Review of

“Understanding Drivers of Glacier Length Variability Over the Last Millennium”

This manuscript uses a linear glacier model forced with output from a global climate model to explore controls on glacier mass balance and length variability over the last Millennium. The relative importance of forced versus internal variability is emphasized. The manuscript explores the importance of glacier response time in controlling the resulting glacier length simulations. The regional correlation of glacier length is revealed as an important indicator of past, forced temperature changes. The importance of single forcings (i.e., GH gases, insolation, etc) in glacier length variability is also considered.

Ultimately there are a number of new insights from this work: 1) that internal variability drives length changes in mountain glaciers when response times are less than a few decades; 2) that glaciers with longer response times are more likely to capture the effects of external variability; and 3) that external forcing dominates when glaciers response is averaged across widely separated regions.

Major comments

As it stands I find that the analyses are very well done and a lot of new insight is provided. This manuscript provides new theory for interpreting past glacial length changes. It uses an approach that honors understandings of climate variability that have been around in the atmospheric science community for decades but have not yet made their way into the glaciological or glacial geology communities.

With a bit of work to improve legibility, the manuscript can be a long-lasting contribution. Further synthesis of the results is needed. Because the implications of this work are most pertinent for folks working on paleoglaciers and the interpretation of the moraine record, the manuscript should be adjusted to make it more accessible for these folks. If not adjusted the important insights provided here might be missed or overlooked. Further suggestions to aid this effort are provided in the minor comments below.

In some parts of the manuscript so much information is presented that the reader is overwhelmed. This is the case even for a reviewer who is familiar with the methods the author’s apply. The analyses vary rapidly in spatial scope (3 glaciers, 76 glaciers, hemispheric) and temporal scope (pre-1880, post-1880) or vary between different components of the mass balance (summer, winter, annual) or the response time (10, 30, 200 yrs). While it is a good ‘problem’ to have too many analyses I think the manuscript would be more effective if there were a more central thread to follow. The introduction as it reads does not lay out the analyses to come. Removing some of the extraneous analyses and points would also help. The authors could also take a bit more space to explain their analyses/ results if more extraneous points were removed. Better transitions between sections 3.1-3.4 are also needed.

The figures can also be overwhelming as they provide a lot of information. Again this is positive but the authors should consider how these figures could be simplified while still allowing the main points to come across. Perhaps some of the multi-paneled figures could be moved into the Appendix or Supplemental and be replaced with simplified versions in the main text to improve legibility?

Along these lines the authors might consider removing the analysis related to individual forcings (section 3.4) and glacier length and save it for another manuscript. Figure 6 was interesting but I felt it was rather hard to take much away from it. From my view there is more than enough new contributions from Sections 3.1-3.3.

The manuscript could also be streamlined by narrowing the temporal scope. If the authors just analyzed 1000 to 1880 then any issues with the GCM output poorly representing the more recent climate would be removed or even put in the supplemental material. Furthermore removing the 1880 to present time period would also lessen some of the more complex items the authors discuss in the manuscript now, allowing for a more streamlined read.

The text should address the paleoglacier literature more directly. The paper dances around ideas related to the moraine record. I think the authors should meld in a bit of the the analysis of Anderson et al., 2014 into the discussion. Who in their table 2 also show SNR as related to response time. While the Anderson paper uses the one-stage version of the linear model the same general trends are apparent with either the 1-stage or 3-stage. Their analysis if nothing else supports the conclusions of this paper: larger SNR result from longer glacier response times. Authors should also consider referencing Young et al. (2011) who at least note the potential role of varying response time in controlling the timing of moraine formation.

The manuscript lays out some very important conclusions for those interpreting the moraine record/ paleoglacier lengths, but these points are not highlighted as much as they could at the end of the manuscript. Or they are overwhelmed by other points made in the discussion/conclusion section.

Minor comments

Line 20-21. A more accessible description of internal climate variability would be helpful here for those that do not think about climate in this way.

Section 1 Introduction would benefit the reader more of a bit more by introducing say glacier response times and signal-to-noise ratios of glacier length/mass balance here. As it stands I was a bit surprised by the breadth of the analyses as I read down.

line 84. Perhaps a bit more about the data used to create these temperature anomalies would be useful here. Really just so the reader doesn't need to go looking.

Line 179-180 See Anderson et al., 2014 Table 2 for similar results.

Line 185. The extension of the analysis to 76 additional glaciers is a surprise. The reader would benefit from a bit of an outline of the simulations at the end of the introduction.

Section 3.1 "Dependence of SNR on timescale" would be more clear as "Response time and SNR" same for Section 3.2 maybe "Spatial scale and SNR"

Line 196. I find this paragraph to be accurate but overwhelming if you are not already an atmospheric/climate scientist or previously familiar with the author's approach to linking climate variability to glacier response. So more simple explanations and simplifying will help.

Line 197. perhaps take a bit more space here to explain what ‘white’ noise means for those who are unfamiliar.

Line 202. This sentence could be rewritten to just state what the source of the differences in slope are. Right now my brain is a bit overwhelmed looking at all the data in figure 3.

Line 255-257. This is a really important observation one that helps bridge the gap between Quaternary geologists and the authors’, more atmospheric science-based approach.
Line 274-276. This seems like a bit of an understatement on the part of the authors. There are scant few glaciers that have advanced through the last century.

Section 4 (Summary and Discussion) would be improved with more synthesis in how these results relate to folks who interpret moraine chronologies and past glacier fluctuations. For example: “The preceding analysis has shown that forced changes in glacier length are driven primarily by globally-coherent changes in summer temperature.” from line 239-240 would be good to emphasize here.

Line 299. It would help to put a range of values of this in numbers as right now I can think of mountain ranges that vary in area by orders of magnitude. The ‘individual mountain range’ phrase was used above as well.

Line 300-302. The discussion from Anderson et al, 2014 is relevant here for moraine ages across the western US for the LGM. It is a real-world example that ties into a similar analysis. Its inclusion would add depth to the discussion.

Line 316. should be a new paragraph.

Figures

Fig. 2. Perhaps the effect of glacier response time would be better shown if the y-axes were the same for all panels.

Fig. 3 Labels on one of the panels outlining what is low frequency and what is high frequency. Otherwise the reader needs to do a bit of math in their head if they are not used to looking at such figures.

Perhaps the spectral slopes portion of the panels could each be in a box or subplot within the panel so they are differentiated from all of the other lines in each panel?

The authors should consider de-emphasizing the data (maybe with transparency?) and emphasizing spectral slopes, which I find to be a more clear expression of the main point.

Fig. 4 This figure is again packed with information. While it is quite interesting and there is a clear trend I come away overwhelmed with information.

Fig. 5 caption: “positive values indicate that summer
temperature accounts for a larger fraction of variance in glacier length than in annual mass balance.” I think the caption is incorrect here. As written temperature accounts for a larger fraction of variance in annual mass balance than in glacier length.

I found that the text written about Figure 5 in section 3.3 was easier to follow than the figure itself. It might be more effective for the authors to just describe the take home here in the text with a few statistics?

Fig. 6 I think this figure could be improved by defining the lines with different linestyles. Right now the take away from this figure is not clear as well. In panels a and b, the lines are so dense that the reader has to work very hard to differentiate them. Maybe there is an easier way to present these results with a couple panels that are more legible or in a table with statistics?

References

Anderson, L.S., Roe, G.H., Anderson, R.S., 2014. The effects of interannual climate variability on the moraine record. Geology 42, 55–58. https://doi.org/10.1130/G34791.1

Young, N.E., Briner, J.P., Leonard, E.M., Licciardi, J.M., Lee, K., 2011. Assessing climatic and nonclimatic forcing of Pinedale glaciation and deglaciation in the western United States. Geology 39, 171–174. https://doi.org/10.1130/G31527.1