Response to the review by Niall Gandy

We thank the reviewer for their helpful comments, and would hereby like to address the concerns they raised. Reviewer comments are shown in bold and our responses in regular font type.

Main points

Experimental design: I appreciate the novel approach of the experimental design, where you have made certain adjustments to better explore the ice sheet behaviour. However, the detailed justification for this is not explained sufficiently in the text, and I am left not fully convinced that your experiments explore the behaviour you intend. For example, the "Rough Water" experiment is designed to show the effect of negligible friction beneath ice shelves, but various feedbacks (surface profile, buttressing effects, a different GIA response to more grounded ice, ect) could be confusing the results. The experimental ethos could be explained in more detail.

We hope to address these concerns with the following changes:

1) We will expand the model description in section 2.1. The way proglacial lakes are included in the model will be explained in more detail. The sub-grid friction scaling scheme, which we use to model the decrease in friction at the grounding line and floating ice, will be explained in more detail. The equations governing the basal roughness, basal hydrology, and the sliding law, will be added in an appendix.

2) We will include a more thorough description of the Rough Water simulation, in which the basal friction is treated the same regardless if the ice is floating or not.

3) We have conducted a few additional sensitivity experiments. We have conducted the Baseline simulation with a respective 50% increase and decrease in the till friction angle. We have conducted similar variations of the Fast GIA and the Rough Water experiments.

   The till friction angle has a strong effect on the deglaciation, with lower friction resulting in a faster deglaciation. We also found that our main conclusions are consistent under the different till friction angle: Fast GIA has the slowest melt compared to the Rough Water in regardless of the till friction angle. Though the length of the deglaciation and the ice volume remaining during interglacial periods does increase with higher friction values.

4) We have added 2D maps of the modelled ice-sheet geometry, including the proglacial lakes, during the last deglaciation for the different experiments, to more clearly show the differences between the experiments.

You could also undertake some offline ice shelf mass budgeting (at each timestep what is the flow over the grounding line, what is lost to surface melt, sub shelf melt, and calving) to disentangle the behaviour.

We will add a figure showing integrated SMB, BMB and calving flux to the supplementary information.

Specific points

18: linger > remain?

This word indeed fits better and will be changed in the manuscript.

67: I think it is common to conflate susceptibility to MISI/PLISI and sub-shelf melting/calving. Could you clarify the mechanistic difference for the reader before this sentence?

We will add a few sentences around line 50 explaining sub-shelf melting and calving. This is before MISI is explained, and should help to prevent confusion between PLISI and sub-shelf melting/calving.

80: Could you comment on the suitability of a Hybrid model to simulate PLISI and grounding line migration? How is this parameterized?

There is no fundamental difference between hybrid SIA/SSA models, and higher-order / full-Stokes models, in their ability to simulate grounding-line dynamics, as the problems in doing so are caused by the discontinuity in basal friction at the grounding line, rather than by missing terms in the momentum balance. While the first MISMIP study (Pattyn et al., 2012; The Cryosphere) suggested that the full-Stokes model showed better results, this was because that model had a higher spatial resolution than the other ones. The need for the very high resolutions suggested in that study has since been negated by other modelling techniques, such as the flux condition scheme and the sub-grid friction scaling scheme.

IMAU-ICE uses a sub-grid friction scaling scheme to achieve good grounding-line dynamics at relatively coarse resolutions, similar to e.g., CISM (Leguy et al., 2014; The Cryosphere) and PISM (Feldmann et al., 2014; Journal of Glaciology). The IMAU-ICE model description paper (Berends et al., 2022; Geoscientific Model Development) showed that this enables IMAU-ICE to resolve the migrating grounding line to within a single grid cell. We will add several sentences explaining this in more detail.

89: In some ways the lacustrine environment might be quite different from the marine environment; the thermal structure may be different, and lakes could become chocked with icebergs. From a practical modelling perspective, it is reasonable that you treat marine and lacustrine the same, but you could discuss this further in the text.

Indeed, there are many differences between the lacustrine and marine environment, which affect BMB and calving. For example, lacustrine calving is thought to be at least one magnitude smaller compared to tide water glaciers (e.g., Warren et al., 1995, https://doi.org/10.3189/S0260305500015998; Warrant and Kirkbride, 2003, https://doi.org/10.3189/172756403781816446). Thermal circulation is also different. In the ocean, circulation is driven by temperature and salinity gradient. The salinity gradient is absent in fresh water.

We will mention these differences in the introduction and discussion sections.

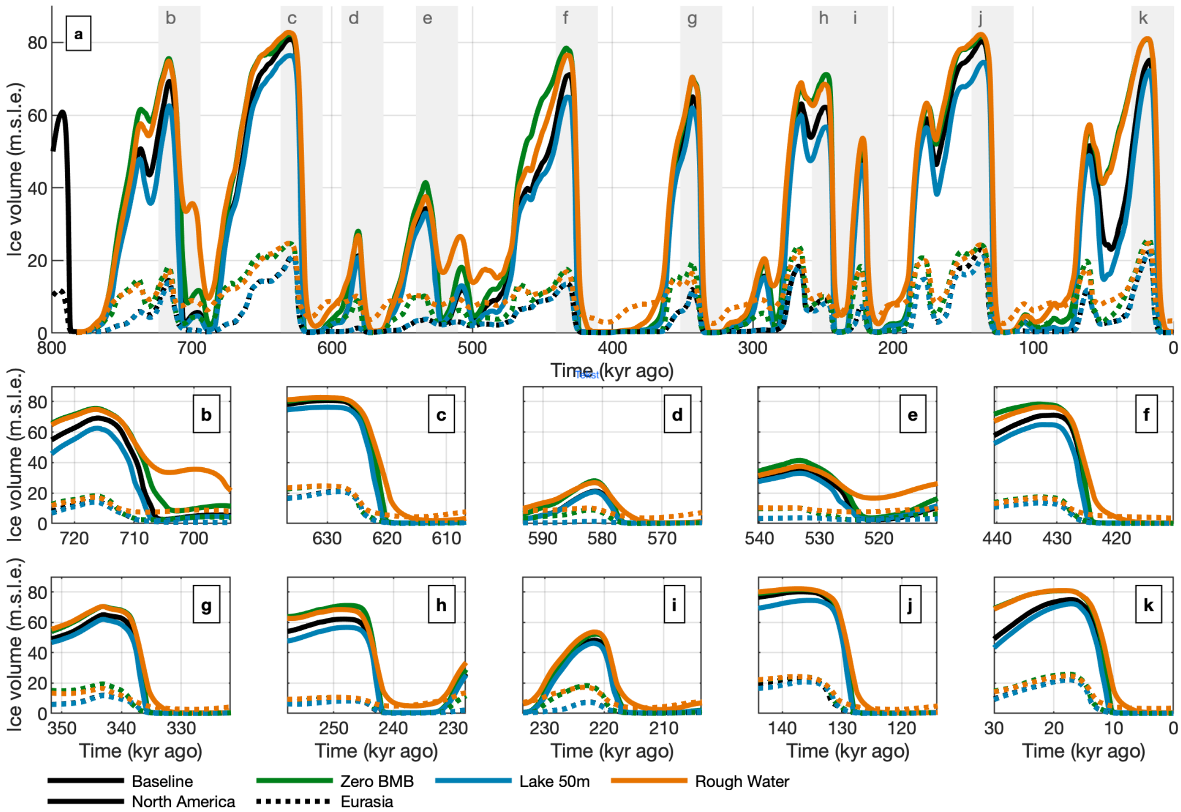
93: Do you know (or could you know with some offline calculations) what proportion of the ice sheet margin is missing lakes because the model cannot simulate above sea level lakes?

While technically possible, calculating the missing lakes is not trivial and computationally heavy.

The water level of a lake can be defined as the level at which water would start to flow towards the ocean. Therefore, it is important to be able to resolve smaller channels and valleys, as these determine lake levels. This requires e.g., a high topographic resolution, as lower topographic resolution can smooth out these valleys.

Therefore, we propose an alternative experiment to quantify the effect of this simplification. We selected a large region in North America where the water level of potential proglacial lakes where set to 50m above present-day sea level.

The results are shown below compared to Zero BMB and Rough Water simulation. The Lake 50m experiment loses more mass during interstadial periods, but is very similar compared to the Baseline during the deglaciation. A most, the ice volume during deglaciation in Lake 50m is a few centuries ahead of the Baseline. This effect is small compared to the Faster GIA and Rough Water experiments.



101: merge > merged

This mistake will be fixed.

108: Not unfeasible! Millennial scale coupled climate-ice sheet simulation studies do exist, but it is understandable why this is not a reasonable modelling choice here. Please clarify.

It is possible to run multiple millennial scale simulations with enough computational resources and time. We will change this in manuscript to explain that it is technically possible to run coupled climate-ice simulations, but at a large computational cost.

126: The use of brackets to describe the reverse behaviour is a tad tricky to follow.

We will change this sentence so it does not use brackets. Any other sentences in the manuscript that uses brackets will also be changed.

164: A set 30% adjustment assumes that distal ice sheets fluctuate in unison with simulated ice sheets. Is this reasonable?

The 30% addition to ice volume represents sea level change that does not result directly from North America, Eurasia and Greenland. These three ice-sheets contribute around 100 meters in sea level decrease at LGM. (e.g., Simms et al., 2019).

In our study, we compare our results to eustatic sea level reconstructions. However, since we do not model all ice or sea level contributions (SLC), we need to add ~30% in order to compare our results directly to sea level reconstructions.

This is not perfect. Every 1 m sea level equivalent change in the Northern Hemisphere ice sheet volume does not necessarily equate to 30 cm additional sea level contribution from other sources.

Though, it should also be noted that Antarctic sea level contribution may be strongly correlated to Northern Hemisphere ice volume change. A sea level drop around Antarctica may prompt a grounding-line advance, which leads to ice volume increases (e.g., Gomez et al., 2020; Nature). A substantial part of the missing sea level may therefore be directly correlated to the modelled ice volume. Additionally, Northern Hemisphere ice volume is strongly correlated to the global temperature and consequentially the density of sea water and volume of smaller glaciers.

As a result, we will address that the 30% added to the ice volume does not perfectly represent the “missing” sea level change. However, it represents a rough estimate of the sea level change that we are not capturing with our model. Additionally, we will refer to the Gomez et al., 2020 paper to show that Antarctic volume and sea level change are correlated.

Figure 4: This figure is challenging to follow, particularly panels b, d, and f. Are the points of deglaciation onset numerically defined? The onset of glaciation curves are difficult to read; I would suggest either removing or replotting. Ideally we shouldn’t need a paragraph (lines 172-176) just to describe how to read a figure, not yet describing the results or discussion the implications.

Figure 4 will be significantly reworked.

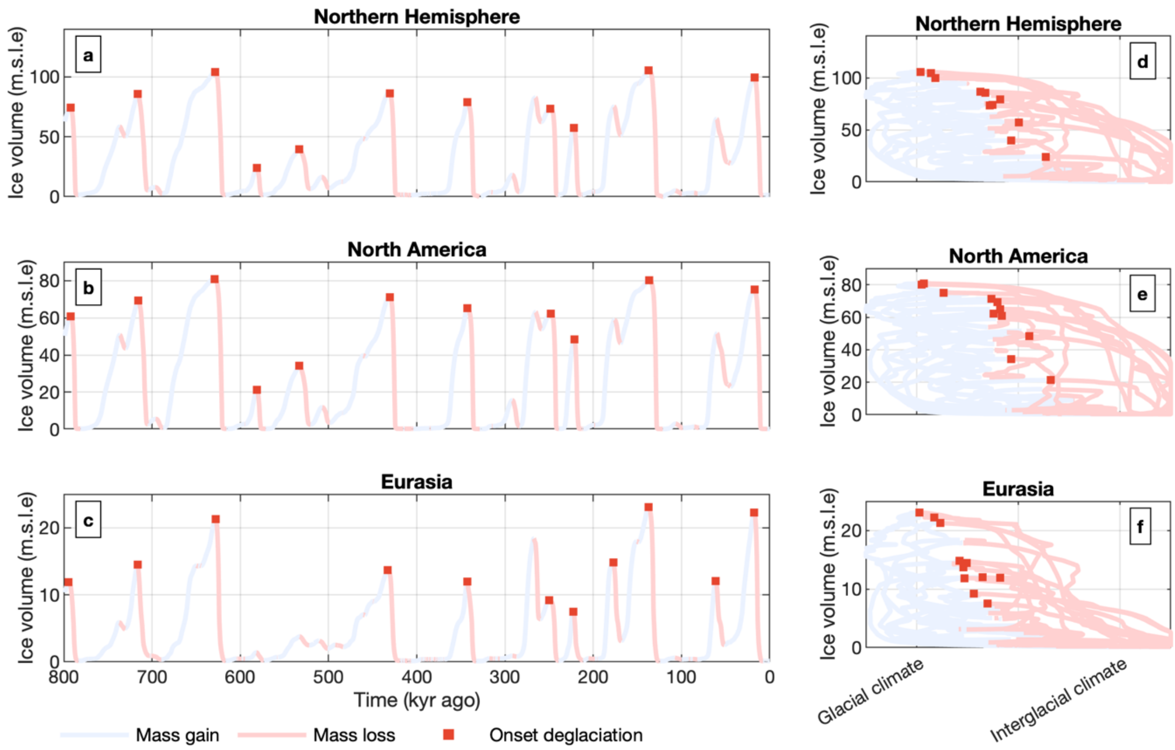
1) The blue “onset of glaciation” points will be removed. The climate that is needed to start a glacial cycle is not relevant to the overall story presented here.
2) The red “onset of deglaciation” points will be altered. These points are relevant enough to keep in the manuscript. However, it currently does not reflect the actual onset of deglaciations.

   Instead, we will now place an “onset of deglaciation” point when the ice sheet melts at a large enough volume (at least 20% of the modelled Late Pleistocene maximum) and has melted enough ice (less than 20% of the maximum Late Pleistocene volume remaining). These thresholds will be added to the caption.

3) External forcing index will be replaced by a simple "Glacial" and "Interglacial" climate to make it easier to understand.
4) Figure 7 (a similar figure) will be removed and replaced by 2D ice thickness maps.

The main goal of this figure is to show the difference in sensitivity between Eurasia and North America. And show that more glacial climates are needed to prevent an ice sheet to melt.

An updated version of the figure can be found below:



190: Can you comment on the mechanism for the higher sensitivity of the Eurasian ice sheet?

In the manuscript we have stated that the Eurasian ice sheet is more likely to melt during climate optima compared to the North American ice sheet.

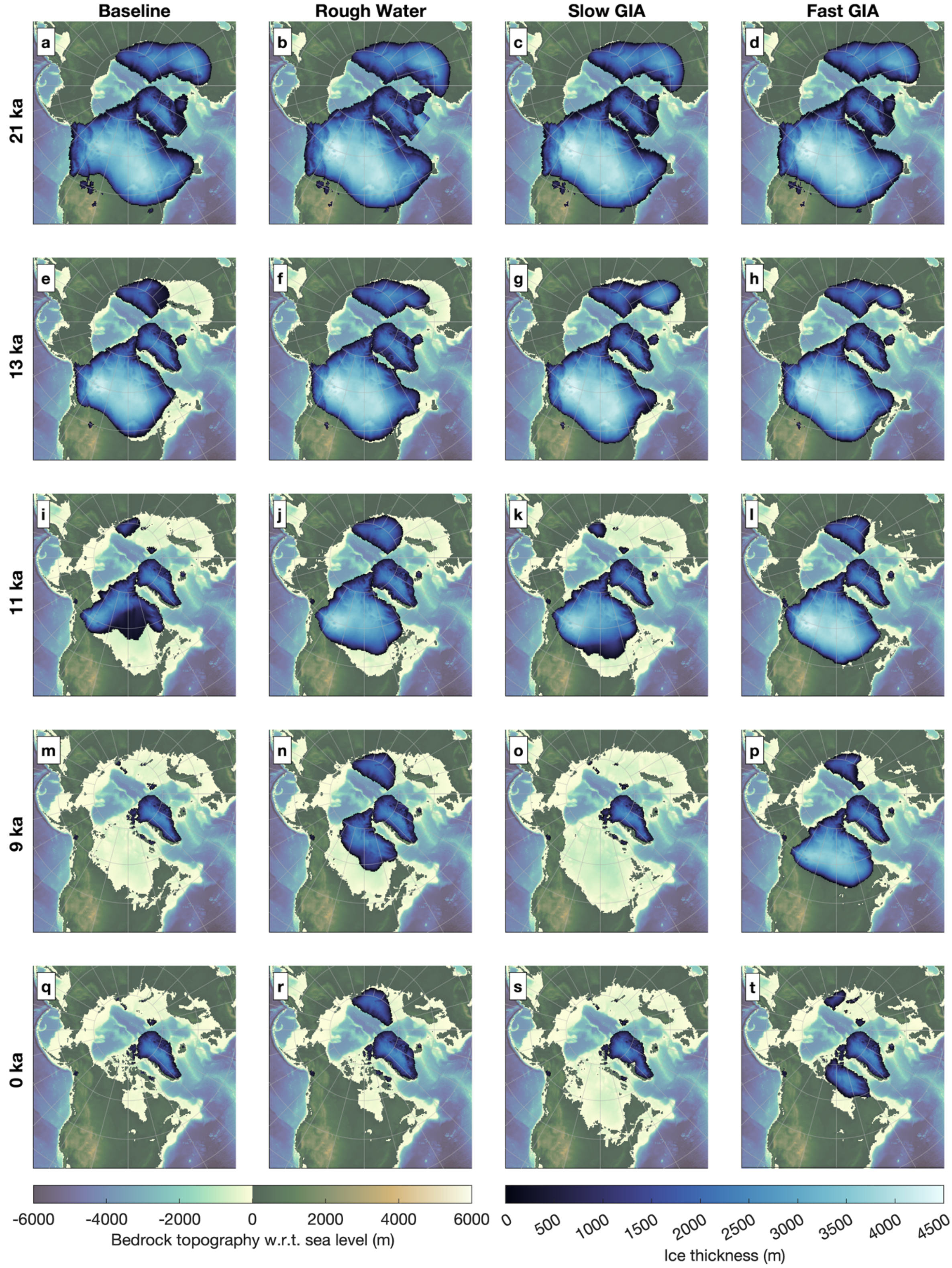
Eurasia is thinner and smaller compared to North America, making Eurasia more likely to melt during climate optima. This is in line with one of the theories from the MPT (e.g., see Berends et al., 2021; Reviews of Geophysics). A small ice sheet (Eurasia), and large ice sheet (North America at LGM) are more likely to melt at climate optimum compared to a medium-sized ice sheet (North America at interstadial). Ice sheets maintain their own cold climate due to ice-albedo and temperature-elevation feedbacks, that may only compensate the climatic effect of an insolation maximum when an ice sheet is at least medium-sized. However, when the ice sheet is too large, bedrock mass balance feedbacks, calving and large proglacial lakes make a large ice sheet more vulnerable to collapse.

The Eurasian ice sheet summer temperatures at LGM are also expected to have been higher (e.g., PMIP3 and PMIP4 LGM temperatures). A smaller increase in temperature may therefore yield a collapse of the Fenno-Scandinavian ice dome.

These processes will be discussed in the revised version of the manuscript. Additionally, this explanation will benefit from the newly added 2D maps of ice thickness and bedrock topography during the last deglaciation.

211: The importance of the simulated ice shelves may depend on their spatial extent and if they are constrained laterally. It would be good to see a figure of simulated ice sheet location and morphometry.

We will add several 2D maps of the last deglaciation showing ice thickness and bedrock topography during the last deglaciations. An example of this map is shown below:



216: I don’t follow the logic here?

In the current version of the manuscript, we have made an attempt at explaining the Rough Water simulation.

To improve the explanation of the experiment, we will make changes in both the method section and results section (around line 216).

The Rough Water experiment benefits from an improved explanation of the sub-grid friction scaling scheme in the method section. In the Baseline simulation, friction is multiplied by the grounded fraction of the grid-cell. Therefore, basal friction is 0 for fully floating ice, and is reduced for partially floating ice (at the grounding line).

This will benefit the explanation of the Rough Water simulation, which will also be improved. In the Rough Water simulation, we do not multiply friction with the grounded fraction. Hence, basal friction is not decreased for floating ice, and is therefore treated as if all ice is grounded.

Discussions: This section is very limited, it could be incorporated into the Results section.

The discussion section will be expanded in the revised version of the manuscript. Therefore, it does not need to be incorporated in the results or conclusion sections.

315: It would be good to develop this point a little further. What are the potential effects of lakes on future Greenland? And do models represent this?

This would be an interesting concluding section to the paper. We will add a very brief discussion on 1) the vulnerability of the Western-Antarctic ice sheet with respect to MISI and 2) discuss the Greenland proglacial lakes, as these lakes may potentially accelerate Greenland melt in the future.

However, while there are analogies between past and future ice sheets, the Greenland and Antarctic ice sheets are very different from the North American and Eurasian ice sheets (for example for Eurasia, see van Aalderen et al., 2023; https://doi.org/10.5194/egusphere-2023-34). Antarctica SMB is low, and mass loss is dominated by basal melt and grounding line dynamics. Greenland is also much smaller compared to the North American and Eurasian ice sheets.

423: It would be preferable for the simulations to be reproducible without contacting the author.

We will add a data-acknowledgement section. To perform IMAU-ICE simulations, information on the initial bedrock topography, prescribed CO_2 (Bereiter et al., 2018) insolation (Laskar et al., 2004), climate (PMIP3) is needed. We are not the legal owners of these data-sets and we therefore cannot place these on a public database without permission. However, we are allowed to create a data-acknowledgement section that provides the urls and references to the necessary data-sets.