Response to RC3 on "*tc-2021-352*"

We would like to thank Prof. David Parks for your careful reading and constructive comments. We have ***clarified the terminology***, ***improved the methodology***, ***reorganized the results*** and ***reworked the figures*** in the revised paper. 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:

This paper exhibits a fairly well-established use case of OGGM that doesn't offer much that's novel over other studies using this model, but I don't consider that particularly necessary – repeated use of models in similar configurations and comparison of results with additional observational datasets is useful in establishing model robustness. The focus on a specific – and important – region and the use of moraine and surface exposure ages adds value to the model runs, and the sensitivity experiments are effective and provide context for glacier response over the study period.

As written, the identification of sub-stages in the LIA does not seem compelling to me, and lacks sufficient cohesion between models to suggest that each is the result of the same set of real changes in climate across models where they are identified. Ideally, I would want to see the material enhanced with an **explicit metric** by which the sub-stages can be identified both within and between the modelled timeseries. I like the idea of identifying smaller periods of pre-industrial variation within a smaller area, as an enhancement to identification of global- and regional-scale long-term variation, but it needs more work.

Assuming a comprehensive revision of the LIA substages material is conducted, addressing the terminology, methodology, and results, I think the paper will be of clear interest and value to the glaciology community.

Reply:

Thank you for your comments and suggestions. As your main concern is the methodology to identify the glacial substages, we have reorganized Section 2 (Method) in our revised paper and added a detailed description of the identification method.

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 ΔL 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.

Specific Comments:

1. Figure 1: The colors for lakes and glaciers in (b) overlap with the colours used in the elevation map they are overlaid on, which hurts readability. It is necessary to represent modern glaciers with two colors, and to represent lakes at all? I would recommend simplifying to a single modern glacier colour, a single LIA glacier extent colour, and the background image.

Reply: We have deleted the lakes and used the light blue to represent the modern glacier extent while the navy blue to represent the LIA glacier extent (here Fig. R1).

2. Including markers for major volcanic events on the graphs of temperature and glacier change is necessary where the LIA substages are identified, as this is one of the major drivers of the negative temperature anomalies resulting in glacier advance.

Reply: We have added a subplot to show the global stratospheric sulfate aerosol loadings (Fig. R7c; Gao et al., 2008), which can represent the volcanic activities. In addition, we have added some discussions on the impact of volcanic activities on the climate during the LIA in Section 4.3 (Climate-forcing Mechanisms).

"The four cold periods during the LIA in Bhutanese Himalaya are closely linked to four large stratospheric sulfur-rich explosive eruptions events (sulfate aerosol loadings > 60 Tg; Figure R7c; Gao et al., 2008). The beginning of oldest cold period (LIA-4) might be forced by a series of volcanic activities, including a massive tropical volcanic eruption in 1257 followed by three smaller eruptions in 1268, 1275, and 1284 (Miller et al., 2012). The volcanoes Billy Mitchell (1580), Huaynaputina (1600), Mount Parker (1641), Long Island (1660), and Laki (1783) may contributed to the cooling events during LIA-3 and LIA-2 (Jonathan, 2007). The 1815 eruption of Tambora and the 1883 eruption of Krakatau are believed to promote the youngest cold period of LIA (LIA-1; Rampino and Self, 1982)."

3. The paper uses the term 'LIA substages' to mean apparently two different things: one is 4 periods of time within the LIA, across all of the BH area, and the other is a variable number (sometimes more than 4) of stages of greater glacier extent identified per-glacier. The latter is not covered in sufficient detail despite showing results in Figure 3.

Reply: We have added more discussions on Fig. 3 (Fig. R5 in this reply) in the revised paper, especially on the relationship between the number of LIA substages across all of the BH area and each glacier.

"Overall, there exist four LIA substages across all of the BH region. However, due to the glacier individualities (different slopes and lengths), this does not mean each glacier in our study area just exists four LIA substages (Fig. R5a). Instead, it reflects that most glaciers in BH have four glacial substages. Further analysis found that the number of glacial substages are significantly correlated to the glacier properties (glacier length and slope). The correlation coefficient (CC) between the number of glacial substages and glacier length at 1950 is -0.23 while the CC between the number of glacial substages and glacier slope at 1950 is 0.34. Both of the CCs can pass 95% significant test. However, when zooming to the main glacial substages numbers (3, 4, 5), the relationship between the number of glacial substages and glacier length does not become that clear (Fig. R5b). Therefore, we argue that glacial slope may dominate the glacial substage numbers during LIA. The negative correlation between the glacier length and glacial substage numbers might be a result of that the longer (larger) glacier has a smaller slope (CC = -0.50).

4. Section 2.3 needs considerably more depth on the methods used. This should outline the process of the identification of the LIA substages a glacier has experienced (presumably from multiple moraine locations dated to different ages) as well as details of how the glacier area is calculated from glacier length (is this am empirical scaling approach or a reconstruction of glacier geometry? Does it relate to the way OGGM calculates glacier area of larger-than-present-day glacier?).

Reply: The method to identify the LIA substages have been described in detail in the reply to general comments. We calculate the glacier area during the LIA based on the mapped glacier extent and the modern DEM. Unfortunately, this method might overestimate/underestimate the glacier area. However, the glacier area changes are not closely relevant to our research purpose which we aim to study the glacial evolution and its mechanism based on the glacier length. Therefore, in order to make the paper clearer, we will not discuss the glacier area changes any more in the revised paper.

5. I have refrained giving a run-down of language errors as providing a comprehensive list should dominate this review and the time and energy is better spent assessing the scientific content. I recognize the biases inherent in a scientific establishment that demands publication in English from native and non-native speakers alike, and I do not think that most of the errors have a major negative impact on the ability of a reader to determine the content of the study. Nevertheless, if at all possible I would recommend having an expert in technical written English help with the revision process after changes to the content are made. I can provide more detailed notes on subsequent revisions, but I don't want to make a host of minor corrections to sections that are likely to see top-down rewrites.

Reply: Thank you for your understanding. We will try our best to improve the English writing in the revised paper.

Technical Corrections:

1. Figure 2 - all panels have Y-axis scales on the left except (g), which should also have one, unless I am misreading the reason the bars are stacked.

Reply: We have added the Y-axis for the subplot g (here subplot b in Figure R4).

2. Figure 2- specific explicitly the values to which the panels showing percentage change are normalized, and the year to which temperature anomalies are relative.

Reply: The regional average glacier length change from 1100 to 1950 CE is normalized by the simulated glacier length at 1950 (same to the concept of GLR in the reply to general comments). The temperature anomalies are relative to 1950s (the average temperature between 1950 to 1959).

3. Figure 3 – does panel (a) really need breaks on the Y axis? All it seems to do is make the graph harder to read and make the lines of best fit less clear. At best it's messy, and at worst actively misleading because the squashing of the data points for 0 substages makes the relationships

appear more linear (even though the lines of best fit indicate that they aren't).

Reply: Thank you for your comments. We have shown the complete Y axis in Fig. 3 (Fig. R5 here).

4. Figure 3 (caption) – panel (b) should be described as showing the number of glaciers with each count of identified substages, not the number of substages for each. In general, I find most of the figure captions in the paper could be more descriptive. I don't know how much of this is personal taste, but I find captions that describe the relationships exhibited by the data shown are better for readability than captions that just describe what the data is.

Reply: We have clarified the figure captions and made them more descriptive for all figures as you can see at the bottom of this reply.

5. Line 255 – please explain what baseline the sensitivity experiment increase/reductions are relative to.

Reply: Sensitivity experiments for temperature and precipitation are relative to the control experiment in which monthly temperature and precipitation use the default forcing data (51-year windows centered at t*).

Figures:

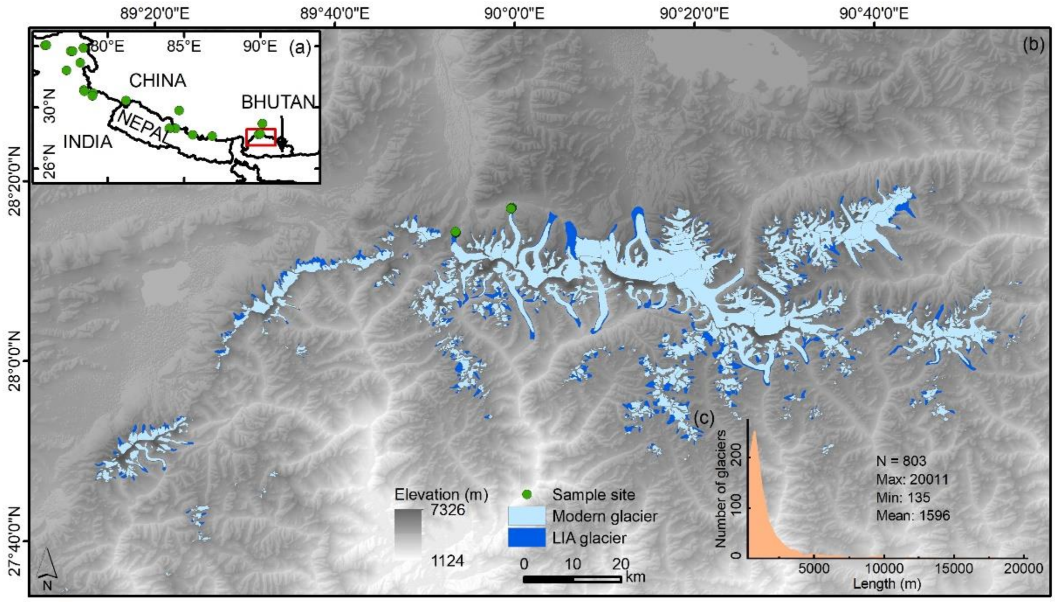

Figure R1. An overview of study area and moraine sites. The red box in (a) shows the location of the study area and the green circles in (a) displays the spatial distribution of the ^{10}Be exposure dating moraines. The basic information of these moraine sites can refer to Table S1. (b) The extent of 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.

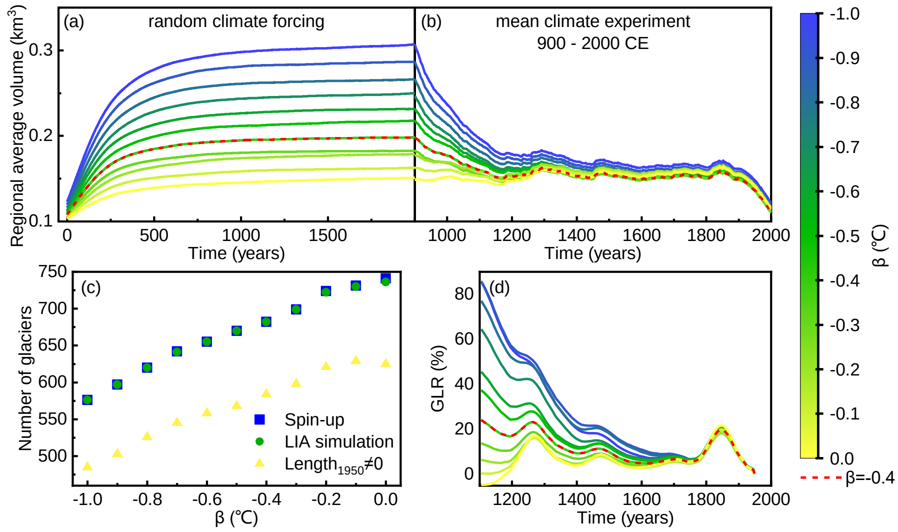

Figure R2. (a) The regional average glacier volume during the 2000-year spin-up with various β. (b) The simulated regional average glacier volume from 900 to 2000 CE with different initial condition. (c) The number of available glaciers with various β. (d) The simulated regional average *GLR* from 1100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

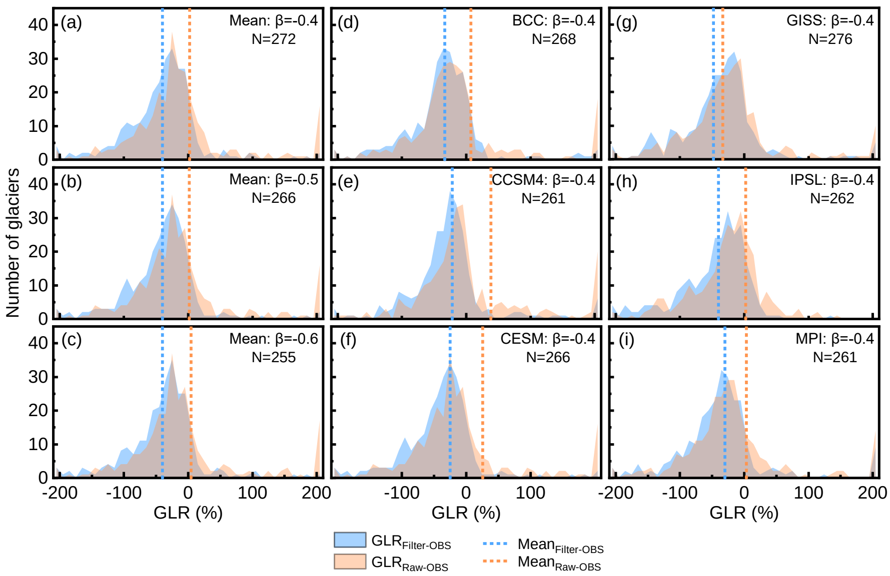

Figure R3. The simulation bias distribution of *maximum peak GLR*. The raw (unprocessed) results are shown in orange while Gaussian-filtered results are in blue. The dash blue line represents the mean value of the Gaussian-filtered results while the dash red line means the mean value of the raw results. 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.

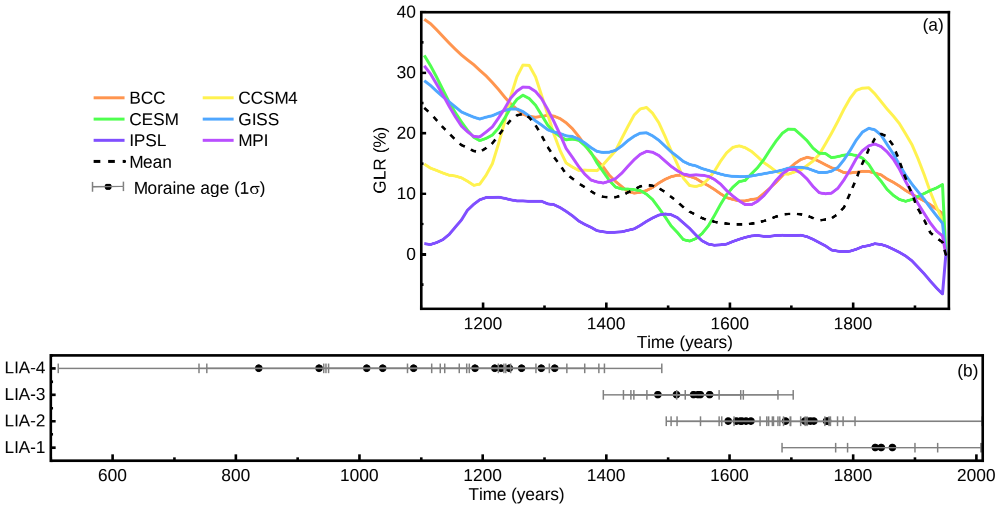

Figure R4. (a) Time series of regional average *GLR* from 1100 to 1950 CE. (b) The moraine ages in the monsoon-influenced Himalaya. The detailed information of the moraines can be found in Table S1.

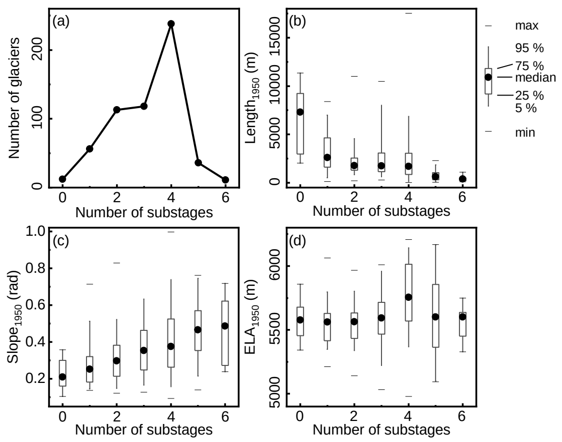

Figure R5. (a) The identified glacial substages number distribution in the mean climate experiment. The relationship between identified glacial substages with (b) glacier length, (c) glacier slope, and (d) glacial ELA at 1950 in the mean climate experiment.

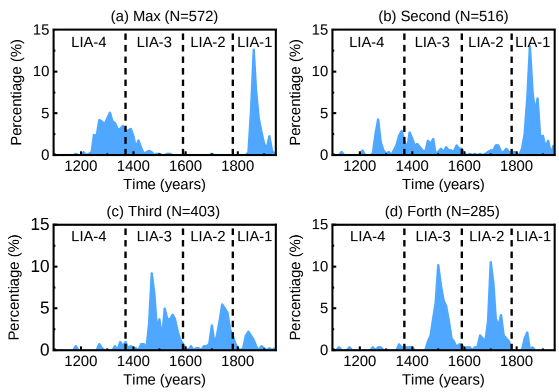

Figure R6 The percentage of the glaciers with (a) *maximum peak* GLR, (b) the *second largest peak* GLR, (c) the *third largest peak* GLR, and (d) the *fourth largest peak* GLR over time in the mean climate experiment.

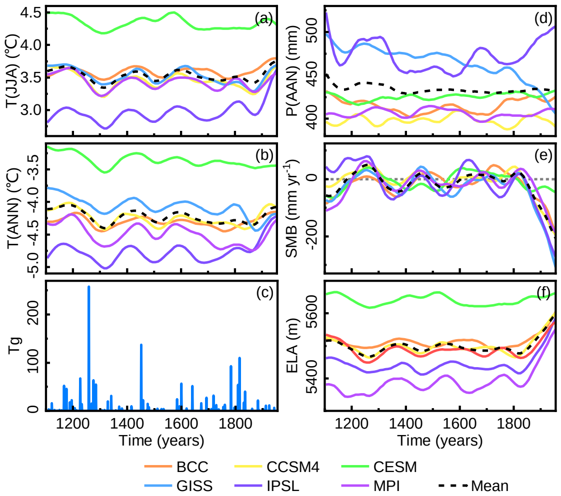

Figure R7. The regional average (a) summer temperature (T(JJA)), (b) annual temperature (T(ANN)), (d) annual precipitation (P(ANN)), (e) SMB, (f) ELA from 1100 to 1950 CE at a decadal timescale. (c) Global stratospheric sulfate aerosol loadings (Gao et al., 2008).

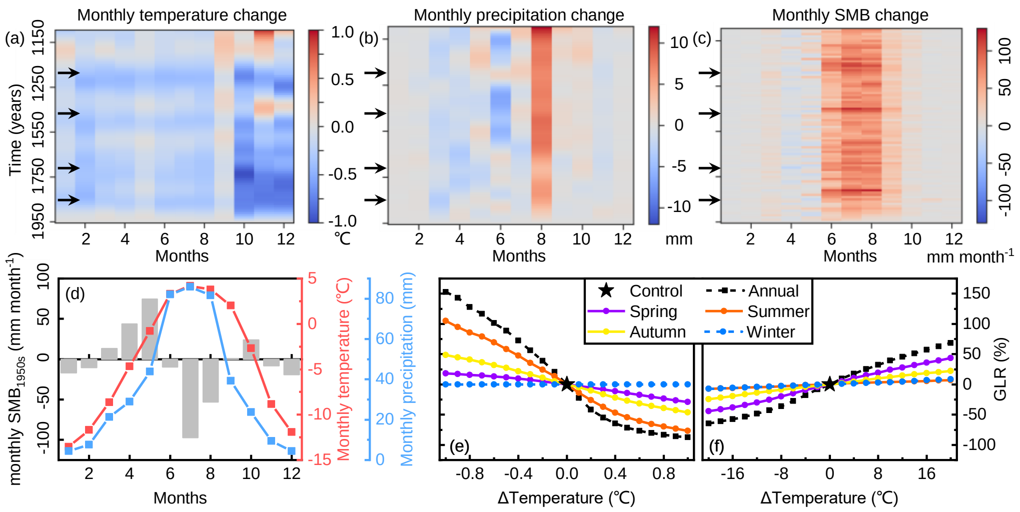

Figure R8. The monthly (a) temperature, (b) precipitation, and (c) SMB changes relative to 1950s at a decadal timescale in the mean climate experiment. The arrows in (a) – (c) represent the time of the four glacial substages, 1270s (LIA-4), 1470s (LIA-3), 1710s (LIA-2), and 1850s (LIA-1). (d) the monthly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

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