Timing and Climate-driven mechanism of Glacier Advances in Bhutanese Himalaya during the Little Ice Age

A review for The Cryosphere

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The authors of this manuscript approach an interesting problem, to link dated moraines in the monsoonal Himalaya, and glacier extents in the Bhutan Himalaya, to large-scale climate over the last millenium through a series of model systems. The authors use a series of CMIP5 GCMs, which were run through the last millenium as part of the PMIP3 project to force a simple glacier mass balance model, and a glacier flow model. This linking of climate models to a glacier model to make paleoclimatic inferences is still rare, and it is an interesting question as to whether the PMIP3 runs contain the forcings that could make glaciers extend to their Little Ice Age (LIA) positions. Applying the model on a regional scale, to examine the response and sensitivity of glaciers in an individual and collective sense is very worthwhile.

The manuscript has been through a previous round of reviews, and is much improved upon the original version, especially with the longer spin-up time, better sensitivity testing and presentation of mean GCM-driven simulations, and further analysis. The finding that LIA glacier advances were caused by cooling, rather than precipitation changes, is interesting, and the further seasonal analysis of sensitivity is welcome.

1 Major comments

While it is an interesting problem, I do have concerns about how grounded in reality the glacier simulations are. The only glacier observations presented are their RGI outlines, and some LIA lengths. Given this paucity of glacier-specific data, one would expect that careful attention would be paid to ensuring that these glaciers are adequately simulated in the present-day, to establish a baseline for comparison to the last millenium.

Unfortunately, the model (as set up) seems unable to simulate many of the present-day glaciers, with a maximum of about ~ 600 glaciers of the 803 in the RGI have length > 0 for any tested value of β (Figure 2c). It might well be that these are small glaciers which rely on local topography, preferential deposition and redistribution of snow, or avalanching for their existence, and the degree-day model is unable to simulate these. However, in the manuscript there is no explanation provided. How do the modelled volumes at the year 2000 compare with global estimates of ice volume in this area? While this is a regional study, and the reluctance to focus on individual glaciers is understandable, the calibration of the model is rather general, and its not clear whether the model set-up performs adequately for individual glaciers, a necessary prerequisite before analysing the collective glacier response.

For the last millenium it is not reasonable to say that the simulated length changes have been validated by the geomorphological maps (L51), the comparision is not that specific. The comparison is largely done through the comparison of 'maximum peak GLR'. Further, only two of the dated moraine ages comes from within the study area, a limitation which is not clear at first.

Many model spin-up simulations are run with the temperature bias β adjusted, and the value $\beta = -0.4$ is taken to best represent the glacier regime during the spinup period, to ensure that not too many glaciers over-run their LIA domains. From Figure 2(b) it would seem that the value of β choosen has a large influence on the early part of the simulation.

In further revising this paper, I would like to see more consideration given to ensuring that the model system adequately simulates present-day glaciers, and how the chosen value of β influences the results, in terms of the number and timing of glacial substages.

2 Minor comments

1. One of the tuning constraints is that the regional average GLR is greater at LIA4 than LIA1 (L128); but this is presented as a result in the discussion (L225, and again at L288),
2. L110: it is good to know the method of finding peak lengths, but it would be nice to have an explanation of what 'findpeaks' this actually does, rather than having to read the Matlab documentation to find out (what does the minimum peak prominence mean?)
3. L122: 'all experiments can reach their steady states after a 5000-years spin-up'. However, looking at Figure 2a, it is clear that some of the simulations still have increasing volume at the end of the spin-up period. For the chosen $\beta = -0.4$ the simulation does appear to have reached a steady state, but the general statement here is not correct.
4. L137: the description of the sensitivity experiments is not clear: what is the 51-year window used for? what is the observed SMB? (this is the only mention of observed SMB)
5. L137: 'We set ϵ to 0 in Eq.1 in order to maintain the contemporary glacier geometry under the contemporary climate condition.'. This is an important point, how well is the contemporary glacier geometry simulated under contemporary climate conditions? Fig 2c would indicate that many glaciers are simlated with length = 0.
6. L162: earlier RGI v6.2 is mentioned, here it says v6 is used.
7. L183: the best fit RMSE of maximum peak GLR is rather high (>100%), and larger than the GLR % change through the LIA (Figure 4).
8. on first reading this manuscript, I thought that the dates presented in Figure 4b were from within the model domain, i.e. were directly related to the glaciers which are modelled. However, only two dates are actually within the domain (Figure 1, Table S1). There is an assumption, which I do not think is anywhere mentioned, that the dated moraines outside of the study area are also representative of the dates of glacial advances within the study area.
9. as a consequence of the previous point, the statement at L227 'specifically, about 12 of the 30 moraine ages shows that the related glaciers reached their maximum peak GLR during LIA-4 compared with only 2 of them during LIA-1', it should be made clear that these 'related glaciers' are not within the study area, but rather in the wider monsoonal Himalaya.
10. also related to that point, the statement L271 'The occurrence time of each glacial substage also varies from glaciers, supported by the dispersal of moraine ages (Fig. 4b)' also implies that it is that moraine ages are directly related to the occurence time of each glacial substage, but the comparison is actually more general that that (LIA dates in the monsoonal Himalaya compared to occurrence time in the study area).
11. the qualitative link make to volcanic eruptions, perhaps not as compelling as one might expect, given the forcing for PMIP3. Reference should be made to the forcings of PMIP3, of which volcanic aerosols is one of the most important. It seems somewhat round-a-bout, inferring a cooling from volcanic aerosols via a glacier model, when the response of the PMIP3 models to volcanic aerosols would most directly be compared by examining the input and output of the GCMs themselves.
12. in the abstract (L12) and the conclusion (L379) it states 'OGGM broadly captures the pattern of glacier length change, but underestimates its amplitude'. I'm not sure which result that statement comes from.

2.1 Minor edits

Much of the text is a little hard to understand and needs careful editing. I have made a few comments here, but there are many more minor changes to the text to improve clarity required.

1. L8: evolutions -> evolution

2. L20 'glacial history for himalayas...' -> 'glacial history of the Himalaya...'
3. L23: more and more interest on -> increased interest in
4. L24: mechanisms behind what?
5. L35: modelling complements field work, but this sentence inplies that its a substitute for field-work.
6. L39: 'study provided...' -> 'study provides...'
7. L45: exist -> are
8. L48: 'The small glaciers...' -> 'Small glaciers...'
9. Figure 1: This map contains much of the information needed to understand this study and its context. It is however quite small and its hard to even see where the mapped LIA extents are for all but the largest glaciers.
10. L77: exceeding -> exceeds
11. L139: is this temperature bias different from β?
12. Figure 2: its a little confusing having the symbols in (c) the same colours as the color scale for β, but different meaning.
13. L202: please rearrange this sentence
14. L223: extremums -> extrema
15. L260: significant -> significance
16. L361: is -> are