## Response to RC2 on "*tc-2021-352*"

We are very grateful to Prof. Julia Eis for your constructive comments after careful reading. Particularly, your suggestions/comments on model spin-up help us a lot to improve the quality of the paper. We have adopted your suggestions and carefully addressed your comments. Therefore, most sections of the paper have undergone substantial revisions.

A large number of simulations have been conducted in order to address the spin-up issues you mentioned and improve our paper quality. Major changes include ***Reworking Figures***, ***Improving Analysis Methods*** and ***Adding sections to introduce the study area and describe the spin-up processes***. According to your suggestions and the comments, our analyses have been focused on simulation results forced by the ensemble average climate (hereafter **mean climate experiment**) rather than each individual climate dataset. In order to alleviate the influence of glacier size to the mean value (i.e., to address the issue that long glaciers dominate the regional average), we use glacier length change ratio ($GLR = \frac{\Delta L}{L_{1950}}$) instead of $\Delta L$, in which $L_{1950}$ represents the simulated glacier length at 1950 while $\Delta L = L - L_{1950}$. Notice that the abbreviation *GLR* will often occur in this reply. We have also added two figures (Fig. R2 and RS1) to illustrate the spin-up processes and one figure (Fig. R3) to show the distribution of simulated *maximum peak GLR* (defined in the reply to p.4, 1.94) bias during the LIA. Fig. 4 and Fig. 5 in the original paper has also been merged together as Fig. R8 in the revised paper. Fig. 2 in the original paper has been split to Fig. R4 and Fig. R7 in the revised paper according to your suggestions. For clarity, we have posted all revised figures at the end of the reply. In addition, we have updated our codes from OGGM v1.2.0 to OGGM v1.5.0. Major changes are summarized here followed by point-to-point responses to each comment. Reviewer's comments are in black color and our responses are in blue color.

### General Comments:

1. **Response time of glaciers:** Previous studies shown 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 complete distribution than on the average value (this comment relates to the analysis shown in Fig. 3a).

**Reply:** We agree with you that there exist complex mechanisms behind the response time of a glacier to the climate, which cannot be easily explained. Therefore, we consider it is a good idea to expand the analysis to more specific glacier properties rather than just glacier length. We have found that glacier slope has the significant positive correlation with the substage numbers while has significant negative correlation with the glacier length. This indicates that the negative correlation between the glacier length and substage numbers might be a result of that the longer (larger) glacier has a smaller slope. Besides, analysis also suggests weak relationship between glacial substage numbers and glacial ELA. In addition, in order to show the performances of each glacier, we use boxplot instead of scatter plot.

2. **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 $\beta$ aren't shown and the tested value range with only 3 values (-1, 0, 1) seems questionable.

**Reply:** According to your comments, we have

1) densified the sensitivity tests that varies $\beta$ from -1 to 0 °C with an increment of 0.1 °C.
2) added a figure (Fig. R2) to show the sensitivity tests results with various $\beta$.
3) added "spin-up" section to explain why the parameter tuning is necessary and how the spin-up is set up.

3. **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 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.

**Reply:** We also feel it is a pity to directly remove three datasets from a total of six. Therefore, we have improved the data analysis methods so that all of the simulation results can be used. As shown in Fig. R4, with improved data analysis methods, the variations of regional averaged *GLR* can be clearly detected from the simulation results forced by CESM, CCSM4 and BCC-CSM, comparable with the others. The improved data analysis methods have been described in detail in the reply to specific and technique comments.

4. **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.

**Reply:** Thank you for your suggestions. Our analyses have been focused on mean climate experiment rather than each individual GCM dataset. We think this change would make the paper clearer and easier for the readers to follow.

5. **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 modelled 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 glacier 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 data for most of your analysis)? Is the regional glacier length dominated by a few large glaciers?

**Reply:** Based on your comments, we have added a paragraph to describe the study sites and reworked the Fig.1 in the original paper (here Fig. R1). Following is brief introduction to our study area:

The BH (27.5~28.3°N, 89.1~91.0°E) is an east-west-trending mountain range belonging to the monsoon influenced Himalaya (Fig. R1a). With an average elevation above 5000 m a.s.l (above sea level), typical high mountain glaciers are developed in BH (Peng et al., 2019, 2020; Fig. 1b). According to the Randolph Glacier Inventory V6.2 (RGI; RGI Consortium, 2017), there exist 803 modern glaciers in BH, covering an area of ~ 1233.685 $km^2$. Fifty-seven glaciers belong to RGI13 region (Central Asia) and 746 glaciers belong to RGI15 region (South Asia East). The average glacier length is 1596 m (950 m for median value) with a range from 135 to 20011 m. The distribution of glacier length is shown in Fig. R1c with small glaciers (length shorter than 3000 m) dominating the BH (accounting for 88.9 %).

6. **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.

**Reply:** Thank you for your comments. We have revised all the figures in the original paper and make them easier for the readers to understand. The revised figures can be found at the end of this reply. Unclear sentences, expressions have been changed according to your specific and technical comments. In addition, we will be very careful to this point when revising the paper.

7. **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 glacier 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.

**Reply:** According to your comments, we have
1) provided a brief introduction to the relevant parameters used in PDD scheme and dynamic core.
2) added a paragraph to describe the study sites and glaciers simulated (including RGI information).
3) added a paragraph to illustrate how the glacial substage is determined (the improved data analysis method).

We will try our best to ensure that our study can be reproduced by fellow scientists.

## Specific and technical comments:

### Title

I have 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.

**Reply:** We have changed the title from "Modelling Glacier Evolution in Bhutanese Himalaya during the Little Ice Age" to "Timing and climate-driven mechanisms of glacier advances in Bhutanese Himalaya during the Little Ice Age".

## Abstract

- **p.1, l.12:** 'six paleo-climate datasets': True, but you exclude three of them and all your finds area based on those three.

**Reply:** As we have improved our data analysis method, the simulation results from six paleo-climate datasets have all been used. In addition, we have added a mean climate experiment according to your suggestions. Therefore, we have changed the expression "… using the Open Global Glacier Model and six paleo-climate datasets" into "… using the Open Global Glacier Model forced by six paleo-climate datasets and their ensemble average".

- **p.1, l.12:** delete the 'the' before mapped

**Reply:** We have deleted.

- **p.1, l.13:** 'driving by' → 'driven by'

**Reply:** We have corrected.

## 1 Introduction

- **p.2, l.34:** delete 'on'.

**Reply:** We have deleted.

- **p.2, l.35:** the word 'substage' is explained in Sect. 3(p.6, 1.133). Please explain it here, as this is the first use (excluding the abstract).

**Reply:** We have explained the word 'substage'. This sentence has been revised to "… how many substages (glacial advances) exist …".

- **p.2, l.39:** 'cross-validated': I think cross-validated is the wrong expression here. The more general term 'evaluated' would fit better. A cross-validation is a specific statistical evaluation method across many others.

**Reply:** Thanks for your correction. We have used "evaluated" instead of "cross-validated".

- **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…'

**Reply:** According to your suggestion, we have revised this sentence into "… resulted from an imperfect understanding on how to bring observation and simulation together…".

- **p.2, l.45:** 'works' → 'work' (work has no plural)

**Reply:** We have corrected.

- **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.

**Reply:** We have fundamentally revised Fig. 1 in the original paper, including removing the redundant elements (Lakes, Elevation at the moraine sites and etc.) and highlighting the necessary information (Glacier locations, numbers and length distribution), making the figure clearer. You can find the revised figure (Fig. R1) at the end of the reply.

We choose to use DEM as the background considering that DEM can gives readers a general overview of the landforms in Bhutanese Himalaya and indicates these glaciers are high mountain glaciers. The DEM used is obtained from the Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Model (DEM) v4.1 (Jarvis et al., 2008; http://srtm.csi.cgiar.org/).

– 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.

**Reply:** We have deleted the gray plot in the upper right corner of Fig. 1a and labelled each subplot in the revised Figure. Please see Fig. R1.

– Elevation labels: The labels in the two subplots are not consistent. In Fig. 1a) the elevation is shown colored with 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.

**Reply:** As we have deleted Fig. 1a, the inconsistent legend issues is no longer a problem. In the revised figure (Fig. R1), we have chosen to use continuous color map to represent the DEM.

– 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?

**Reply:** We have reworked the Fig. 1 to make it clearer. We grouped the moraine ages based on their temporal distances to each glacial substage simulated in mean climate experiment. However, the age of moraine M1 (Cogarbu valley) is range from 1077 ± 228 to 1867 ± 15 CE. Due to its large bias, it cannot be grouped to any substage. In the revised paper, we have improved the moraine age determination method advocated by Chevalier et al. (2011) and Dong et al. (2018). As a result, all the moraines can be 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 I the figure caption) the number of glaciers shown here.

**Reply:** In original paper, "Glacier" class in Fig. 1a refers to modern glaciers. In the revised paper, we have deleted the Fig. 1a. In addition, we have added the reference of the modern glacier outlines in the new figure (Fig. R1).

– 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.

**Reply:** According to your suggestion, we have deleted the lakes in the new figure (Fig. R1).

– 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 moraine. Please, add the information about the recalculation of the ages in the text and not in the figure caption.

**Reply:** We have revised and clarified the figure caption as "Fig. R1. An overview of study area and moraine sites. The red box in (a) shows the location of the study area and the green circles in (a) displays the spatial distribution of the $^{10}$Be exposure dating moraines. The basic information of these moraine sites can refer to Table S1. (b) The extent of the modern glaciers (in light blue; RGI Consortium, 2017) and LIA glacier (in navy blue). The background DEM is obtained from the Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Model v4.1 (Jarvis et al., 2008; http://srtm.csi.cgiar.org/). (c) The length distribution of modern glaciers."

## 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 the 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).

**Reply**: Thanks for your suggestions. We will add a brief introduction to parameters used in the dynamic core, as well as the relevant parameters used in the SMB calculation. E.g., "The creep parameter $A$ and the sliding parameter $f_s$ in the dynamical core are set to their default vales ($A = 2.4 \times 10^{-24}\ s^{-1}\ Pa^{-3}$, $f_s = 0$, 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 wishes to reproduce the results.

**Reply:** We have added some sentences to introduce the border parameter used in this study as "According to the observations, the largest simulation domain is set to 160 grid points outside the modern glacier boundaries to ensure that glaciers large enough for the LIA can be generated. If one glacier advances exceeding the domain during the simulation, we will exclude this glacier in the further analysis due to its large simulation bias."

- 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 exist (via geometrical centerlines and via elevation bands flowlines). Please, add an information which OGGM version you used for the study, as well as which parameter representation was used.

**Reply:** We have corrected this sentence and added the information of the flowline exist.

“The OGGM (v.1.50) is a 1.5D ice-flow model, to simulate…”.

“… flowlines that are diagnosed from a pre-process algorithm (via geometrical centerlines).”

- 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

**Reply:** Thank you for your information. We have added some information about previous studies using OGGM in High Mountain Asia. For example:

“In addition, OGGM has also been successfully applied to simulate High Mountain Asia glaciers, including their thickness, velocity, and future evolution (Dixit et al., 2021; Pronk et al., 2021; Shafeeque & Luo, 2021; Furian et al., 2022; Chen et al., 2022).”

- 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.

**Reply:** We have added the reference there.

“… with a dynamic core (Marzeion et al., 2012; Maussion et al., 2019).”

“… of non-climate factors (Marzeion et al., 2012; Maussion et al., 2019).”

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

**Reply:** We have corrected.

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

**Reply:** We have corrected.

- 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 glacier 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 the default setting of OGGM (due to 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 need 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 from 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.

**Reply:** Thank you for your kindly reminder. We have deleted the expression “to better capture the changes of individual glaciers" in the text.

## 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 cover of the GCMs (e.g. all datasets cover the period 850 CE – 2000 CE)

**Reply:** We have added the above information as "The monthly temperature and precipitation datasets from six different GCMs (BCC, CCSM4, CESM, GISS, IPSL, and MPI), covering the period from 850 CE to 2000 CE, were used as climate forcing to drive OGGM".

- 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.

**Reply:** We have rearranged this sentence into "We spined-up the model to avoid the influence of the initial condition and tuned the parameter, temperature bias ($\beta$) in Eq. 1, to obtain a better estimation of the long-term glacier evolution (Eis et al., 2019)."

- p.4, 1.89: '600-year spin-up': Please, proof that the 600 years are long enough and the initial condition does not influence 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 extent 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 data) 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.

**Reply:** With extending the spin-up time to 5000 years in the sensitivity tests (varying $\beta$ from -1 to 0), we agree with you that 600 years spin-up time are really not long enough for all the glaciers reaching steady state. From the experiments, we have found that all glacier can go into steady state within 2000 years spin-up time and the required spin-up time decreases with increased $\beta$. Therefore, we have re-simulated all the control experiments ($\beta$ = -0.4) with the spin-up time extending to 2000 years.

In addition, in order to examine whether the glaciers reach the "true" steady state, we compared the spin-up results from two different beginnings, a) present-day condition and b) zero-ice volume condition, with $\beta = -1$ (as $\beta = -1$ requires longest spin-up time). We found that no obvious difference between two simulations. Therefore, we ensure that the glaciers do reach steady state within 2000 years spin-up time. The spin-up results are shown in Fig. R2.

- p.4, 1.90: '51-year window': The default value in OGGM is 31 years. Is there a specific reason that you chose 51 years?

**Reply:** There is no specific reason for us to choose "51-year window". Our original choice of "51-

year window" is motivated by Parkes & Goose (2020) as they have done similar simulation as our study. They simulated the regional glacier length changes over the last millennium using the OGGM. A 300-year spin-up using annual climate data selected randomly from a 51-year window of 875-925 CE from each GCMs is adopted in their study.

- p.4, 1.90: '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?

**Reply:** This choice is still motivated by Parkes & Goose (2020). In addition, we have limited our simulation to the year 1100 in the revised paper just for clearly showing the glacial fluctuations during the LIA (1300-1850 CE).

- p.4, 1.91: 'tunable parameter $\beta$': Please, add the name of the parameter as well (temperature bias).

**Reply:** We have added the name. "We spined-up the model to avoid the influence of the initial condition and tuned the parameter, temperature bias ($\beta$), in Eq. 1 in order to better estimate the long-term glacier evolution."

- p.4, 1.92: 'adjust $\beta$ from -1 to 1 °C with an increment of 1 °C': testing 4 values (-1, 0, 1) isn't enough for a sensitivity test. Besides that, deciding for a 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.

**Reply:** We have densified the sensitivity tests varying $\beta$ from -1 to 0 °C with an increment of 0.1 °C. The simulation results are shown in Fig. R2.

- p.4, 1.92: '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 years spin-up or after the start of your simulation in 900 CE?

**Reply:** We only applied $\beta = -1$ during the spin-up period. In the original paper, "*The first 250 years*" refers to the first 250 years after the simulation in 900 CE. However, in the revised paper, this sentence will be deleted, as a detailed analysis on the impact of $\beta$ on spin-up results will be introduced in the spin-up section.

- p.4, 1.94: Please, reformulate this sentence. It is hard to understand. If I understood it correctly, you tuned $\beta$ 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 constant value over time. Thus, the volume trajectory is shifted the time of a glacial maximum to an earlier/later time. I may have misunderstood this part, and I 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.

**Reply:** This sentence might be misleading and we will reformulate it in the revised paper. As $\beta$ is applied only during the spin-up period, it directly controls the initial condition (i.e., the length/area/volume of initial glaciers) and largely impact the *GLR* during LIA substage 4 (LIA4).

However, it does not have obvious influence on the start time of LIA4. Fig. R2 shows the parameter tuning results. Our tuning strategy is to:

1) ensure the regional average *GLR* is longer during LIA4 than LIA1 as in the observations (more LIA1 moraines can be detected than LIA4). According to this criterion, simulations with $\beta \geq -0.3$ will be excluded.

2) make the simulated ***maximum peak GLR*** (*defined as the GLR when a glacier reaches its maximum peak during a period. It is different from the maximum GLR. For example, in Fig.R2, the maximum peak GLR occurs around 1300 CE rather than 900 CE (maximum GLR) in all simulations*) closer to the observations (i.e., has smaller bias; Fig. R3). Notice that we use *maximum peak GLR* because the observations derived from the geomorphological mapping methods (find the most obvious moraines) can only obtain this variable during LIA. This is due to the fact that moraine will only be formed when the glacier experiences a fluctuation (an advance followed by a retreat). The stronger the fluctuation is, the more obvious the moraine will be formed.

3) let more glaciers be available in the analysis. For example, the simulation bias of *maximum peak GLR* has no obvious differences between $\beta = -0.4$ experiment and $\beta = -0.5$ experiment (Fig. R3 a, b). However, more glaciers would be available in the $\beta = -0.4$ experiment (N=272) as less glaciers will run out of the border with a larger $\beta$.

- 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!

**Reply:** We agree with you. With extending the spin-up time to 2000 years, all the glaciers simulated reach steady state. This issue no longer exists! However, we still start our analysis at the year 1100 in the revised paper for a better display of the glacial fluctuations during the LIA (1300-1850 CE).

- 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.

**Reply:** Thank you for your suggestion. We will add some transitional sentences here to briefly describe the purpose of sensitivity tests in the revised paper. "In addition, we also conduct a series of sensitivity experiments to explore the glaciers response to monthly climate changes as more and more studies have found that the seasonal climatic factors are more important to glacier evolutions than the annual climate (Yan et al., 2020, 2021)."

## 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.

**Reply:** Tuning temperature bias (e.g., artificially set a negative bias when using CESM forcing data) is indeed a good method to obtain a best performance of the glacier simulation. However, in this study, our purpose is to explore the glacial substage numbers during the LIA as well as its mechanism. Using different climate datasets to force the OGGM is to show the robustness of the signal (four glacial substages during LIA) rather than pursuing a best performance. For this goal, we think tuning temperature bias during simulation is unnecessary.

Meanwhile, we also feel great pity to directly remove three datasets from a total of six. Therefore, we have improved the data analysis methods so that all of the simulation results can be used. As shown in Fig. R4, the variations of regional averaged *GLR* can also be clearly detected from the simulation results forced by CESM, CCSM4 and BCC, comparable with the other three.

- p.6, 1.127-192: The BCC-CSM and CCSM4 simulation: I agree that the temperature 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, 1.130: 'we removed this simulation': I would like to encourage you to rethink, if the complete remove is really necessary.

**Reply:** As we have improved our analysis methods, it is able to include all six simulation results. Please see Fig. R4.

- 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.

**Reply:** We have reworked the Fig. 2 in the original paper according to your suggestions. Fig. 2 in the original paper has been split to Fig. R4 and Fig. R7 in the revised paper and the important figures has been enlarged.

– 'Regional averaged ΔELA': It is unclear to me, if this stem from observation or if this an (with OGGM) simulated regional average?

**Reply:** In the original paper, the regional averaged ΔELA is stemmed from the observation. In the revised Fig. R7, we have replaced ΔELA by real ELA.

– Fig.2d-2i: Please add the information about the exact number of glaciers used for the mean calculation.

**Reply:** In this revised paper, we will discuss the number of glaciers used for each experiment in the spin-up Section.

– Fig.2d,e,i: Where does the Observation (dotted, black line) stem from and which year does it present?

**Reply:** ΔLength in Fig. 2d in original paper is the same concept as *GLR* but for observation length. Similarly, Δarea in Fig. 2e in original paper is also the same calculation method as *GLR* but for observation area. As for the black dotted line in Fig. 2i, it just represents the zero line.

### 4.1 The Comparison between Simulations and Observations

- p.7, 1.161: 'using mapped LIA glaciers': add a linkage to Section 2.3.

**Reply:** We have added the linkage. **"**We validated the simulation results using mapped LIA glaciers (Section 2.3)."

- p.7, 1.167: 'studies from nearby area': add references

**Reply:** We have added the references. "… from nearby area (Qiao & Yi, 2017; Zhang et al., 2018)."

- p.8, 1.171: 'overestimated of the area change': delete 'of the'

**Reply:** We have corrected.

- p.8.1.180: 'makes the glacier advanced and the ELA dropped' → 'lead to an advanced glacier and the ELA falls'

**Reply:** We have corrected.

- p.8, 1.180: '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.

**Reply:** Although the slope has great impact on glacier ELA, the slope of a certain glacier does not experience obviously change during the LIA based on our simulations. Therefore, we argue that ΔELA of a certain glacier is dominated by the SMB change during LIA. As the regional average ΔELA is the average of each glacier ΔELA, we conclude that the regional average ΔELA is largely affected by regional average SMB change.

## 4.2 Why exists four LIA substages in BH

- p.8, 1.195: '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 the 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 slope and ELA would be interesting.

**Reply:** According to your suggestions, we have expanded our analysis to glacier slope and ELA. We have found that glacier slope has the significant positive correlation with the substage numbers while has significant negative correlation with the glacier length. This indicates that the negative correlation between the glacier length and substage numbers might be a result of that the longer (larger) glacier has a smaller slope. I Besides, analysis also suggests weak relationship between glacial substage numbers and glacial ELA.

- p.8, 1.196: 'length of glacier': at which time? Modern glaciers? at the reference date 1950? or during the LIA?

**Reply:** "length of glacier" refers to the modeled glacier length at 1950.

- p.8, 1.198: '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, are, volume) only.

**Reply:** We agree with your opinion that the mechanisms behind the response time of a glacier to the climate is complex, which cannot be simply ascribed to the glacier length. Therefore, we have tried to expand our analysis to more specific glacier properties (i.e., ELA and slope). We have found that glacier slope has the significant positive correlation with the substage numbers while significant negative correlation with the glacier length. This indicates that the negative correlation between the glacier length and substage numbers in the original paper might be a result of that the longer (larger) glacier has a small slope. We will add a detailed discussion about this in the revised paper.

- p.8, 1.199: '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?

**Reply:** According to your comments, we have added a paragraph to describe the identification method of glacial substages in detail.

"Similar to Goosse et al., (2018) and Parkes & Goosse, (2020), we used simulated glacier length change ($\Delta L = L - L_{1950}, where\ L_{1950}\ represents\ the\ simulated\ glacier\ length\ at\ 1950$) to analyze glacier evolution. In order to alleviate the influence of glacier size to the mean value (i.e., to address the issue that long glaciers dominate the regional average), we further convert $\Delta L$ into glacier length change ratio ($GLR = \frac{\Delta L}{L_{1950}}$). Before we start our analysis, we firstly exclude the glaciers with simulated length equal to zero at 1950 because these glaciers have large simulation biases according to the observations (RGI). Then, decadal mean GLR was calculated for each glacier in order to smooth the annual cycles. Next, the Gaussian Filter (standard deviation is set to 3) is applied to the decadal mean GLR for each glacier in order to extract the main oscillations. After that, we calculated the regional average GLR by averaging all glaciers' GLR (decadal averaged and Gaussian Filtered) within the domain. Finally, we try to find all peaks and their corresponding times in the regional average GLR based on the "findpeaks" function embedded in Matlab Software. Each peak found is defined as a glacial substage during the LIA. We name the substages from new to old (LIA-1, LIA-2…). We applied this identification method to all experiments and the identification results can be seen in Fig. R4."

p.9, 1.201: '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, or the reference date 1950 or to the LIA)? I assume, that modern glaciers are meant, please correct me, if I'm wrong.

**Reply:** In the original paper, "the average length of glaciers" is refer to the average length of the modern glaciers which have four glacial substages during LIA.

- p.9, 1.202: '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 closet to the regional value.

**Reply:** This is true.

- 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:

**Reply:** Thank you for your suggestions. We have changed original scatter figure into boxplot (Fig. R5) and used median value rather than average value to do the analysis.

– Please, add to the Fig.3b) the information about the total number of glaciers (n=...)

**Reply:** We will give the detailed information in the spin-up section in the revised paper.

– 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)

**Reply:** We will only show the results of the mean climate experiment here in the revised paper instead of every GCM result for clarity (Fig. R5). Each GCM result will be posted in the supplementary.

– 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.

**Reply:** We have revised this figure. In the new figure (Fig. R5), we use linear y-axis.

– Add a label for the colored lines (I guess this is a linear regression).

**Reply:** In Fig. R5a (revised), we do not use the lines.

- P.9, 1.218-226: 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 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.

**Reply:** We have reworked the Fig. S3 – Fig. S5 for a clearer display. We have added the time periods LIA-4 to LIA-1 in the figure and change Y axis into percentages. In addition, we have moved revised the Fig. S3 to Fig. S5 from supplement to the main text (Fig. R6).

- P.9, 1.219: '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?

**Reply:** It means the ***second largest peak GLR***. For clarity, we have changed this expression into "As illustrated in Fig. R7, among all the glaciers with multi peaks (substages), 49.0 % of the *glaciers experienced their second largest peak GLR* during LIA-2 while 25.5 % of *glaciers experienced their second largest peak GLR* during LIA-3."

- p.9, 1.220: 'if the dated moraine belongs to these 25 %': Would it be possible to link the moraine to the simulated RGI glaciers directly?

**Reply:** When we focus on simulating one certain glacier, we can directly link the moraine to the simulated glaciers if the dated moraine sequences are complete and accurate. However, it is useless for our study to do this because our purpose is to explore regional glacial evolutions rather than accurately simulating one certain glacier. In fact, there only exist two dated moraines in our study area and unfortunately, they do not have complete sequences. Therefore, as we just want to represent the regional average situation, we also adopt many dated moraines outside our study area as supplements.

- p.9, 1.222: 'by the GISS and MPI climate datasets (Fig. S4)': Figure S4 shows the IPSL dataset, not the GISS or the MPI dataset.

**Reply:** We have focused on the mean climate simulation results instead of each GCM simulation results in the revised paper. Therefore, we will delete this part in the revised paper.

### 4.3 Climate-forcing Mechanisms

- In the introduction (p.1, 1.23) you 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 finds from other studies. Please add references and discuss, if your findings agree with them.

**Reply:** We will add the relevant references and discussions in revised paper. "Our study has revealed that the summer temperature dominates the glacier changes at sub-orbital scales in the monsoon-influenced Himalaya. This extends the previous conclusion that not only at the orbital scales (Yan et al., 2020, 2021) but also at the sub-orbital scale, the glacial evolutions are mainly regulated by the summer temperature changes. In addition, we have found that the summer temperature changes during LIA are closely related to volcanic activities (Miller et al., 2012; Gao et al., 2008)."

P.10, 1.239: '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'.

**Reply:** We have changed this sentence into "Our study revealed that the summer temperature plays a dominant role in controlling glacier changes at suborbital scales in the monsoon-influenced Himalaya."

- p.10, 1.241: 'at present': In the figure is stated between modern (1950). Please, be more precise here (1950 isn't present to me).

**Reply:** Thank you for your suggestion. We will change all the words "modern" (which represents 1950 in the original paper) into 1950 for clarity in the revised paper.

p.10, 1.241: 'magnitude of SMB changes in summer': Do you mean cumulative values over the summer month (which month exactly)?

**Reply:** Yes, SMB here means cumulative SMB over the summer month (JJA).

- p.10, 1.245: 'precipitation is mainly categorized as liquid in the model…, summer temperature was about 6.6 ℃ during LIA, larger than 2 ℃ (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 -6.5 K $km^{-1}$. Did you take this into account or did you only had a look at the summer temperature averaged over the region?

**Reply:** Further analysis found that strong ablation at the lower part of the glacier (below ELA) is the key to the fact that increasing/decreasing summer (JJA) precipitation does not have much influence on the simulation results of glacier length. We have checked that glacier volumes increase with enhanced precipitation in JJA (i.e., still exists solid precipitation in JJA), but the length of glacier changes only a little due to the strong ablation at the lower part of the glacier. Therefore, we will change this expression in the revised paper.

- p.10, 1.243: 'increasing summer precipitation': add cumulative

**Reply:** We have added.

- p.10, 1.247: 'cumulative positive temperature': Do you mean decreased number of positive degree days?

**Reply:** Reducing summer temperature will not only decrease the number of positive degree days but also decrease the average temperature during the 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 or modern-LIA.

**Reply**: Fig. 4 (here Fig. R8) in the original paper has been thoroughly changed according to your suggestions.

1) positive SMB is shown in red while negative SMB is shown in blue.
2) Precipitation and Temperature are divided into two sub-figures for clarity.
3) We use exact years instead of LIA4-LIA1.
4) ΔSMB is LIA-1950s.

- p.11, 1.255: 'sensitivity analysis': Please, remind the reader that you performed the sensitivity experiment based on climate conditions around $t^*$. Make clear, that you increased/decreased the annual temperature observed in year $t^*$ by a spec. factor.

**Reply:** We will clarify this expression in the revised paper.

- p.11, 1.256: 'Glaciers shrink': Which glaciers? The ones of your study area? The modern or the LIA glaciers?

**Reply:** We have changed this sentence into "The regional average glacier length decreases gradually in response to …".

- p.11, 1.257: 'after the annual temperature is larger than 0.5': Not the annual temperature itself is larger than 0.5, but the increase of annual temperature in you sensitivity experiment. Some holds true for the statement with the summer temperature. Please, correct.

**Reply:** We will change this expression into "…and disappear after the annual temperature increases by more than 0.5 °C" in the revised paper.

- p.11, l.270: ‘present’: present or 1950?

**Reply:** “… glacier length increased about 187.1 %, 267.5 %, 91.0 % longer than the simulated modern glacier length.”

## 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.

**Reply:** We have deleted this figure and shown the results of the BCC, CCSM4, and CESM experiment in Fig. R4.

- Figure S3-S6:

– Add number of glaciers represented in this (sub-)figures (e.g. n=...)

**Reply:** We have added the number of glaciers (Fig. R6).

– 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.

**Reply:** We will only show the results of the mean climate experiment in Fig. R6.

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

**Reply:** We have added the vertical lines.

## Figures:

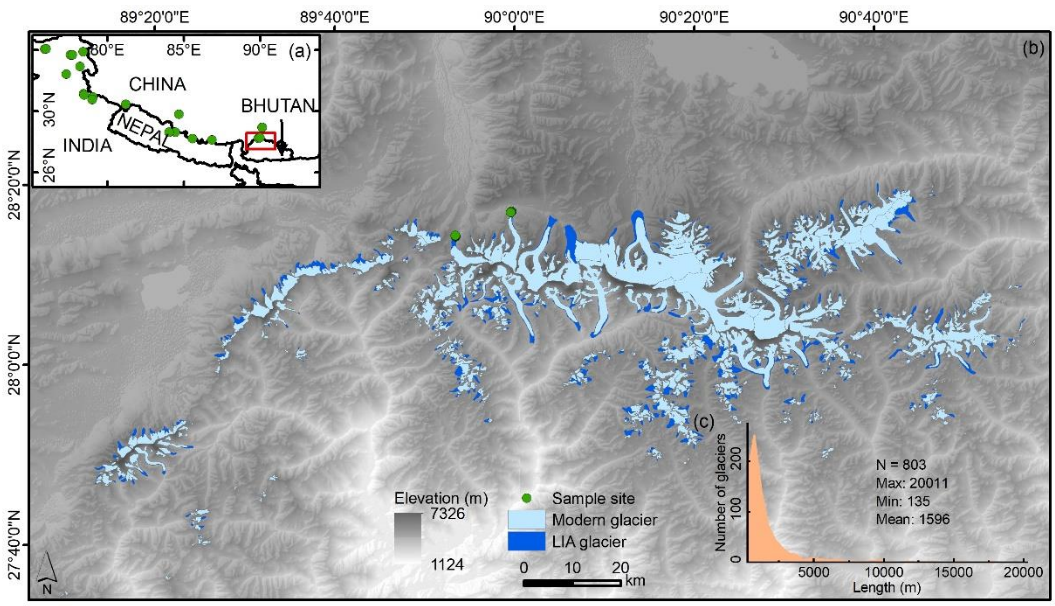


Figure R1. An overview of study area and moraine sites. The red box in (a) shows the location of the study area and the green circles in (a) displays the spatial distribution of the $^{10}$Be exposure dating moraines. The basic information of these moraine sites can refer to Table S1. (b) The extent of the modern glaciers (in light blue; RGI Consortium, 2017) and LIA glacier (in navy blue). The background DEM is obtained from the Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Model v4.1 (Jarvis et al., 2008; http://srtm.csi.cgiar.org/). (c) The length distribution of modern glaciers.

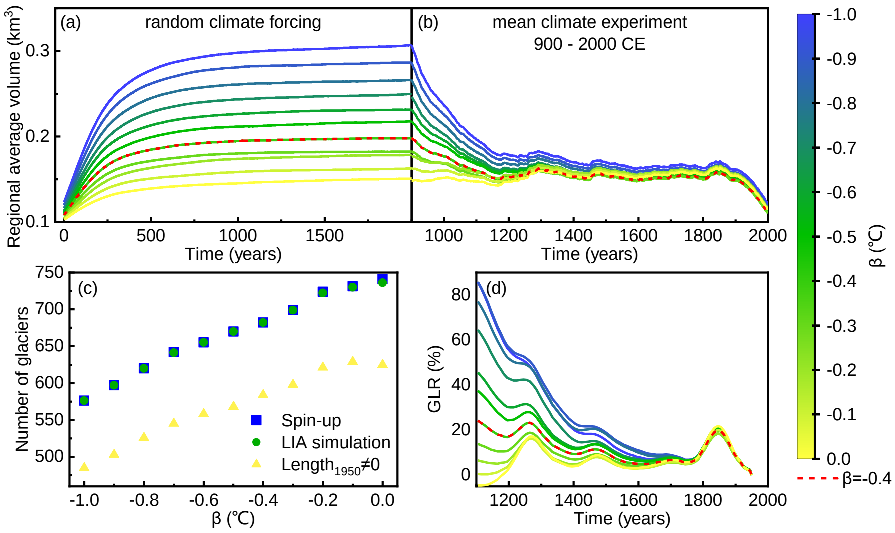


Figure R2. (a) The regional average glacier volume during the 2000-year spin-up with various *β*. (b) The simulated regional average glacier volume from 900 to 2000 CE with different initial condition. (c) The number of available glaciers with various *β*. (d) The simulated regional average *GLR* from 1100 to 1950 CE.

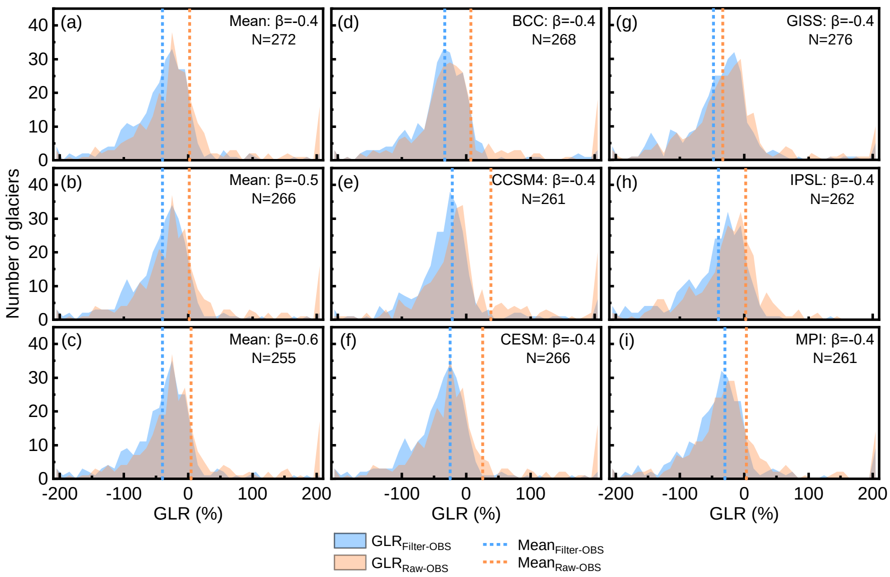


Figure R3. The simulation bias distribution of *maximum peak GLR*. The raw (unprocessed) results are shown in orange while Gaussian-filtered results are in blue. The dash blue line represents the mean value of the Gaussian-filtered results while the dash red line means the mean value of the raw results. The forcing data, *β*, and the number of glaciers used to observation-simulation comparison (N) are also shown in the top right corner of the figure.

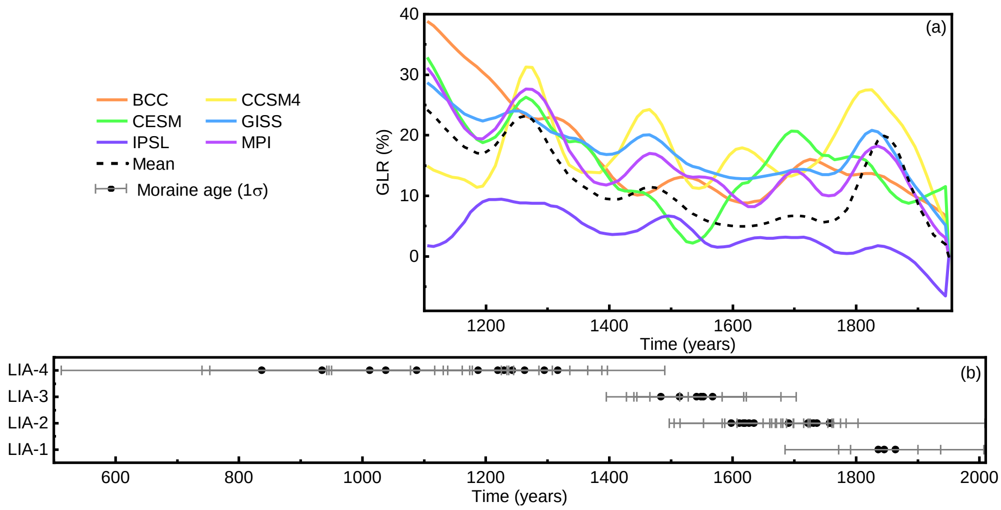


Figure R4. (a) Time series of regional average *GLR* from 1100 to 1950 CE. (b) The moraine ages in the monsoon-influenced Himalaya. The detailed information of the moraines can be found in Table S1.

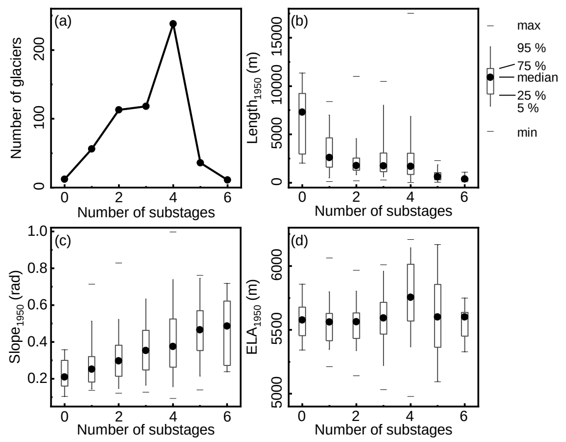


Figure R5. (a) The identified glacial substages number distribution in the mean climate experiment. The relationship between identified glacial substages with (b) glacier length, (c) glacier slope, and (d) glacial ELA at 1950 in the mean climate experiment.

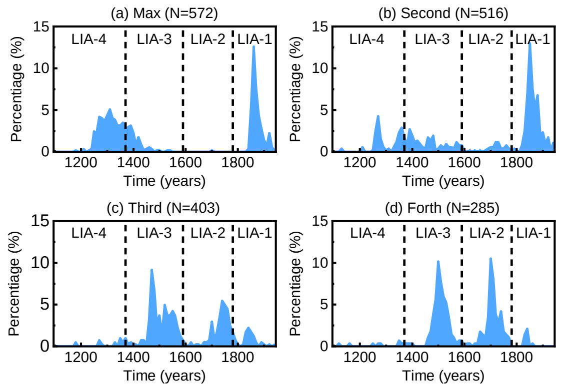


Figure R6 The percentage of the glaciers with (a) *maximum peak* GLR, (b) the *second largest peak* GLR, (c) the *third largest peak* GLR, and (d) the *fourth largest peak* GLR over time in the mean climate experiment.

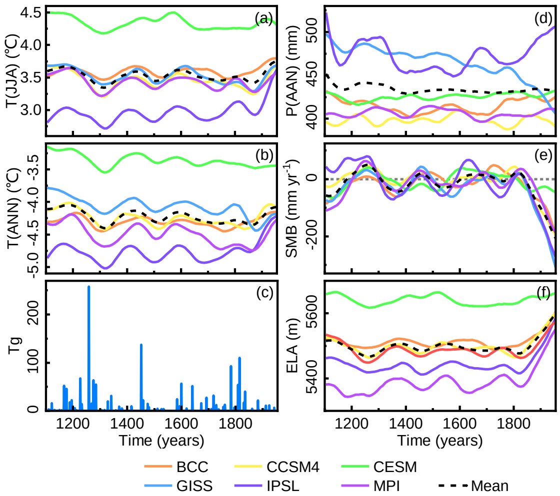


Figure R7. The regional average (a) summer temperature (T(JJA)), (b) annual temperature (T(ANN)), (d) annual precipitation (P(ANN)), (e) SMB, (f) ELA from 1100 to 1950 CE at a decadal timescale. (c) Global stratospheric sulfate aerosol loadings (Gao et al., 2008).

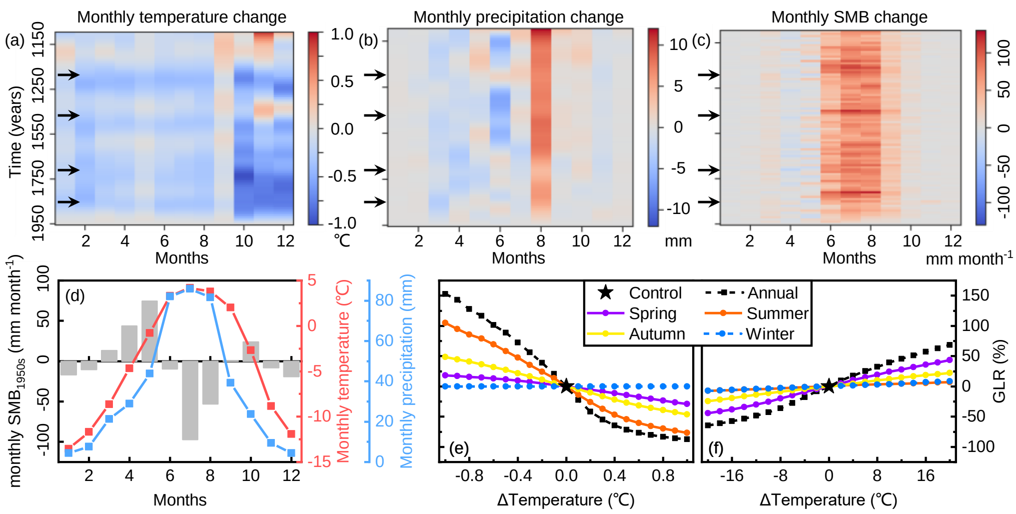


Figure R8. The monthly (a) temperature, (b) precipitation, and (c) SMB changes relative to 1950s at a decadal timescale in the mean climate experiment. The arrows in (a) – (c) represent the time of the four glacial substages, 1270s (LIA-4), 1470s (LIA-3), 1710s (LIA-2), and 1850s (LIA-1). (d) the monthly temperature, precipitation, and SMB distribution in 1950s. Sensitivity of GLR to annual or seasonal (e) temperature and (d) precipitation.

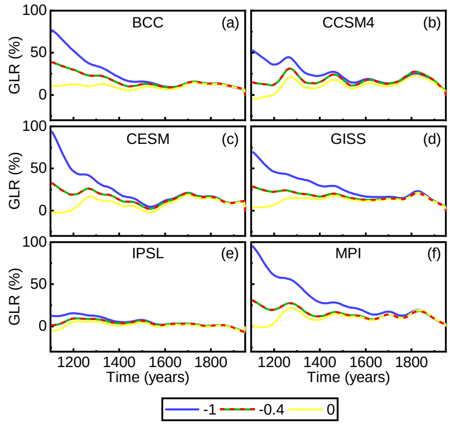


Figure RS1. The regional average GLR from 1100 to 1950 CE with different $\beta$ in (a) BCC, (b) CCSM4, (c) CESM, (d) GISS, (e) IPSL, and (d) MPI experiment.

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