Review of “*Evaluating different geothermal heat flow maps as basal boundary conditions during spin up of the Greenland ice sheet” by Zhang, T., Colgan, W., Wansing, A., Løkkegaard, A., Leguy, G., Lipscomb, W., and Xiao, C.*

Overview

This study uses the Community Ice Sheet Model (CISM) to investigate the sensitivity of the ice sheet thermal state to the geothermal heat flow (GHF) model, using long, transient simulations. The authors find that there is considerable variation in the basal ice temperatures, depending on the GHF model used. The appropriateness of each of the 7 GHF models is discussed.

The findings of study have significant implications for intercomparisons between ice sheet model simulations, both in terms of englacial and basal temperatures and ice dynamics, as well as assumptions for the present-day thermal state of the ice sheet. This study is timely, given that ISMIP7 is currently spinning up, and makes an important contribution to ice sheet modelling studies of the Greenland ice sheet.

Overall, the study is well-designed, the manuscript is well written, the main points well argued, and it's easy to follow.

I have three main comments:

1. Initialisations. It would be good to see a few more details about the ice sheet initialisations and experiments, to provide as much information for reproducibility as possible. See detailed comments below.
2. Visualisations. The spatial maps are very helpful for visualising spatial differences between the results. In some cases it might be helpful to consider investigating/visualising relationships between different variables. For example, in exploring the basal temperature differences, it might be interesting to produce scatter plots of temperature vs thickness or velocity to see which has the greater influence on the basal temperature. I’d expect that under thicker ice you might see temperatures closer to the pressure melting point, but that is not necessarily the case in the Case 2 simulations here, so it’d be helpful to be able to visualise why. This is also a similar question for the GHF → temperature → friction coefficient → ice velocity relationship reported for Case 1.
3. This study made me wonder: what are the dominant basal heat sources that we expect to operate in different regions of Greenland and what are their magnitudes? Obviously frictional heating is going to play an important role (e.g. Karlsson et al. 2020). But what about conductive heat transfer from subglacial hydrology? Do we know anything about the distribution of temperate ice? Groundwater? And where might we expect high deformational heating that could influence the basal heat (e.g. where there’s high topographic roughness; Law et al. 2023)? Although these

questions are outside the remit of this study, drawing from different sources is one avenue to constrain GHF (as you've already also demonstrated in the discussion on Eemian ice persistence), and could be discussed in a bit more detail.

Detailed comments

- Methods: what is the mechanical model used? Does it include both bed-parallel vertical shear deformations as well as membrane stresses?
- L116: "All floating ice is assumed to calve immediately." Does this mean that there are no floating ice shelves/tongues?
- L116-117: What does it mean that the "...basal shear stress is weighted using a grounding-line parameterization."? What is the parameterisation? Does this mean sub-grid cell grounding line migration, as per Seroussi & Morlighem (2018)?
- Case 1 iteration:
    - Are the friction coefficients locally nudged? How does the nudging work differently for the cases where momentum balance can/cannot be achieved locally (i.e. bed-parallel vertical shear stress dominates or membrane stresses are significant)?
    - What are the consequences of initialising by looking at the misfit to the observed thicknesses rather than observed velocities? What's the order of magnitude of error/uncertainty in thicknesses over the domain?
    - Is there a reason to use *m=3*? I'm not as familiar with Greenlandic applications, but this parameter value can have large impacts on the sliding behaviour reproduced.
- L141-142: What is the idealised vertical englacial temperature profile that is used?
- L144-145: "By the end of spin-up, the ice sheet is assumed to have achieved a transient equilibrium…". Is this the case? How much of a difference do you see in temperatures, velocities and thicknesses between final timesteps?
- What are the model timesteps
- L146: How is the CISM bed interface temperature field calculated?
- L178: "coldest basal temperature" → "lowest basal temperature"
- L181: "warmest basal temperature" → "highest basal temperature"
- L190: "South Dome". It'd be great to add the names of the locations referred to in the text (including South Dome, NEGIS, Central East/West Greenland, Flade Isblink, etc) to one of the figures.
- L196-203: I'm not sure I understand what is meant here. For both the friction coefficient and GHF discussion, do you mean the highest absolute surface ice velocities or the largest positive/negative deviations from the mean in the ice surface velocities? It might be helpful to plot these as scatter plots (deviations from the mean in GHF/friction coefficient vs deviations from the mean in ice surface velocities) to visualise this. Also, does this mean that there's a coherent relationship between GHF, friction coefficient, and surface velocity?
- L203-206: Why do we see high friction coefficient where there is high GHF (compared with ensemble mean)? What is the friction coefficient compensating for? Does the calving behave differently for cases 1 and 2 because the high GHF→high friction effect is not as marked in the transient case?
- L215-218: However, this sensitivity depends on a range of other factors that might change the outcome between the nudged and transient runs. For example, the

choice of flow relation and the parameters incorporated in that will impact the relative contributions of deformation and sliding to overall surface flow, and also hence the deformational heating. Do you think that the transient experiments could be more sensitive than those of the nudged simulations to variations in such other parameters, which might ultimately reduce their sensitivity to GHF?

- L218-223: Does this result relate to how close the basal temperature is to the pressure melting point due to heat sources other than the GHF? That is, in the absence of any GHF, what is the minimum basal heating required to bring the basal ice temperature to the pressure melting point? This would be a clear metric to shed light on the sensitivity to GHF variations.
- L266-269: Interesting. I hadn't seen this paper by Ryser et al. (2014), so this is good to know. This effect might also be related to the neglect of anisotropy in the flow relation, as highlighted in some recent studies (Rathmann et al., 2021; McCormack et al., 2022).
- L277-278: How do you think this effect (increased thickness under decreased heat flow) in case 2 would differ if the effect of subglacial hydrology were incorporated? Previous studies have shown that the GHF influences the extent of the subglacial hydrological system (e.g. Smith-Johnsen et al., 2020). This also is relevant for your results, where the thawed-bedded ice sheet area ranges from ~20 to 55% depending on the choice of GHF. Although subglacial hydrology was not considered in this study (and is beyond the scope), it would be interesting to know a bit more about how that process might feed in here in the discussion. Also, is it possible to delineate between/plot where the different models predict the ice to be flowing by sliding or by deformation?
- General question for discussion: how do you expect the results might depend on the choice of mechanical model and flow relation used?
- L323-324: comparison of results with borehole measurements. Perhaps I misunderstood, but in the results, it's mentioned that the evaluation against the 27 Greenland borehole measurements is not conclusive. Are there comments that could be made about the local appropriateness of the GHF models? I guess the resolution of these datasets is not sufficient to say whether they're getting the GHF right at specific points for the right reasons?
- L332-336: Do you mean that your simulations suggest that unconstrained transient spin ups are more appropriate for understanding how/why the GHF impacts ice sheet geometry/velocity because the nudged spin up hides some effects?

- Figures 1-3: panel (h) is missing, but there's an (i)?
- Figure 4: I find the colours a little bit difficult to differentiate. Would it be possible to find another colour ramp where there are some larger differences in hue?
- Figure 8: would it be possible to use a larger spread in colours? Again, I found it a bit difficult to differentiate between the lines.
- Colour ranges in figures: In some of the figures that show % differences compared with the ensemble mean, the colour bars saturate really quickly (e.g. fig2, 4, 6, 7, 9, 11. It might be helpful to extend the colour bar range, e.g. -150:150% or -200:200% to see more variation in the spatial patterns.
- All figures: it'd be helpful to add units to the colour bars in each panel

Two things I liked about this paper

1. GHF matters. Producing differences in thawed-frozen areas of 21.8-54.4% depending on the GHF model that is used is huge and will have significant impacts on the evolution of the ice sheet. It's easy to neglect GHF because it's small in comparison with frictional heating, but it clearly has a big impact on ice dynamics
2. I appreciated the discussion on nudged vs transient simulations. Sometimes I think the focus on matching observations can make it difficult to understand the processes that are operating in models and why, but by including both transient and nudged simulations, it's possible to highlight why certain behaviours were observed.

References

McCormack, F.S., Warner, R.C., Seroussi, H., Dow, C.F., Roberts, J.L. and Treverrow, A., 2022. Modeling the deformation regime of Thwaites Glacier, West Antarctica, using a simple flow relation for ice anisotropy (ESTAR). Journal of Geophysical Research: Earth Surface, 127(3), p.e2021JF006332.

Rathmann, N.M. and Lilien, D.A., 2022. Inferred basal friction and mass flux affected by crystal-orientation fabrics. Journal of Glaciology, 68(268), pp.236-252.

Seroussi, H. and Morlighem, M., 2018. Representation of basal melting at the grounding line in ice flow models. The Cryosphere, 12(10), pp.3085-3096.

Smith-Johnsen, S., Schlegel, N.J., de Fleurian, B. and Nisancioglu, K.H., 2020. Sensitivity of the Northeast Greenland Ice Stream to geothermal heat. Journal of Geophysical Research: Earth Surface, 125(1), p.e2019JF005252.