Response to Reviewer#2 (Dr Sarah Bradley)

We are grateful to Dr Sarah Bradley for the constructive comments and the time for reviewing our manuscript. As described below, we will take all the suggestions by the reviewer into account in the revised manuscript. We also performed additional analysis to address the reviewer's concern. Our responses will be shown in blue and the comments by the reviewer will be shown in black.

Responses to comments:
The authors have presented a comprehensive paper tackling an ongoing issue in climate-ice sheet modelling which is the uncertainty in parameter space within the model. Focusing on the ice sheet southern margin extent, which as the authors state is an ongoing problem to achieve was a very original approach. I enjoyed reading the paper but have several main points that I would like the authors to provide more information for or make small changes in the manuscript.

Thank you!

LGM temperature. I found the paragraph describing the uncertainty calculation hard to comprehend. There has been several specific publications which have estimate LGM global temperature with an uncertainty range (Tierney, 2022, Osman). What was the authors reasoning for this approach?

The estimated magnitude of LGM cooling differs among studies and it has a range from 1.7˚C to 8.3˚C cooling as summarized in Tierney et al. (2020). In this study, we wanted to cover all the possibilities of the actual LGM temperature for the temperature constraint. Therefore, we decided to take all the previous studies into account in an objective way, including Tierney et al. (2020), rather than being subjective and picking one particular study. This caused a wide range of acceptable LGM actual temperature in this study. We will add the following sentence in the revised manuscript;

"According to previous studies, the LGM global cooling relative to the Preindustrial has a range of -1.7˚C to -8.3˚C (e.g., -1.7˚C to -3.7˚C with a probability of 90% in Schmittner et al. (2011) and -4.6 ˚C to -8.3˚C with a probability of 90% in Holden et al. (2010), see Fig. 4a in Tierney et al. 2020). To objectively cover all the possibilities, we take into account all of these studies to define our range of plausible LGM GMST."

<u>**Lower limit**</u>:50m The reference the authors have chosen to define their LGM NAIS and GrIS ice sheet volume is old. A lower limit, which the authors use of 60m is from ICE4G, which has been preceded by ICE6G and ICE7G. Both these latter two studies have a larger total ice volume, ~ 76m. Therefore, I do not think a lower limit of 50m is a good value to use. Tarasov et al., 2012 Table1, has published a study exploring a range of LGM NAIS volumes., but there are others. I am not sure how much this lower limit influences the authors parameter space, as from Figure 8, the minimum volume of the 16 parameters > 80m.

First of all, we apologize to the reviewer that the explanation of ice volume constraint was unclear in the original manuscript. While we used the North American ice volume as the constraint, some of the sentences described that the constraint was on the North American and Greenland ice volumes. We will clarify in the revised manuscript that the ice volume constraint is only applied to the North American ice sheet.

Second of all, as the reviewer pointed out, the lower ice volume limit didn't have an effect on the selection of best performing members due to the stronger southern extent constraint. In fact, we performed a test analysis changing the value from 50 to 60, but did not find any major changes.

Nevertheless, we will change the lower ice volume limit of the North American ice sheet to 60 m following the reviewer's advice. Accordingly, we will update Figs. 2 and 3 using 60m SLE as the minimum ice volume constraint for the North American ice sheet.

Upper limit: Have the author considered using an 'upper limit' for the total ice sheet volume. From the Figure 8; some of the best 16 members, (black dots) have total volumes of ~ 110m. Given that this number does not include the Antarctic ice sheet (~10m) or the Eurasian ice sheet (~24m; number from the authors paper), this would produce a total global sea level at this time would be too large, 144m. (rough calculations). This may reduce the possible parameter space, but it will also rule out ice sheet volume that do not appear viable.

We reanalyzed Figs. 2 and 8 with the max ice volume limit of 100m SLE. This caused a reduction of numbers of best 16 members to 10, however the preferred parameter space did not change.

In general, equilibrium LGM simulations tend to overestimate the ice volume once the simulation has a net positive SMB since it keeps growing during the integration (e.g. Alder and Hostetler 2019). In this regard, setting an upper limit can be tricky. Therefore, we would like to add the following sentence in the revised manuscript to inform the readers that future study should consider this point.

"Applying an upper ice volume limit may also be important in constraining the parameter space. However, in general, equilibrium LGM simulations tend to overestimate the ice volume if once the simulation has a net positive SMB (e.g. Alder and Hostetler 2019). In this regard, setting an upper limit can be tricky, and therefore needs to be examined in a different experimental set-up."

Southern margin extent: Including the southern margin as a metric to evaluate the ice sheet-climate simulation is an original approach. The extent of the box the authors have used (Figure 2), from my understanding consider a margin that has retreated up to Hudson Bay as reasonable?

We did not have an intention to say that members showing ice sheet beyond Hudson Bay are reasonable, but now that the reviewer has mentioned, it might be an valid point to mention. We will add the following sentence in section 2.4;

"This area corresponds to the south of the Hudson Bay".

Parameter testing procedure: The authors have taken the temperature as the primary criteria and then adding ice volume and southern margin extent. I am interested to know if the authors started with a 'ice volume' if this would have impacted on their results? As this is to some extent, a study focused on the ice sheets.

Thanks for the comment. We will add the following subsection in the revised manuscript.

"**3.6 Sensitivity of influential parameters to individual constraints**

Applying our three simulation constraints simultaneously may be hiding relationships that exist between model parameters and simulation behaviour. We perform additional analyses to explore how each constraint individually affects the relationship between our model parameters and North American ice sheet volume. In the case of no-constraints (139 members), the albedo parameters are important, but the influence from *ct* becomes more important (Table 3). This is due to the increased range of GMST allowed by varying *ct* (Fig. 5). Having a much colder or warmer climate allows the ice sheets to grow or melt, and the resulting feedback further enhances the role of *ct*. In contrast, most members with extremely warm climates crashed during the 5000 year simulation. This means that, *entcoef* does not appear to have so large an effect on ice sheet volume directly, unlike its importance in setting the GMST.

In the case of applying only the ice sheet volume constraint (73 members), *avgr* and *fsnow* still show relatively high correlations with ice sheet volume. However their influence is less than when GMST constraint alone is applied (Table 3). The ice volume constraint alone results in a preferred selection of members exhibiting colder climates (46 members have a GMST below 4 ˚C). As a result, the members are less sensitive to albedo related parameters.

When the southern extent constraint alone is applied, 33 members remain. Similar to above, members satisfying this condition tend to have very cold climates, where 24 members have GMST colder than 4˚C and 14 members colder than 0.63˚C. In this case, *avgr* and *beta* appear to be most influential. This may imply that snow albedo and basal conditions play an important role in maintaining an extensive ice sheet once the climate allows the ice sheet to reach this size. Further discussion on the maintenance of the southern margin of the North American ice sheet is in subsection 4.1.“

Table R2 Effects of constraints on the relation of parameters and North American ice sheet volume at year 5000. The four most influential parameters on ice volumes are shown.

Region	1	2	3	4
No Constraint (139 members)	*daice* (0.51)	*avgr* (-0.45)	*ct* (0.45)	*fsnow* (0.35)
GMST-alone (87 members)	*avgr* (-0.56)	*daice* (0.48)	*fsnow* (0.37)	*ct* (-0.33)
Min Ice volume-alone (73 members)	*avgr* (-0.39)	*fsnow* (0.33)	*smb* (0.33)	*daice* (0.24)
Southern Extent-alone (33 members)	*avgr* (-0.71)	*beta* (0.51)	*smb* (0.44)	*fsnow* (0.39)

Spin up procedure: What was the authors reasoning for ice-sheet spin up and then adding in the climate parameters? I understand that running the climate model is computationally expensive, however from the SOM figure including the climate parameters seemed to feedback onto the ice sheet?

We have two reasons for this. The first one is related to the efficiency and the initial stability of the simulation. The geometry of GLAC1D ice sheet used as the initial condition can have some areas with blocky and cliffy surfaces. As a result, running the first couple of hundred years can take a while since BISICLES adjust dx, dy and dt depending on the ice velocity and others. In this situation, coupling with the climate model made the entire simulation extremely long and starting with the BISICLES-only simulation was much more efficient (L271-273). Secondly, we wanted to introduce some variety in the initial ice volume and thickness in the coupled simulations since these are uncertain but can have an impact on the evolution of ice sheets due to the hysteresis (by making the climate slightly colder, e.g. Abe-Ouchi et al. 2013). Running a spin-up with BISICLES with different magnitude of SMB allowed us to implement this (L269-271).

Comments about figures:

Figure 11: I really liked this figure to try and understand how the different criteria used in the study relate. Is this all 200 ensemble members? What I find interesting, which I hope the authors can comment on is in panel (a) the same ice sheet volume, ~ 70m is produced for a GMST between 5C and 12C. Has the ice sheet not thicken? Changed in extent? I am trying to understand the 3 factors together. In terms of the southern margin, about ~ 11 C the southern margin has undergone a large retreat. Perhaps if the authors plot North American volume vs ice sheet margin this will become apparent.

Thank you! The figure includes 87 members satisfying the GMST constraint and Fig. R2 shows the relation between the southern extent and volume of the North American ice sheets. The result shows more variety in ice extent once the ice sheet volume exceeds 80m SLE.

It is very interesting to see similar ice volumes under different GMST. We have created a figure comparing the shape of the ice sheet within a particular ice volume range (80m - 90m SLE). The result implied a thicker but narrower ice sheet under warmer condition, but thinner and wider ice at colder conditions. This is implies some control from GMST on the shape of the ice sheet and is consistent with Fig. R2 showing a larger variety in the simulated ice extent beyond the ice volume of 80m SLE. However, we also need to be aware that these differences can be caused by differences in albedo and other parameters (Fig. S4). In this regard, we think further analysis is necessary to make this argument in the current paper. We might write a follow-up paper on this point, though, so thanks for the comment!

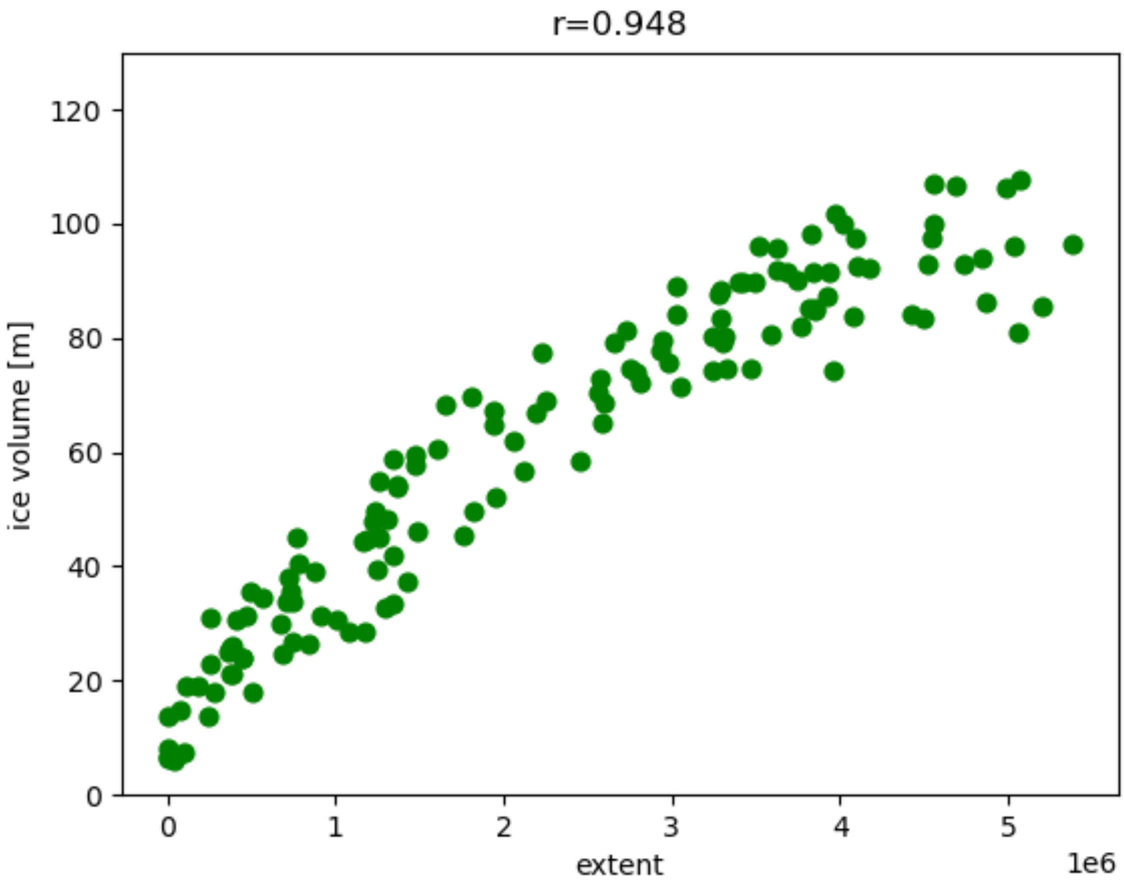

Fig. R2 Relationship of the North American ice volume and Southern extent at year 5000 of FAMOUS-BISICLES coupled simulations.

Figure S3: This is an interesting figure and from my understanding this is after the spin-up procedure (ice sheet only parameters)? If this is the case, the ice volume can reduce by up to 40m? Given than in the ice sheet-only stage (Fig S1) the volume in some simulation increases by ~ 20m, does this climate influence (feedbacks?) reduce this? This possible relates to my above question about spin-up, why not spin up with the climate feedbacks?

Fig. S3 shows responses of ice sheet in the first 500 years after the coupling of FAMOUS-BISICLES. The figure does show members with a reduction of ice volume by up to 40m SLE in the first 500 years. This is largely caused by the combinations of parameters producing very low albedo values, which result in as very large negative SMB. Having a larger ice sheet at the beginning of the coupling can induce a colder climate due to the cooling by the ice sheet itself. This may reduce the initial ice sheet melt, even if the albedo is low. However, Fig. S3 shows a very small impact from the initial ice volume on the ice sheet mass loss in the first 500 years. This means that, even starting from a larger ice sheet, the ice sheet can melt drastically if the albedo value is set to be low. We will add a following sentence to clarify this point;

"This suggests only a weak connection between final ice sheet volume at 5000 years and its initial volume at the beginning of the coupled simulations. (Similar results are also obtained for ice volume changes in the first 500 years.)".

Figures changes: The figures with multiple panels are small for the reader to see. This might be the typesetting of the manuscript but can the authors try to increase.

Done!

Figure1: I would suggest changing the title to a more general phrase. I am confused how there are SST across the land region? Is it SAT?

Masked out the values on land since it is SST.

Figure2: Can you add a key onto the figure to state: light blue = GMST; dark blue ...

Done!

Figure 3: Can you highlight the edge of the actual simulated ice sheet? It is hard to identify where the edge of the ice sheet is (panelsb,c,d,e) without guessing in reference to the ablation area. Does this figure only show grounded ice?

Done! The blue shades show the ice thickness, therefore it does contain some floating ice.

Figures 4 and 7: For these graphs can you add on the limit of GMST and ice volume as you have, for example on Figure 5.

Done! For Fig. 7, we could not include the shade since the ice volume constraint is applied only on the North American ice sheet, while the Figure shows the ice volume evolution of North America and Greenland.

Minor comments

Line 217: Laurentide> this is one ice sheet which makes up the LGM North American ice sheet: change to North American

Done!

Terminology: Can the author clarify from the beginning the difference between FAMOUS- ICE (is this with always an ice sheet? Or just the climate component): FAMOUS-Ice (Gandy et al., 2023) - this is when it is coupled to Glimmer, and FAMOUS-ICE, which then is referred to in the abstract as FAMOUS-BISICLES.
GMT - this is a very common abbreviation for other things: please change to GMST, Sat or something else.

Clarified the difference between FAMOUS-Ice and FAMOUS-BISICLES in the method section!

Changed GMT into GMST!