarim basin glacial water supply changes our best guess at future hydroclimate conditions from increasing drying through the 21st century to a future with greater on the ground water availability in the 21st relative to the 20th century.

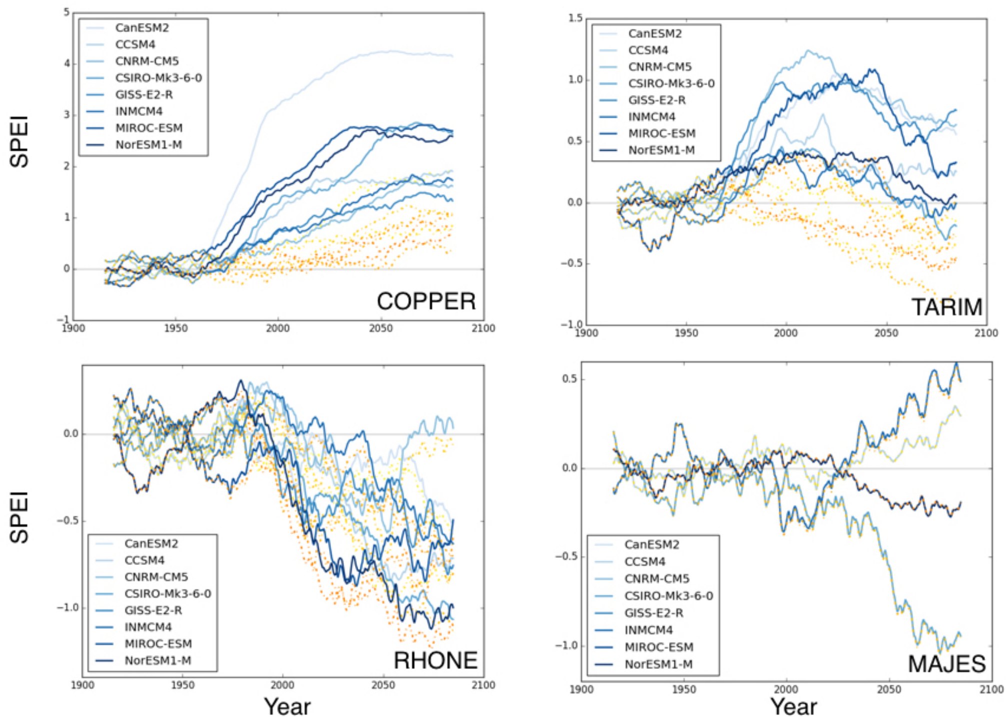

Figure 1. 30-year running mean time series of SPEI with glacial runoff (blue solid) and without (orange dotted) for the RCP 4.5 scenario in four example basins (name in lower right corner of each figure panel).

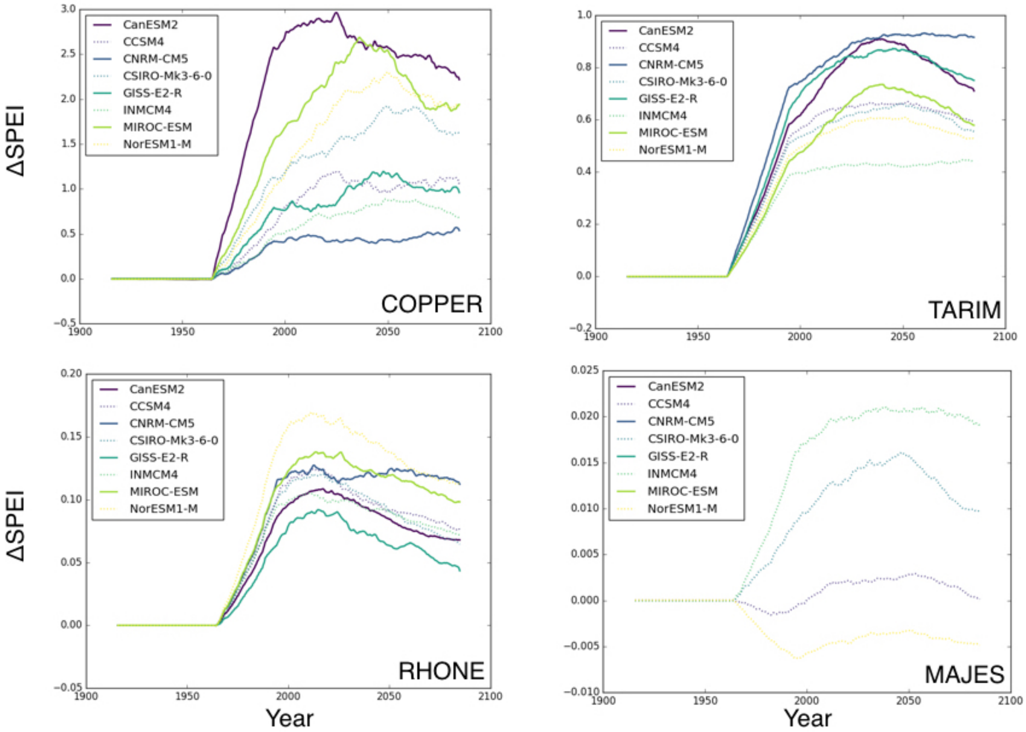

Figure 2. The effect on mean SPEI of including glacial runoff in four example basins. Curves shown are a 30-year running mean of the difference $SPEI_W$-$SPEI_N$, where "W" and "N" denote "with glacial runoff" and "no accounting for glaciers", respectively. A different vertical scale has been applied to each plot to aid readability. These case studies are computed with climate scenario RCP 4.5, but are very similar under RCP 8.5.

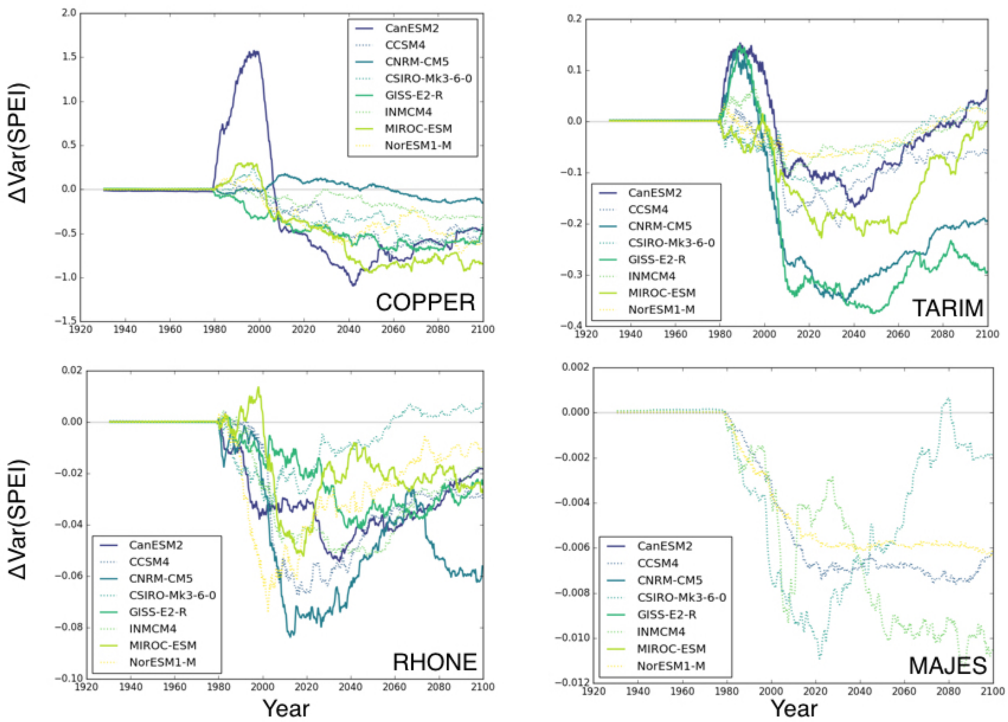

Figure 3. The effect on SPEI variance of including glacial runoff in four example basins. Curves shown are the difference of rolling 30-year variances, Var($SPEI_W$)-Var($SPEI_N$), where "W" and "N" denote "with glacial runoff" and "no accounting for glaciers", respectively. A different vertical scale has been applied to each plot to aid readability. These case studies are computed with climate scenario RCP 4.5, but are broadly similar under RCP 8.5.

Isolating the glacial effect in each basin further highlights its tendency to reduce drying, regardless of the baseline trend in SPEI. Figure 2 shows the glacial effect (Δ SPEI = $SPEI_W$ - $SPEI_N$) for the same four example basins. In the Copper basin, which is the most heavily glaciated of any we study ($A_g/A = 0.2001$) the glacial effect exceeds 1 SPEI unit and remains high throughout the 21st century. This means that future hydroclimate in the Copper basin is 1 standard deviation wetter on average with glacial runoff included, with the standard deviation being relative to interannual (15 month) hydroclimate variability over the late 20th century–in short, glacial runoff has a very large impact on average hydroclimate in the Copper Basin. The glacial effect is also high, on the order of 1 SPEI unit, in the Tarim basin, even though the Tarim is an order of magnitude less glaciated ($A_g/A = 0.0234$) than the Copper. In the Rhone basin ($A_g/A = 0.0093$) there is a moderate glacial effect that declines throughout the century, and in the Majes basin ($A_g/A = 0.0031$) the glacial effect on SPEI is negligible.

3.2 Heterogeneous changes in SPEI variance between basins

Figure 3 shows the time-varying effect on SPEI variance of including glacial runoff. In the Majes basin, the glacial effect on variance is just as negligible as the effect on mean SPEI. In the remaining three basins, the glacial effect is an initial increase in variance at the beginning of the period during which glacial runoff is added to the SPEI computation. This suggests that accounting for glacial water supply can produce a wider range of interannual variability of the water source term in the SPEI calculation–an effect more

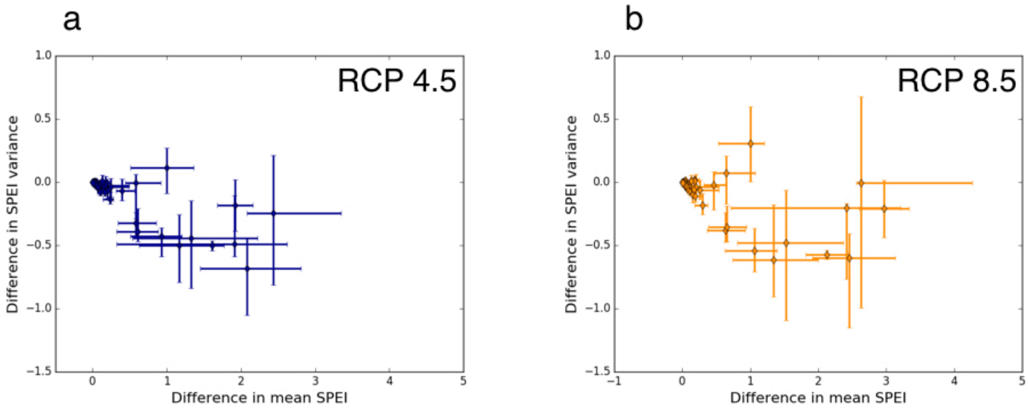

Figure 4. Difference due to explicit accounting of glacial runoff in SPEI 30-year mean and variance at end of 21st century (2070-2100), for climate scenarios RCP 4.5 (panel a) and RCP 8.5 (panel b).

likely to be numerical than physical in nature. After the initial peak, there is a decrease in variance in the Copper, Rhone, and Tarim basins that mirrors the increase in mean SPEI shown in Figure 2. In the Tarim and Rhone basins, where glacial runoff begins to taper before the end of the century, some models show variance increasing again at the end of the century. This indicates that SPEI can become more variable when climate change decreases glacial water supply and associated runoff below 20th century values, despite the non-glacial components of the formula remaining unchanged.

Despite this tapering effect in some basins, Figure 4 shows that accounting for glacial water supply decreases SPEI variance through the end of the 21st century in most basins. Under the more moderate RCP 4.5 climate scenario, there is only one basin for which all models agree on increased variance: the Rio Negro of Argentina. There are more projections of increased variance due to changing glacial water supply, and more heterogeneity among basins and among model projections in general, under the high-end RCP 8.5 climate scenario. Nevertheless, glacial runoff, on average, provides a moderating influence not just on mean hydroclimate but also the year-to-year variability that is typically associated with on-the-ground impacts.

4 Discussion

In most basins, the effect of including glacial runoff is an increase in mean SPEI that diminishes later in the 21st century. This pattern is consistent with the "peak water" framing of Huss and Hock (2018). We note, however, that the time evolution of this glacial effect is not consistent across models, with some models showing a pronounced "peak" shape and others showing a "plateau" or a more steady slope (Figure 2). The variety among models is evident in the Copper basin, for example, where CanESM2 produces a large, sharp peak in glacial effect early in the century while MIROC-ESM produces a slower, nearly monotonic increase in the glacial effect mean SPEI. Further, for several basins including the Copper and Tarim, even the eventual decline in glacial water supply and associated runoff does not return mean SPEI to non-glacial values by 2100. That is, the relevance of glaciers for future drought projections is not necessarily limited to this century.

Theoretical understanding suggests that interannual variance in water availability should be lower when basins have substantial glacial meltwater supply, a sort of glacial interannual drought buffering (Fountain & Tangborn, 1985; Fleming & Clarke, 2005). We find that accounting for glacial runoff initially can increase SPEI variance, which while superficially inconsistent with the theoretical prediction is actually indicative of buffering. In running windows that include some years before 1950 (when the glacier model is switched on) and some after, the glacial increase in mean SPEI can manifest as a peak in variance. The initial increase in variance is thus a numerical effect that demonstrates the strength of the glacial signal in reducing aridity. The reduction, on average, of SPEI variance during the 21st century is also consistent with the theoretical prediction. Further, our finding of reduced effect on variance as glacial water supply and associated glacial runoff taper (Figure 3) supports the prediction that glacial drought buffering will decline with 21st century climate change (Biemans et al., 2019). Consistent with this, under the RCP 8.5 warming scenario, there are more basins in which accounting for glacial runoff results in higher end-of-century SPEI variance (positive y-axis values in Figure 4b). We interpret that these projections reflect basins in which seasonally-available meltwater (or "buffering capacity") declines due to the declining precipitation storage capacity of shrinking glaciers, such that the basin transitions to a precipitation-dependent regime. The decline in buffering capacity would happen faster with stronger warming, as in RCP 8.5.

We assess that there are two categories of basins in which glacial effects are large and long-lived. The first category consists of heavily glaciated basins such as the Copper, where there is a large quantity of water stored as glacial ice. The second category consists of arid basins such as the Tarim, in which glacier runoff is a substantial fraction of total moisture supply in the basin. Basins in this category may not be heavily glaciated—the Tarim basin is only 2% glaciated by area—but other moisture sources are sufficiently small that even limited glacial runoff has a pronounced effect on basin aridity. Previous authors have also commented on the particular importance of glacial runoff in arid basins (Pritchard, 2019) and dry seasons (Soruco et al., 2015; Frans et al., 2016; Biemans et al., 2019).

The magnitude of the glacial effect varies not only per basin but also per model, as the examples in Figures 1 - 3 illustrate. There is no consistent ordering to the model estimates of the glacial effect. That is, no one model of the eight we test is consistently wetter or drier, or more or less variable, across basins. Figure 2 also shows that the glacial effect on SPEI peaks in different years for different models. The heterogeneity of SPEI projections reflects the complexity of basin-scale hydroclimate, with multiple relevant factors treated differently in each model. For example, the CanESM model is the only one to use the Canadian Land Surface Scheme ("CLASS", Verseghy, 2000) and in the Copper basin CanESM has a glacial effect much stronger than any other model (Figure 2). Yet the same figure shows that glacial effects computed with CCSM and NorESM, both of which account for (static) glacier ice cover in the Community Land Model (Lawrence et al., 2018), but which utilize different atmospheric models, peak in different years and with different magnitudes. We deduce that there are processes within both land surface schemes and atmospheric model components of Earth system models that must be addressed to account for dynamic glacier changes. Because the glacier model of Huss and Hock (2018) is forced by GCM-derived temperature and precipitation, the SPEI_W we calculate accounting for glacial runoff can compound inter-model differences in hydroclimate. Thus, although it is essential to account for glacial meltwater in future projections of basin-scale aridity, more fundamental work remains before a consistent physical picture emerges.

The simple offline computation we present here helps account for the first-order glaciological effect on future basin drought. However, offline computations are unable to capture atmospheric feedbacks of changing mountain glacier extent. For example, ice and snow-covered surfaces reflect more incident radiation to the atmosphere than bare rock or soil surfaces do. Water vapor sublimated from glacier ice or evaporated from supraglacial meltwater pools is a ready source of moisture to the local atmosphere. Finally, glacier surfaces are favorable for creation of strong downslope (katabatic) winds, which can be the dominant feature in local-scale atmospheric circulation (e.g. Obleitner, 1994; van den Broeke, 1997; Aizen et al., 2002). To the extent that any of these local processes are parameterized in current GCMs, their projection into the future will suffer from the inaccurate assumption that glacier ice cover is permanent. The effects of these feedbacks will only be resolved with eventual fully coupled mountain glacier schemes in Earth system models.

Here, we have focused on global intercomparison of basin-scale aridity. However, local-level water resource studies may benefit from more granular information (Milly et al., 2008; Head et al., 2011; Frans et al., 2016). Our method can be adapted for use with regional climate models, such as the Regional Atmosphere Climate Model (RACMO) for glaciated areas (Noël et al., 2015) or the more general Weather Research and Forecasting Model (Skamarock et al., 2019), with models simulating individual glacier evolution such as Elmer/Ice (Gagliardini et al., 2013) or Open Global Glacier Model (Maussion et al., 2019), and in probabilistic ensemble simulations.

5 Conclusions

Basin-scale hydroclimate as observed and experienced in the present is affected by numerous regionally-variable factors, including the supply of water from glaciers. Global climate models in use to study past and future hydroclimate are ill-equipped to capture decade-to-century scale variation in glacial meltwater supply. Although fully dynamic representations of glacier ice within GCMs will be necessary to produce a physically consistent projection of hydroclimate change in glaciated basins, we have presented a simple method to leverage recent glacier model developments (Huss & Hock, 2018) and account for changing glacial runoff in 21st-century projections of drought. Our analysis shows that applying dedicated glacier model output to account for basin glacial water supply in the Standardized Precipitation-Evapotranspiration Index (SPEI) tends to decrease drought and reduce interannual variability in water supply, even in basins with $< 2\%$ glaciation by area. However, as glaciers continue to retreat late in the century, their "drought buffering" effect on SPEI diminishes. Nevertheless, the glacial effect shows strong variation across basins and across models, suggesting considerable model structural uncertainty. More fundamental work on the modelling of hydroclimate is thus clearly needed. Of greatest relevance to hydroclimate in glaciated basins will be the inclusion of online glacier models, increasing model resolution and associated improvements in the representation of hydroclimate topography interactions, and improved simulation of frozen precipitation processes.

Acknowledgments

Monthly glacial water runoff model results were kindly provided by Matthias Huss. Readers are encouraged to reproduce the analysis for any basin of their choice using the code, data, and Jupyter notebook guide we have made available at `http://github.com/ehultee/glacial-SPEI`. This manuscript is SOEST publication number [XXXXX - *number will be provided if accepted and must be added to final version*].

References

Aizen, V. B., Aizen, E. M., & Nikitin, S. A. (2002). Glacier regime on the northern slope of the Himalaya (Xixibangma glaciers). *Quaternary International*, *97-98*, 27–39. doi: 10.1016/S1040-6182(02)00049-6

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration—guidelines for computing crop water requirements. In *FAO Irrigation and drainage paper* (Vol. 56). United Nations Food and Agriculture Organization.

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303–309. doi: 10.1038/nature04141

Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., ... Immerzeel, W. W. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, *2*(7), 594–601. doi: 10.1038/s41893-019-0305-3

Bliss, A., Hock, R., & Radić, V. (2014). Global response of glacier runoff to twenty-first century climate change. *Journal of Geophysical Research: Earth Surface*, *119*(4), 717–730. doi: 10.1002/2013JF002931

Cook, B. I., Smerdon, J. E., Seager, R., & Coats, S. (2014). Global warming and 21st century drying. *Climate Dynamics*, *43*(9-10), 2607–2627. doi: 10.1007/s00382-014-2075-y

Decharme, B., Delire, C., Minvielle, M., Colin, J., Vergnes, J.-P., Alias, A., ... Voldoire, A. (2019). Recent changes in the ISBA-CTRIP land surface system for use in the CNRM-CM6 climate model and in global off-line hydrological applications. *Journal of Advances in Modeling Earth Systems*, *11*(5), 1207–1252. doi: 10.1029/2018MS001545

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S., Collins, W., ... Rummukainen, M. (2013). Evaluation of climate models. In T. Stocker et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Fleming, S. W., & Clarke, G. K. (2005). Attenuation of high-frequency interannual streamflow variability by watershed glacial cover. *Journal of Hydraulic Engineering*, *131*(7), 615–618. doi: 10.1061/(ASCE)0733-9429(2005)131:7(615)

Fountain, A. G., & Tangborn, W. V. (1985). The effect of glaciers on streamflow variations. *Water Resources Research*, *21*(4), 579–586. doi: 10.1029/WR021i004p00579

Frans, C., Istanbulluoglu, E., Lettenmaier, D. P., Clarke, G., Bohn, T. J., & Stumbaugh, M. (2016). Implications of decadal to century scale glacio-hydrological change for water resources of the Hood River basin, OR, USA. *Hydrological Processes*, *30*(23), 4314-4329. doi: 10.1002/hyp.10872

Gagliardini, O., Zwinger, T., Gillet-Chaulet, F., Durand, G., Favier, L., Fleurian, B. d., ... others (2013). Capabilities and performance of Elmer/Ice, a new-generation ice sheet model. *Geoscientific Model Development*, *6*(4), 1299–1318. doi: 10.5194/gmdd-6-1689-2013

Head, L., Atchison, J., Gates, A., & Muir, P. (2011). A fine-grained study of the experience of drought, risk and climate change among Australian wheat farming households. *Annals of the Association of American Geographers*, *101*(5), 1089–1108. doi: 10.1080/00045608.2011.579533

Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, *8*(2), 135–140. doi: 10.1038/s41558-017-0049-x

Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science*, *328*(5984), 1382. doi: 10.1126/science.1183188

Immerzeel, W. W., van Beek, L. P. H., Konz, M., Shrestha, A. B., & Bierkens, M. F. P. (2012). Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climatic Change*, *110*(3), 721–736. doi: 10.1007/s10584-011-0143-4

Juen, I., Kaser, G., & Georges, C. (2007). Modelling observed and future runoff from a glacierized tropical catchment (Cordillera Blanca, Perú).

Global and Planetary Change, *59*(1), 37–48. doi: https://doi.org/10.1016/j.gloplacha.2006.11.038

Kaser, G., Großhauser, M., & Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences*, *107*(47), 20223–20227. doi: 10.1073/pnas.1008162107

Lawrence, D., Fisher, R., Koven, C., Oleson, K., Swenson, S., & Vertenstein, M. (2018). *Technical description of version 5.0 of the Community Land Model (CLM)* (Tech. Rep.). National Center for Atmospheric Research.

Mankin, J. S., Seager, R., Smerdon, J. E., Cook, B. I., & Williams, A. P. (2019). Mid-latitude freshwater availability reduced by projected vegetation responses to climate change. *Nature Geoscience*, 1–6. doi: 10.1038/s41561-019-0480-x

Mankin, J. S., Seager, R., Smerdon, J. E., Cook, B. I., Williams, A. P., & Horton, R. M. (2018). Blue water trade-offs with vegetation in a CO2-enriched climate. *Geophysical Research Letters*, *45*(7), 3115–3125. doi: 10.1002/2018GL077051

Marzeion, B., Kaser, G., Maussion, F., & Champollion, N. (2018). Limited influence of climate change mitigation on short-term glacier mass loss. *Nature Climate Change*, *8*(4), 305–308. doi: 10.1038/s41558-018-0093-1

Maussion, F., Butenko, A., Champollion, N., Dusch, M., Eis, J., Fourteau, K., … Marzeion, B. (2019). The Open Global Glacier Model (OGGM) v1.1. *Geoscientific Model Development*, *12*(3), 909–931. doi: 10.5194/gmd-12-909-2019

Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, *319*(5863), 573. doi: 10.1126/science.1151915

Milly, P. C., & Dunne, K. A. (2016). Potential evapotranspiration and continental drying. *Nature Climate Change*, *6*(10), 946. doi: 10.1038/nclimate3046

Noël, B., van de Berg, W., van Meijgaard, E., Munneke, P. K., van de Wal, R., & van den Broeke, M. (2015). Evaluation of the updated regional climate model RACMO2.3: summer snowfall impact on the Greenland Ice Sheet. *The Cryosphere*, *9*, 1831-1844. doi: 10.5194/tc-9-1831-2015

Obleitner, F. (1994). Climatological features of glacier and valley winds at the Hintereisferner (Ötztal Alps, Austria). *Theoretical and Applied Climatology*, *49*(4), 225–239. doi: 10.1007/BF00867462

Pritchard, H. D. (2019). Asia's shrinking glaciers protect large populations from drought stress. *Nature*, *569*(7758), 649–654. doi: 10.1038/s41586-019-1240-1

Rowan, A. V., Quincey, D. J., Gibson, M. J., Glasser, N. F., Westoby, M. J., Irvine-Fynn, T. D. L., … Hambrey, M. J. (2018). The sustainability of water resources in High Mountain Asia in the context of recent and future glacier change. *Geological Society, London, Special Publications*, *462*(1), 189. doi: 10.1144/SP462.12

Schaefli, B., Manso, P., Fischer, M., Huss, M., & Farinotti, D. (2019). The role of glacier retreat for Swiss hydropower production. *Renewable Energy*, *132*, 615–627. doi: 10.1016/j.renene.2018.07.104

Scheff, J., Seager, R., Liu, H., & Coats, S. (2017). Are glacials dry? Consequences for paleoclimatology and for greenhouse warming. *Journal of Climate*, *30*(17), 6593–6609. doi: 10.1175/JCLI-D-16-0854.1

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., … Huang, X.-Y. (2019). *A description of the Advanced Research WRF version 4.* NCAR Tech. Note NCAR/TN-556+STR. doi: 10.5065/1dfh-6p97

Soruco, A., Vincent, C., Rabatel, A., Francou, B., Thibert, E., Sicart, J. E., & Condom, T. (2015). Contribution of glacier runoff to water resources of La Paz city, Bolivia (16 °S). *Annals of Glaciology*, *56*(70), 147-154. doi: 10.3189/2015AoG70A001

Swann, A. L., Hoffman, F. M., Koven, C. D., & Randerson, J. T. (2016). Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. *Proceedings of the National Academy of Sciences*, *113*(36), 10019–

10024. doi: 10.1073/pnas.1604581113

Takata, K., Emori, S., & Watanabe, T. (2003). Development of the minimal advanced treatments of surface interaction and runoff. *Global and Planetary Change*, *38*(1), 209–222. doi: 10.1016/S0921-8181(03)00030-4

van den Broeke, M. R. (1997). Structure and diurnal variation of the atmospheric boundary layer over a mid-latitude glacier in summer. *Boundary-Layer Meteorology*, *83*(2), 183–205. doi: 10.1023/A:1000268825998

van de Wal, R. S. W., & Wild, M. (2001). Modelling the response of glaciers to climate change by applying volume-area scaling in combination with a high resolution GCM. *Climate Dynamics*, *18*(3), 359–366. doi: 10.1007/s003820100184

Verseghy, D. L. (2000). The Canadian land surface scheme (CLASS): Its history and future. *Atmosphere-Ocean*, *38*(1), 1–13. doi: 10.1080/07055900.2000.9649637

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2009). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. doi: 10.1175/2009JCLI2909.1

Yang, Y., Roderick, M. L., Zhang, S., McVicar, T. R., & Donohue, R. J. (2019). Hydrologic implications of vegetation response to elevated CO2 in climate projections. *Nature Climate Change*, *9*(1), 44. doi: 10.1038/s41558-018-0361-0