Review of "Ice sheet model simulations reveal polythermal ice conditions existed across the NE USA during the Last Glacial Maximum" by Cuzzone et al.

I apologise for the late return of this review, and any inconvenience it may have caused the authors or editor.

Cuzzone et al. here present simulations of the Laurentide Ice Sheet, using small regions of high horizontal resolution to explore the basal thermal regime in areas of variable topography. Simulations at a continental scale require such coarse resolution that the thermal effect of mountainous regions may be excluded. In this paper, extremely high-resolution simulations demonstrate a polythermal bed and sharp thermal gradients in regions across the eastern Laurentide Ice Sheet.

Overall, the authors present some impressive simulations with interesting results. The work is well-described and presented, with some minor corrections to the figures suggested below. The research is clearly a good fit for the journal, and the work is worthy of publication.

We would like to thank Niall Gandy for the review and encouragement of our results. We are much appreciative for your time taken to help improve our manuscript. We have taken into account the reviewers' comments to improve some of our figure clarity and have modified some text (particularly discussion) to address some of the points raised below. Thanks again for your help.

Major points

1. A mini-ensemble is presented, with simulations using boundary conditions from 5 different climate models, but I am left wondering if we are confident that the variation between climate model output is certainly the first-order uncertainty to be explored. Perhaps this is a reasonable assumption, but I think this should be discussed in the text. If varying other parameters (such as elements of the PDD scheme of the basal sliding law) would be produce larger variation, plots like figure 3 may provide a false confidence in the certainty of the results.

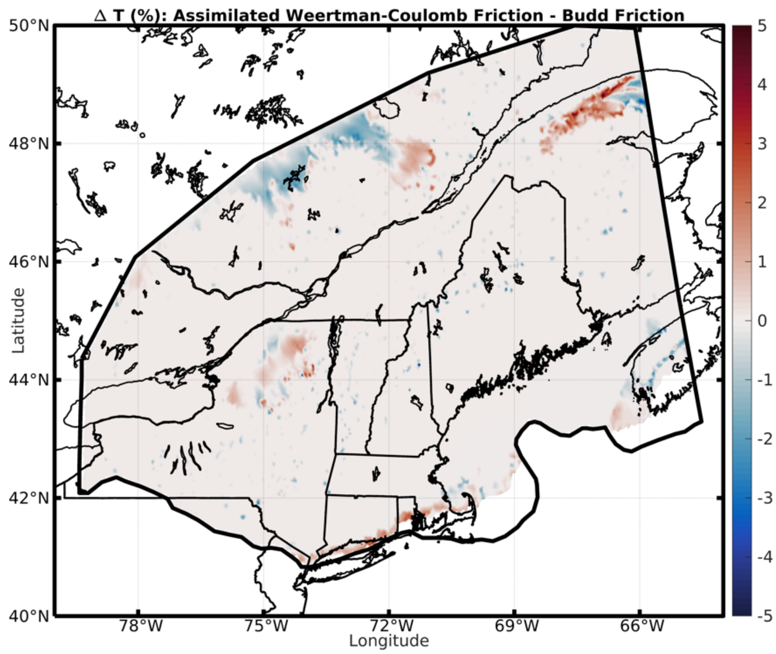
The PDD factors can/do influence the overall surface mass balance. In general, less melt and higher rates of snowfall in the ice sheet interior will lead to an increase in vertical advection. This would cause the vertical distribution of ice temperature to trend colder, and may result in increased potential for frozen bed conditions. However, the PDD factors do not have a large influence across this domain during the LGM. During the LGM surface temperatures were below freezing across most months. Only near the ice sheet margins did summertime temperature exceed freezing. Therefore, there is little to no snow melt across the interior of the ice sheet at the LGM across this domain, and the effect of the pdd factors on surface melt and accumulation are limited to marginal areas where summertime melt occurs during the LGM. From a climate perspective, the input climatology of temperature and precipitation influence the basal thermal state as these forcings influence the surface temperature and accumulation. We show this in Figure S5 and describe in text (lines 445-453), in those simulations with lower LGM temperature, higher accumulation, and ultimately higher SMB, the basal conditions are colder (more frozen bed).

To clarify this better, we adjusted the text in lines 474-477 to read: *"Those experiments with colder LGM boundary conditions and higher accumulation simulated higher SMB (Figure S5; TraCE-21ka, MPI, and IPSL) and therefore resulted in a stronger magnitude and a wider swath of cold based ice conditions across the Adirondacks (Figure S4; TraCE-21ka, MPI, and IPSL)."*

This is not to say the PDD factors do not have an impact. It is just that this impact is limited during the LGM when sfc. Temperatures are below freezing. It is possible that the PDD factors may have an increasing influence during the deglaciation, when sfc. Temperature rises and melt across interior locations ensues. Therefore we have added text on lines 487-509 to discuss this:

"We note that while the impact of degree day factors is unexplored in this work, we expect this to have a limited influence on the simulated thermal characteristics of the LIS across the NE USA. During the LGM, monthly surface temperatures remain below freezing across the ice sheet interior, with exception of the Southern margin (Figure S5). Therefore, surface melt is limited across the ice sheet interior, and instead the prescribed surface temperature and accumulation are the primary factors driving the simulated differences in the thermal conditions (Figure S5). Nevertheless, for simulations across the last deglaciation, the choice of degree day factors can have a large influence on the simulated ice history and ultimately the transient evolution of ice temperature as deglacial surface temperature and melt rise (Matero et al., 2020)."

With respect to the basal sliding law, we performed an additional simulation following our experimental setup, but instead used the Assimilated Weertman-Coulomb Friction Law (otherwise known as Schoof Law: Schoof et al., 2005). We find that the influence on the simulated steadystate basal temperatures are small (on the order of <5% difference) when compared to the basal temperatures simulated using the Budd friction law. Because of this, we do not think the choice of friction law would strongly influence the conclusions reached in our manuscript. However, the choice of friction law may become increasingly important during transient simulations across the last deglaciation. This question has not been addressed in current literature, but is something we will pursue in future work when performing transient simulations across the last deglaciation.



A subpoint is that it would be useful to have a sense of the computational expense of these simulations, both to help the planning of future studies and perhaps to further justify the limited size of the ensemble.

In general our models are around 200,000 elements. We note that we use a higher order stressbalance approximation. Simulations takes ~4-12 days for a LGM relaxation to steadystate (NE Model), although with iterative solvers (which we are experimenting) this can be cut in half. Smaller models are between 200,000-300,000 elements. Relaxation is shorter however as model reaches convergence faster.

2. A broader justification of the work would be useful in both the Introduction and Conclusion. Understanding the thermal effect of small-scale topography may be important for understanding the past evolution of LGM ice sheets, and future evolution of Greenland and Antarctica. But that is my interpretation, and it would be better to state your justification more explicitly. There is mention of models providing geologic constraints across a wide area, but I'm clear on what this would be useful for (because of my own ignorance, I'm sure!).

Thanks for this question. The ability to resolve basal topography can have large impacts on the simulated ice sheet history due to its impact on grounding line stability and ultimately ice retreat/advance as well as attendant feedbacks on the ice thermal regime. While this is an important consideration, we do not aim to frame our results in this manner. Perhaps future work could address this as we move towards transient simulations across this domain.

Ultimately, we hope our work is first useful for geologists/geomorphologists to help infer basal conditions where geologic data is limited. We hope that this conundrum was clear in our Introduction (Paragraph #2) and Discussion/Conclusions. The issue at hand is that some geologic data suggests the presence of cold-based ice conditions, and ultimately incomplete erosion. This becomes apparent when looking at cosmogenic surface exposure ages that have inheritance issues, which is particularly abundant in high elevation sites. Dipstick studies that aim to constrain vertical thinning histories across the NE USA suffer from this issue in some regions, making interpretations of vertical thinning difficult. Our results present a tool (from model outputs) that may inform where geologists sample along vertical transects, by choosing peaks that may have been (at least simulated to have been) warm based ice and erosive. While this model informed sampling technique has yet to be put to the test (co-authors Barth and Barker on this paper will use these outputs in field sampling summer 2025), it may become a tool for future sampling campaigns not only across the NE USA but other areas where polythermal conditions existed. While we did not want to overstate this as a tool, we did provide text in the Discussion and Conclusion highlighting this. If the reviewer does indeed want further clarification, we would be happy to add more, but feel our current justifications are adequate.

3. There are a few points where you compare your results to geologic evidence or other empirical evidence (some specific examples are highlighted below). A more robust quantitative comparison may be insightful, or at least a discussion of why this might not be possible.

We agree that a more robust comparison between the existing geologic/isotopic data would be beneficial. However, for the purposes of this manuscript that may be difficult. Any geochronologic data (e.g., TCN exposure ages) from the high peaks demonstrate nuclide inheritance and provide little benefit in constraining a time component. Additionally, as our model simulations are solely concentrated on the LGM, any geochronologic data younger than the LGM, that indicate warm-based ice conditions, are not yet relevant and would require a transient simulation of the deglaciation. Therefore, geologic/isotopic data are primarily considered spatially as indicators of basal thermal conditions with correlations drawn against modeling results. As this approach is not statistically robust, we have softened some of the language (e.g., "…simulations *broadly* agree with geologic interpretations…") and hope that addresses the reviewers' concerns.

Minor points

Figure 1: Could the model nesting be incorporated into this figure, rather than a separate figure in the SI?

After trying to satisfy this request, we would like to keep these figures separate as we could not find a suitable fix that was visually appropriate.

Line 167: Adjustment for clarity? "…independent of the thermal state but *this* has been explored…"

Requested change has been made.

Line 167: I'm not sure I'm following the final sentence of this paragraph. The differences between simulations with and without thermal-friction coupling are measurable but small? Could this be quantified?

Here we are referring to discussion in Moreno et al., 2023, in that the thermal-friction coupling tends to have little impact across the NE USA domain in those experiments.

Line 201: Is "downscale" the accepted word here? I (rightly or wrongly) interpret that as a statistical process.

We believe the appropriate usage is dynamical downscaling. We have modified the text.

Line 207: It seems odd that these locations are partly informed by state boundaries that didn't exist during (and have no impact on) glaciation. Would a purely geomorphic apolitical process have identified the same location?

Because geomorphic studies are at state level they are informed by local entities research (e.g. state geologists, etc), and often refer to these data (citations with our manuscript) at state level. Making our results most amenable to those fields we decided to keep as is but have adjusted the text in line 206 to differentiate that our choice relies on the highest elevation in each state:

"The three locations were chosen based on their geomorphic qualities, as each represents three of the highest peaks in the NE USA, and has pre-existing geologic data on glaciation (e.g., cosmogenic surface exposure ages; Bierman et al., 2015; Barth et al., 2019)."

Line 228: And is this climate data also used as the surface temperature flux to calculate the ice sheet thermal state?

Yes, the surface temperature is prescribed directly at the ice surface. We have updated the text ~ line 254:

"The thermal regime is assumed to be in steady-state with the LGM climate, and we perform a thermomechanical steady state calculation with a fixed ice sheet geometry and apply surface air temperatures directly at the ice surface until the ice sheet velocities are consistent with ice temperature (i.e., convergence) following Seroussi et al. (2013)."

Line 228: Given the focus of the paper I think it is entirely reasonable PDD values are prescribed and unexplored, as long is it produces a SMB field that serves the simulations. An additional justification may be useful for some readers, though.

Paleoclimate remains one of the largest uncertainties in paleo ice sheet model boundary conditions. While the PDD factors can influence the SMB and ultimately the ice sheet geometry (e.g. thickness, extent) and ultimately ice velocity and temperature, we feel that by using a range of plausible climate states we capture with some fidelity a range of simulated ice conditions. As described in the response above (Point #1), during the LGM, surface temperatures across the ice sheet interior remain below freezing during all months. Therefore, surface melt is limited across the ice interior, and the influence of the PDD factors on the ice temperature is likewise limited. It has an effect closer to the ice margin where melt is simulated (see Figure S5 for SMB maps), but this is not critical to our conclusions regarding the thermal characteristics of the LIS across this region, particularly at high (bedrock) elevation sites across the ice interior.

To clarify further, we have added some text to our discussion Line 461:

"*We note that while the impact of degree day factors is unexplored in this work, we expect this to have a limited influence on the simulated thermal characteristics of the LIS across the NE USA. During the LGM, monthly surface temperatures remain below freezing across the ice sheet interior, with exception of the Southern margin (Figure S5). Therefore, surface melt is limited across the ice sheet interior, and instead the prescribed surface temperature and accumulation are the primary factors driving the simulated differences in the thermal conditions (Figure S5). Nevertheless, for simulations across the last deglaciation, the choice of degree day factors can have a large influence on the simulated ice history and ultimately the transient evolution of ice temperature as deglacial surface temperature and melt rise (Matero et al., 2020).*"

Section 2.2: Could this process be summarised in a diagram or table in the SI? I found myself drawing in my notebook to help keep track of the process.

Would something like this be of use to make things more clear? If so, we could put this into the supplemental and reference it as a quickguide.

1.) 2D LIS Model: Spinup with constant LGM climate to arrive at equilibrium ice geometry and flow.
2.) 3D LIS Model: Extrude the 2D model to 3D
    a. Conduct a thermomechanical steady state computation to initialize model ice temperature and rheology.
    b. Perform an additional relaxation with constant LGM climate to allow model ice temperature and rheology to adjust to ice geometry and flow.
3.) NE USA Model: Construct a 3D model of the NE USA.
    a. Interpolate ice geometry, temperature, rheology, and velocity from LIS 3D model onto NE USA model mesh.
    b. Perform a thermomechanical steady state computation to downscale the coarser (LIS model) initial temperature and rheology inputs onto the higher resolution NE USA domain.
    c. Perform a relaxation with constant LGM climate to allow ice geometry, velocity, temperature, and rheology to adjust to higher resolution model mesh and reach equilibrium.
4.) Local Models: Construct 3D model of local domains (Adirondacks, Mt. Washington, and Mount Katahdin)
    a. Interpolate ice geometry, temperature, rheology, and velocity from NE USA 3D model onto local model meshes.

b. Perform a thermomechanical steady state computation to downscale the coarser (NE USA model) initial temperature and rheology inputs onto the higher resolution local model domains.
c. Perform a relaxation with constant LGM climate to allow ice geometry, velocity, temperature, and rheology to adjust to higher resolution model mesh and reach equilibrium.

Figure 2: Could colour-blind friendly ramps by used on ice velocity figures? The use of white stippling is nice.

We are more than happy to adjust this per the reviewer's request, however, in making this colormap initially we consulted with the BYU colorblind image tester and found the colormap to be colorblind friendly. https://bioapps.byu.edu/colorblind_image_tester.

If needed we would be happy to change, but feel the current colormap is satisfactory.

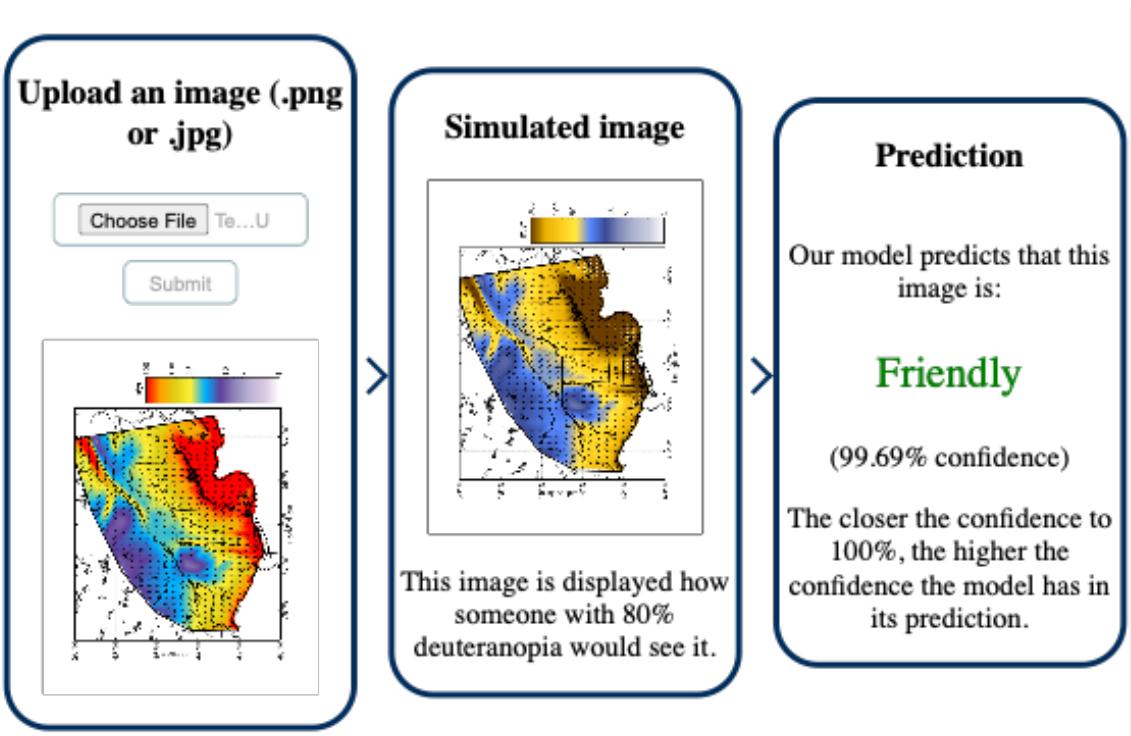


Figure 4: This figure contains a lot of useful information but it takes some work to fully appreciate! To improve readability, you could include a location panel to save readers bouncing between figures? The position and scale of various axis and legend labels could be refined to increase readability. The figure is a bit small, but panel B doesn't add much to panel E. If you

removed B the remaining panels could be enlarged. A scale bar would be useful alongside the graticule.

Figure 5: As above.

Figure 6: And again.

We agree with the reviewer that the figures here could be modified to improve readability. Thanks for the help here.

Following your recommendations, we opted to remove the ‘panel B’ and replace that with ‘panel E’ from our original submission. There are now 4 panels which have allowed us to enlarge the overall figure size – which we hope improves readability. A scale bar and inset map showing the location of the subdomain has been added to panel A.

Line 417: “Our results agree with geologic interpretations”. Is it possible to provide a more robust statistical or graphical comparison between your results and geological interpretations?

To address this, we refer to our answer to point 3 above.

Line 424 onwards: It would be interesting to see a comparison of the simulated velocity field at different scales? If these regions are important, I suppose it would have a measurable impact on the flux across the domain?

Our apologies, but we are unclear what/where the reviewer is referring to with the different scales and regions? We think the comparisons between Figures 2&3 and the local model figures (4,5,6) illustrate these differences adequately. Here we are referring to the resolution of topographic features in coarse resolution models, and the inability to capture the thermal gradients that existed across the high gradients in terrain. The boundary conditions for the higher resolution simulations come from our coarser regional models, which still are pretty high resolution. They capture the general ice flow (direction, speed; Figure 2 & 3) across the NE USA well. These boundaries do not disagreement in cross boundary fluxes (i.e. coarse model simulating flow into or out of domain where high res. model would simulate the opposite), so therefore we do not expect the downscaling to be impacted by the boundary conditions.