Review of
"Modelling Glacier Evolution in Bhutanese Himalaya during the Little Ice Age"

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In this manuscript, Yang et al. use a numerical approach to simulate the glacier evolution in Buthanese Himalaya during the Little Ice Age (LIA). For this purpose, they utilize the Open Global Glacier Model (OGGM), a state-of-the art glacier evolution model that has the capacity to model a large ensemble of glaciers over a longer timescale (here centennial). The authors forced OGGM with six paleo-climate datasets, however 3 of them were excluded from the analysis/discussion due to performance issues. The main objective of this study is to discover periods of glacier advance (substages) during the LIA. The authors could identify four glacial substages (called LIA-4 to LIA-1) in the regional pattern and compared their findings with observations (dated moraine and mapped LIA outlines). They discuss the influence of glacial sensitivity to climate by inspecting a correlation between glacier length and the number of substages. And finally, the authors investigate which climatic mechanisms influenced the glacier evolution in this region most and come to the conclusion that summer temperature is a dominant factor.

The manuscript is of great interest of the community as it gives a good picture of the regional glacier evolution in the Bhutanese Himalaya over the Little Ice Age. Numerical simulations (as done in study) are the only way of getting an overall view about a complete region. They showed that the glaciers responds differently (with a different number of substages during the LIA) to the same climate conditions. This makes clear why it is impossible to get an overall picture over the hole region by a few moraine samples of a handful of glaciers. However, I have the feeling that some parts of the manuscript deserve greater consideration in this study:

General Comments

- **response time of glaciers**: Previous studies showed that the response time of a glacier (equal to the sensitivity to climate conditions) depends more on the steepness of the surface than on glacier size attributes (e.g. glacier length). Thus, the analysis from Sect. 4.2 should be expanded to more glacier properties (e.g. slope, ELA, ...). The individuality also explains why the associated analysis should rather be based on the the complete distribution than on the average value (this comment relates to the analysis shown in Fig. 3a)
- **spin-up**: It becomes not clear, why the parameter tuning is necessary and how exactly the spin-up was set up. The results of the sensitivity test performed with the temperature bias β aren't showed and the tested value range with only 3 values (-1,0 1) seems questionable.

- **reduction to 3 (out of 6) simulations**: It is a pity that the results/analysis were reduced to the half of the simulations. The authors gave justifying reasons, but I believe that from the 3 (at least 2 of them) excluded simulations one could still get information out of. The BCC-CSM and the CCSM4 simulation could be cut down to the years (1000-1850). Both simulation seems to be reasonable over this period and could be included to the analysis. For the CESM simulation (which has to high temperatures) a temperature bias could be applied, such that it fits the mean of the other GCM's.

- **GCM analysis**: Usually (when working with different GCMs), the mean over all GCMs is shown and the results are often analyzed based on this mean value. In this study, I'm missing the mean calculation of the results over all GCMs completely. The study explains in very detail all the results for each of the three GCM's used. I fear that, at some parts, this is oversupplied and I have the feeling that a discussion based on the mean with highlighting only specific behavior of some individual GCMs at some parts, would be sufficient and more interesting for the reader.

- **overview about the test site**: I'm missing in general a better overview about the test site. Figure 1 is the only part in the paper where one can get a rough idea about the study site. How many glaciers are actually simulated with OGGM is not even mentioned in the paper. Which region/subregion (from the RGI (?)) is used and how are the glaciers selected? I'm myself are not sure, if you modeled in the end all glaciers shown in Fig.1a) with OGGM or the 408 glaciers shown in Fig. 1b). Perhaps you can also give a bit more insights about the glaciers simulated? As the glacier length is an important property in your study, how is the distribution of the glacier length today/or 1950 (as this is the reference date for most of your analysis)? Is the regional glacier length dominated by a few large glaciers?

- **clearer expressions**: When going through this manuscript, I kept stumbling over unclear expressions/names/definitions. It really makes the text harder to understand and a substantial revision of the text will be necessary. Just to name a few examples:
  - Is there a difference between present, modern and 1950?
  - Every time when you write 'glacier length' (or outline), you need to make sure that the reader knows to which date you refer to. The LIA length or the modern glacier length?
  - When you refer to SMB changes in summer and you sum up all values, you need to make clear that you mean cumulative SMB changes over the summer months.
  - Please, make sure that the figure captions describe all elements that can be seen in the figure and that only relevant items are shown there.

- **reproducibility**: One criteria of TCD is that the description of experiments and calculations is sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results). I myself, as an experienced OGGM user and developer, would not be able to reproduce your results with the information given in the current version of the manuscript. Information about relevant parameters (e.g. the border parameter) are not given. It is not clear, which RGI glaciers you have simulated and I am missing a detailed description how the number of substages for each glacier were calculated and which criteria was used to define the local maxima of the length trajectories.

Specific and technical comments

Title

I have the feeling that the title does not reflect well the main point of your study. As your study focus more on discovering periods on glacier advance (substages) during the LIA, I think that this should be part of your title as well.

Abstract

- p.1, l.12: 'six paleo-climate datasets': True, but you exclude three of them and all your findings are based on those three.
- p.1, l.12: delete the 'the' before mapped
- p.1, l.13: 'driving by' → 'driven by'

1 Introduction

- p.2, l.34: delete 'on'
- p.2, l.35: the word 'substage' is explained in Sect. 3 (p.6, l.133). Please explain it here, as this is the first use (excluding the abstract).
- p.2, l. 39: 'cross-validated': I think cross-validated is the wrong expressions here. The more general term 'evaluated' would fit better. A cross-validation is a specific statistical evaluation method across many others.
- p.2, l.43: I would not say that it is possible to 'cross validate observation with simulations' as a simulation always need an observation to be calibrated/working well. I suggest that you just say here: '... resulted from an imperfect understanding on how to bring observation and simulation together...'
- p.2, l.45: 'works' → 'work' (work has no plural)
- Figure 1: I guess that the idea of the figure is to give the reader an overview about the test site and the location of the data used in this study, but a fundamental revision of the figure will be necessary, because it is overloaded and should be reduced to necessary information concerning the study.
  - What is shown in the background (DEM(?)) and where is the source/reference of the data?
  - In general, I have to say that I don't understand why the background information (elevation) is necessary here. A general map (e.g. showing the different subregions of the Himalaya (e.g. western Karakoram, central and western Himalaya, ...) would give a better overview and the reader would have a better picture of the distribution of the different locations. In my opinion the information about the elevation at the moraine sites is not relevant for the study. The figure (as it is now) looks at a glance quite overloaded and showing a map only could improve this.

– The gray plot in the upper right corner of Fig.1a) is not meaningful (no coordinates, no scale, no information at all). Here again a map with e.g. country shapes would give more information. In addition, this subplot needs a label (e.g. Fig. 1c or you consider a relabeling of all three subfigures, starting with 1a) for this one) as well.
– Elevation labels: The labels in the two subplots are not consistent. In Fig. 1a) the elevation is shown colored with a continuous color map and in Fig. 1b) with 8 different classes. Please, decide for one of method here and only use rounded numbers as label.
– Dating sites in Fig. 1a): Until here, the reader has no idea what LIA-4 - LIA-1 means, as this is explained in Sect. 3 the first time. What does 'Ungrouped' mean? This is not explained in the text. Why can't some moraines being grouped?
– "Glacier" class in Fig. 1a) refers to which date (I guess modern glaciers)? It is confusing, because in Fig.1b there is a distinction between modern and LIA glacier extent. In addition, please add a reference of the glacier outlines shown in the two figures and mark (or describe in the figure caption) the number of glaciers shown here.
– It is unclear to me, why the two lakes in Fig. 1b) are shown. Are they relevant for the study? Please, don't use a blue color here, if one elevation class is also colored in blue.
– figure caption: The caption doesn't explain well what actually can be seen in the plot. To my understanding the plot doesn't show the individual calculated exposure ages of ^{10}Be sites or the ages of the moraines. Please, add the information about the recalculation of the ages in the text and not in the figure caption.

2 Methods

2.1 The Open Global Glacier Model

- While this paragraph gives a detailed overview about the surface mass balance model and their (default) parameters used in this study, basically no information about the dynamical model is given. I'm missing information about relevant parameters: creep parameter A and the sliding parameter f_s, which usually are the same for each glacier (defaults $A = 2.4 \times 10^{-24} s^{-1} Pa^{-3}$, $f_s = 0$, no lateral drag).

- Please, add information about the border parameter used in this study. This parameter plays an important role for this study. Only a high value can ensure that glaciers large enough for the LIA can be generated. It is also an important parameter in case a reader wish to reproduce the results.

- p.3, l.59: OGGM is a not a "2D" flowline model, but "1.5D".
Since OGGM version 1.4. two different representations of the flowline exists (via geometrical centerlines and via elevation bands flowlines). Please, add an information which OGGM version you used for the study, as well as which centerline representation was used.

- p.3, l.60-62: OGGM was also successfully applied many times in High Mountain Asia before. Please add some information about previous studies in the same/similar region. To get a better overview yourself about existing studies making use of OGGM, you can have a look here: `https://oggm.org/publications`

- p.3 l.63- p.4 l.76: Please, add references to Maussion et al. (2019) and Marzeion et al. (2012) to this paragraph. All information/or parts mentioned here stem from the two publications.

- p.4, l.66: Where does the +10 in the definition of dx comes from? To my knowledge, dx in OGGM is defined as $dx = 14\sqrt{S}$

- p.4, l.67: The citation of Bahr et al. needs to be wrong here. Please correct to Maussion et al. (2019) .

- p.4, l. 79: 'to better capture the changes of individual glaciers': Please, be more carefully with this statement. It is true, that OGGM might be able to capture changes of individual glaciers better than other models do, but ONLY if OGGM's parameters (from the SMB and the dynamical model) are well calibrated for those individual glaciers. Unfortunately this is with the default settings of OGGM (due to the lack of available data) not possible and not the case. Even, if it is possible to easily apply OGGM on individual glaciers or smaller regions, the results needs to be handled with care. If the user of OGGM wants to apply OGGM on an individual scale, it is the task of the user to make sure that the model is well calibrated for those glaciers. It is very important to keep in mind that all default parameters given by OGGM are chosen or calibrated such that OGGM performs well on a global scale (by accepting larger errors for single glaciers) and not on an individual scale.

2.2 Climate forcing and experimental design

- p.4, l.81: OGGM uses 'monthly' temperature and precipitation data. Please, add this information.

- p.4, l.84: 'details listed in Gosse et al. and Table S2': although one can find the information there, please add the time coverage of the GCMs (e.g. all data sets cover the period 850 CE - 2000CE)

- p.4, l.88-l.89: Please, rearrange the sentence and split the 2 information. To initialize the model, you used a spin-up (in order to avoid the influence of the initial condition) and in order to better estimate the long-term glacier evolution an additional parameter tuning is necessary. The better estimation is not the reason for the spin-up. Every model needs to be initialized before usage.

- p.4, l. 89: '600-year spin-up': Please, proof that the 600 years are long enough and the initial condition does not influence the results anymore. You could do this by repeating the spin-up with a) zero-ice volume and b) e.g. double ice volume at the beginning of your spin-up. All lines, needs to converge during the 600 years. If not, you need to extend the spin-up time. Please, add a figure showing the spin-up as well, ideally including a proof as suggested above.

  I doubt that the 600 years will be enough. The required spin-up time will depend on the initial condition of your spin-up. As you did not mention this in the text (please add this information to the text), I assume that you start your spin-up with present-day condition (RGI inventory date) and I expect a large difference between the present day state and the state around 900 CE. Thus, 600 years might not be enough for the today's glaciers to adjust to the climate around 900 CE.

- p.4, l. 90: '51-year window': The default value in OGGM is 31 years. Is there a specific reason that you chose 51 years?

- p.4, l. 90: '875-925 CE': All GCM's start in 850 CE. Why don't you make use of this? I see, that you want to have a good starting point for the year 900, but later in the text you write that you limit your simulation to the year 1000. That's why I wondered why you don't start earlier?

- p.4, l.91: 'tuneable parameter β': Please, add the name of the parameter as well (temperature bias).
- p.4, l.92: 'adjust β from -1 to 1 °C with an increment of 1 °C': testing 3 values (-1,0,1) isn't enough for a sensitivity test. Besides that, deciding for an value at the end of the tested value range, shows that the range of tested values wasn't large enough. Please show a figure of this experiment.
- p.4, l.92: ' 250 years': To me it is unclear, if you applied $\beta = -1$ only during the spin-up or for all experiments. Are these the first 250 years of the 600 year spin-up or after the start of your simulation in 900 CE?
- p.4, l. 94: Please, reformulate this sentence. It is hard to understand. If I understood it correctly, you tuned β such that the LIA start time of the OGGM simulation matches the ^{10}Be chronologies? The temperature bias reduces/increases the input temperature by a fixed factor and thus it increases/decreases the volume of a glacier by a constant value over time. Thus, the volume trajectory is shifted up or down. I don't see, how the temperature bias can shift the time of a glacial maximum to an earlier/later time. I may have misunderstood this part, and I would gladly be corrected, but in that case I am afraid this part may also be problematic to understand for some other readers. A figure showing the parameter tuning could improve the understanding why this is necessary.
- p.4, l.95-96: 'Because the simulation of the first 100 years is influenced by the choice of initial condition ...': This should not happen, as the reason for a spin-up is to not have the influence of the initial condition any more. This shows, that your spin-up time wasn't long enough!
- p.5, l. 98: 'We also test the sensitivity of glaciers': This disturb the flow of reading as it is a sudden change in topic. Please add a justification why you are doing this.

3 The pattern of glacier changes during the LIA

- p.5, l.126 - p.6, l. 127: The CESM simulation: This is a perfect example for what the temperature bias could be used to. As you have stated in the text, the temperature over BH in the CESM climate data is to high, but in Fig. S2d) the substages still seem to match with the others. So you could make use of the temperature bias and decrease the CESM temperature (e.g. such that the mean of the (then) biased CESM temperature agrees with the mean temperature over all the other GCMs). Note that in this case the temperature bias needs to be applied additionally to the temperature bias of your spin-up and during simulation from 900-2000 CE.
- p.6, l.127-129: The BCC-CSM and CCSM4 simulation: I agree that the temperatures from 1850s onward are rising too much, but why don't you clip the results for the two simulations to the year 1850? The years 1000-1850 seem to be in the average of the results from the other GCMs. They still could provide information about the substages LIA4-LIA2.
- p.6, l.130: 'we removed this simulations': I would like to encourage you to rethink, if the complete remove is really necessary.

- Figure 2: The most important figures of this study are Fig. 2d) and 2g). That's why I would either put them in an extra figure or make them much larger (compared to the other subfigures of Fig. 2) in order to highlight them.
  - 'Regional averaged Δ ELA': It is unclear to me, if this stem from observation or if this an (with OGGM) simulated regional average?
  - Fig.2d-2i: Please add the information about the exact number of glaciers used for the mean calculation.
  - Fig.2d,e,i: Where does the Observation (dotted, black line) stem from and which year does it represent?

4.1 The Comparison between Simulations and Observations

- p.7, l.161: 'using mapped LIA glaciers': add a linkage to Section 2.3.
- p.7, l.167: 'studies from nearby area': add references
- p.8, l.171: 'overestimated of the area change': delete 'of the'
- p.8, l.180: 'makes the glacier advanced and the ELA dropped' → 'lead to an advanced glacier and the ELA falls'
- p.8, l.180: 'the amplitude of ΔELA is determined by the amplitude of SMB': I don't agree here. The glacier geometry (e.g. slope) also play an important role. The same change in SMB can lead to very different ELA changes for e.g. very steep and flat glaciers.

4.2 Why exists four LIA substages in BH

- p.8, l.195: 'is caused by the sensitivity of different glaciers': This is due to the different response times of glaciers. Unfortunately, the name 'response time' does not occur once in your text. The story about the response time/sensitivity of glaciers to climate is more complex, and can't be reduced to a correlation with glacier size only (as in your study with glacier length). Various studies (Lüthi, 2009; Zekollari and Huybrechts, 2015; Bach et al., 2018; Eis et al., 2019) showed that that response times depend more on the steepness of the surface than on the glacier size attributes (as the glacier length). To this end, I suggest that you consider other glacier characteristics than the glacier length in your analysis as well, as this would give much more weight to your argumentation. A similar plot as Fig.3 for the slope and ELA would be interesting .
- p.8, l.196: 'length of glaciers': at which time? Modern glaciers? at the reference date 1950? or during the LIA?
- p.8, l.198: 'that smaller glaciers are more sensitive to climate change compared to larger glaciers': See my first point in this section. This effect can't be reduced to the glacier size (length, area, volume) only.
- p.8, l.199: 'frequency of number of LIA substages': How are they determined for each glacier? I assume that local maxima of the length trajectory were determined for each glacier, but on which criterion is this based on?

- p.9, l.201:'the average length of glaciers': Please clarify what you mean exactly. To me, it is not clear how the "average length" (also in plot 3a) is defined exactly. To which date does the average length refer to (to the modern glacier, to the reference date 1950 or to the LIA)? I assume, that modern glaciers are meant, please correct me, if I'm wrong.

- p.9, l.202: 'consistent with the regional average length of modern glaciers': It is not surprising that they are consistent with the regional average. As it can be seen in the histogram (Fig.3b.) the majority of glaciers in the IPSL and MPI run belongs to the class with 4 substages and consequently their average is closest to the regional value.

- Figure 3: Unfortunately the number of glaciers belonging to the classes 0,1,2,6,7 is not representative and I fear that single outliers may have large influences on the average length shown in Figure 3a). When considering the representative classes (3,4 and 5) only, the relationship between the length and the number of substages does not become that clear.
  Instead of the average value you could e.g. use the median instead, as this would avoid the influence of potential outliers. Perhaps you can also show a complete distribution (e.g. by a scatter plot with points for each glacier) or (even better) a boxplot instead. This would give a much better picture, if one could see different distributions over the different substages. Please, consider the following suggestions to improve the figure, as well:

  - Please, add to the Fig.3b) the information about the total number of glaciers (n=...)
  - in fig. 3a) The different GCM's already have different colors. In my opinion, the readability of the plot could be improved by showing one marker only (e.g. points for all GCMs)
  - Is it really necessary to break the y-axis two times? The interrupted regression lines are harder to understand. If necessary, consider a logarithmic scale instead.
  - Add a label for the colored lines (I guess this is a linear regression).

- p.9, l.218-226: This paragraph is really hard to follow, as neither time periods LIA-4 to LIA-1 nor the percentages described in the text can be directly seen in the figures(S3-S5). The three figures from the supplement are relevant for this part of the study, so they should be shown here directly. This avoids that the reader needs to open the supplement in order to follow the text.

- p. 9, l.219: 'about 49% of glaciers occurred during LIA-2': In this sentence is not clear was is meant by 'of glaciers'. Do you mean the second longest length?

- p.9, l.220:'if the dated moraine belongs to these 25%': Would it be possible to link the moraine to the simulated RGI glaciers directly?

- p.9, l.222: 'by the GISS and MPI climate datasets (Fig.S4)': Figure S4 shows the IPSL dataset, not the GISS or the MPI dataset.

4.3 Climate-forcing Mechanisms

- In the introduction (p.1, l.23) your wrote that other studies showed that the advances are related to overall summer temperature. I'm missing in this section a discussion based on the findings from other studies. Please add references and discuss, if your findings agree with them.

- p.10, l.239: 'Our study revealed that the summer temperature plays a dominant role in controlling glacier changes at suborbital scales': Please, add 'in the monsoon-influenced Himalaya'.
- p.10, l.241: 'at present': In the figure is stated between modern (1950). Please, be more precice here (1950 isn't present to me).
- p.10, l.241: 'magnitude of SMB changes in summer': Do you mean cumulative values over the summer month (which month exactly)?
- p.10, l.245: 'precipitation is mainly categorized as liquid in the model ..., summer temperature was about 6.6°C during LIA, larger than 2°C (Eq.1)': I'm not sure, if this is really that simple. OGGM takes an elevation dependency for the temperature into account. The default is to use a fixed lapse rate of -6.5K km $^{-1}$. Did you take this into account or did you only had a look at the summer temperature averaged over the region?
- p.10, l.243: 'increasing summer precipitation': add cumulative
- p.10, l.247: 'cumulative positive temperature': Do you mean decreased number of positive degree days?
- Figure 4:
  - Perhaps you can consider different colors for neg. and pos. SMB changes.
  - It is confusing to me, having the label of the precipitation next to the axis of the temperature and vice versa.
  - Perhaps you can highlight the summer months in the plot.
  - 'from LIA-4 to LIA1' Please, state in the Figure caption the exact years instead of LIA-4 ...
  - Please make clear, if ΔSMB is LIA-modern oder modern-LIA.
- p.11, l.255: 'sensitivity analysis': Please, remind the reader that you performed the sensitivity experiments based on climate conditions around t^*. Make clear, that you increased/decreased the annual temperature observed in year t^* by a spec. factor.
- p.11, l.256: 'Glaciers shrink': Which glaciers? The ones of your study area? the modern or the LIA glaciers?
- p.11, l.257: 'after the annual temperature is larger than 0.5': Not the annual temperature itself is larger than 0.5, but the increase of the annual temperature in you sensitivity experiment. Same holds true for the statement with the summer temperature. Please, correct.
- p.11, l.270: 'present': present or 1950?

Supplement

- Figure S2: Please, choose different colors as in Fig.2 (from the main manuscript). This is confusing, as once associate with the same colors not different GCM's.
- Figure S3-S6:

  - Add number of glaciers represented in this (sub-)figures (e.g. n=...)
  - Perhaps you can combine these three subfigures in one figure by using different (transparent) colors. Then it would be easier to see at which time which type would be dominant at a comparison among the different types would be easier.

- Table S3: Please, add vertical lines in order to separate the four LIA events. This will improve the readability.

References

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