Response to Reviewer#1 (Dr Evan Gowan)

We are grateful to Dr Evan Gowan for all the constructive comments and 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. Below, our responses are shown in blue and the comments by the reviewer are shown in black.

Responses to comments:

I appreciate the advance this study makes to create a coupled ice sheet-climate-ocean model that can be applied to paleo-simulations. Being able to explore a wide range of factors to discern ice sheet behavior is an exciting development.

Thank you!

The main weakness of this study is with the use of Latin Hypercube sampling to determine the values of the parameters of the model simulations. I have mentioned this in a previous review of this model (Gandy et al., 2021) that by varying a large number of parameters simultaneously, it becomes difficult to discern the relative impact that each parameter has on the evolution of the the simulation. This is the case here (i.e. Figures 8 and 9), where aside from the sliding parameter β for the Greenland Ice Sheet, there is only a weak relationship between the varied parameters and resulting ice sheet volume. Part of this is because some parameters (e.g. the parameters related to albedo and sliding) can cancel each other out. It would have been easier to determine the relationship between variables if a smaller number were selected, then varied in a controlled way. I suppose this may not have been known at the start of the study that this kind of cancellation would happen. However, I think a change of study design would lead to a more interesting result. I think the current results should be published, though I hope the authors consider this in the future. At the very least, the results from Greenland, where the ice sheet volume is controlled by basal conditions rather than global climate, is a very interesting result.

Thank you for the comment. As the reviewer rightly points out, in such a complex model, it is difficult to tease out the sensitivity of the results to individual model parameters. This is because of the many interactions between the different climate and ice sheet processes in the model, which leads to what the reviewer calls the "cancellation" of the effects to the parameters. We will clarify the reason of the choice of Latin Hypercube sampling in the Method as follows;

"We perform 200-member ensemble simulations by varying16 parameter values associated with climate and ice dynamics, as summarised in Table 1, using a Latin-hypercube sampling method (Williamson 2015). Latin-hypercube sampling technique is useful as it allows us to explore all the uncertain parameter spaces in an efficient way. While some cancellations among parameters can cause lower correlation values between inputs and outputs, the method also provides quantitative insights on the interactions among different parameters (e.g. Fig. 6 and Fig. S7 in this study)."

As the reviewer suggests, performing sensitivity experiments modifying small numbers of parameters in a controlled way are definitely a good way to understand how each parameter affects and interacts with the coupled climate-ice sheet system. Perhaps, combining the Latin-hypercube sampling and the controlled way sampling might be an ideal way, e.g. finding out important

parameters in wave1 with Latin-hypercube sampling and then performing controlled sampling in wave2 or wave3 with smaller sets of parameters.

Another way of doing this is could be to perform a Sobol sensitivity analysis on an ensemble of simulations (Sobol', I. M.: On Sensitivity Estimation for Nonlinear Mathematical Models, Matematicheskoe mod- elirovanie, 2, 112–118, 1990) as we have recently done with an ice sheet and sea level model (Pollard et al., submitted to Quaternary science review)." We will consider doing them in the future!

I think one way to improve this study would be to break up the North American ice sheets into smaller regions and see if different sectors are sensitive to specific parameters. For instance, I would expect the Cordilleran Ice Sheet, which is underlain by mountainous topography, will be sensitive to β, similar to the Greenland Ice Sheet. I would also expect that there will be different sensitivities to the parameters for the southern, land terminating part of the Laurentide Ice Sheet, versus the marine terminating eastern part. Similarly, I would expect different sensitivities between the southern Laurentide and the Innuitian/Northern Laurentide Ice Sheets in terms of climatic parameters. Perhaps cluster analysis could also be applied to see if better relationships between the overarching parameters (e.g. related to sliding, albedo) can be deduced.

This is a very good point! We conducted additional analysis separating the North American ice sheet into seven different sectors (NW, SW, N, M, MS, NE, E in Fig. R1). Table R1 summaries the relation among parameters and ice volumes at each sector. While the most important parameters remained to be the albedo ones (*daice* and *avgr*), we found that *beta* has an increased influence over SW and M, as suggested by the reviewer. We will add a following subsection in the revised manuscript.

"3.5 Localities in the effect of parameters

The different sensitivities to parameters between the North American and Greenland ice sheets imply that similar variations in sensitivity to parameters may exist between different local regions within the huge North American ice sheet. To explore this point, we separate the North American ice sheet into seven different sectors (NW, SW, N, M, MS, NE, E), where a substantial amount of ice remains in the ensemble mean of members satisfying the GMST constraint (Fig. 12). Results are summarized in Table 2. While the albedo parameters remain the most important ones (*daice* and *avgr*) in each region, we find that *beta* has an increased influence in SW and M. These areas either exhibit a mountainous bedrock topography or have very thick ice, hence can be more affected by the basal sliding parameters. Additionally, we find that *ct* has a relatively strong influence on the northern (N) and eastern (E) parts of the North American ice sheet. Our analysis indicates some variation in regional sensitivities to climate and ice sheet parameters in different sectors of the ice sheet sectors. Further analysis beyond the scope of this study would be required to explore this regional dependency in detail."

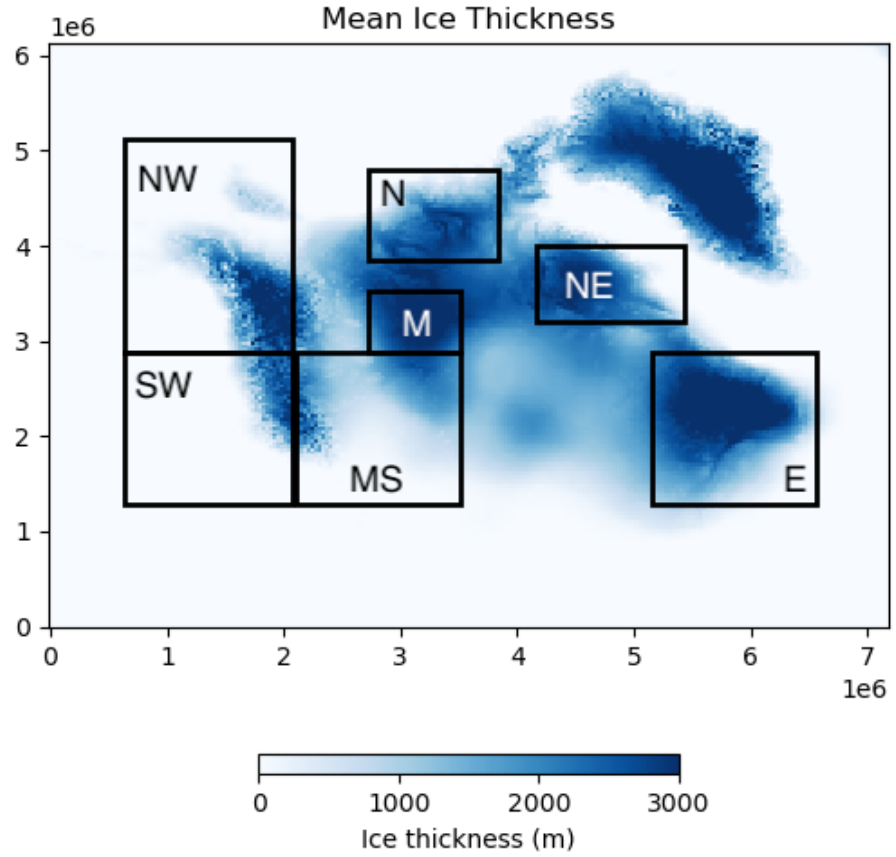

Fig. R1 Six different areas (NW, SW, N, M, NE and E) of the North American ice sheet used for the additional analysis (black rectangle). Blue shades show the mean ice thickness [m, colour] of members satisfying the global mean surface temperature constraint.

Table R1 Four most influential parameters on ice volumes at different regions. Values in the bracket show the correlation. For the Southern Extent, results from Fig. S4 are used.

Region	1	2	3	4
NW	*avgr* (-0.48)	*fsnow* (0.47)	*daice* (0.4)	*ct* (-0.25)
SW	*fsnow* (0.42)	*daice* (0.4)	*beta* (0.39)	*avgr* (-0.35)
N	*avgr* (-0.44)	*daice* (0.37)	*ct* (-0.36)	*fsnow* (0.28)
M	*daice* (0.53)	*avgr* (-0.49)	*beta (0.29)*	*ct* (-0.25)
MS	*avgr* (-0.58)	*daice* (0.47)	*fsnow* (0.39)	*ct* (-0.30)
NE	*avgr* (-0.52)	*daice* (0.49)	*smb* (0.30)	*fsnow* (0.26)
E	*avgr* (-0.48)	*daice* (0.43)	*fsnow* (0.33)	*ct* (-0.30)
Southern Extent	*avgr* (-0.52)	*daice* (0.41)	*fsnow* (0.36)	*ct* (-0.33)

Southern extent of the Laurentide Ice Sheet and ice streams

Much of section 4 discusses how the model is unable to reproduce the ice streams and ice lobes that existed in the southern Laurentide Ice Sheet. However, the explanations given ignore what I would

consider the most likely reason the ice streams and lobes existed – the presence of ice marginal proglacial lakes (e.g. Cutler et al., 2001; Quiquet et al., 2021). The proglacial lakes destabilized the ice sheet and encouraged the flow of ice in much the same way as marine terminating ice streams. The presence of shallow lakes that were insufficient to act as destructive calving margins would have increased the subglacial water pressure, encouraging a decoupling of the ice-bed interface, causing the ice sheet to advance in a lobe. When we added proglacial lakes in the PISM ice sheet model (Hinck et al., 2022), we demonstrated the presence of lakes greatly enhanced ice flow, and we also had some limited success in simulating ice lobe formation in shallow lakes.

If this is correct, then it is not surprising that the FAMOUS-BISICLES model is unable to simulate the southern margin of the Laurentide Ice Sheet or terrestrial ice streams, since it lacks this mechanism. The simulation is also of an LGM climate. Since the ice streams and lobes are largely acknowledged to be a result of ice sheet dynamics rather than climatic impacts (Jennings, 2006), perhaps this should not be a target metric for the success of the model. The extreme southern limit of the ice sheet was not achieved at the LGM, because the dynamics requires large amounts of meltwater, which was inhibited by the cold temperatures at that time. Perhaps a simpler target, such as an ice margin near the Canada-US border, would be better.

Thanks for the comment! We will add the following sentence in Discussion 4.1.

“Bedrock conditions: creating a slippery bedrock condition would enhance ice flow from the ice sheet interior towards the margin, and so may be instrumental in redistributing ice outwards. In this regard, adding a scheme that allows the generation of proglacial lakes and increase ice flow at the southern margin would help advance the lobe (Hinck et al. 2022).”

While the ice dynamics part is essential in completing the ice lobe, we do think that the climate part is also important for simulating the lobe. This is because, without simulating appropriate climate, there won’t be any ice close to the lobe in the first place. In this regard, we think that understanding the relation of climate-albedo parameters and the southern extent of the North American ice sheet is meaningful and important.

For the last point, we conducted analysis focusing on the performance of the ice volume near the Canada-US border (MS in Fig. R1). It turns out that the members showing extensive southern margin in Fig. S4 are the members simulating the largest ice volume at the MS region. Hence, we will keep using the same box in Fig. 3 as the metric for the southern margin.

- Figure 3: please explicitly define ”GMT” in the caption.

Done!

- Figure 13: I would recommend adding details of which simulation was used to produce this (i.e. what were the atmospheric conditions in this model simulation).

Done!

- Some of the references mentioned in the text are not in the reference list, please check.

Done! Thanks!