Reply to Reviewer 2:

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.

We thank the reviewer for the positive support!

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.

Thanks for the suggestions. Please see replies 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.

We are afraid there are hardly easily-detected relationships between velocity, temperature and thickness, as shown in the following figure. The thermomechanical coupling makes it a complicated question to answer. Regarding the GHF → temperature → friction coefficient → ice velocity relationship, we find different change patterns for Case 1 and 2. For Case 1, we have lower T --> lower friction --> higher velocity, and for Case 2, we have lower T --> higher friction --> lower velocity, as normal. The Case 1 uses a nudging scheme, thus CISM will change basal frictions to modulate ice flux in order to match ice geometry. We also explain this below.

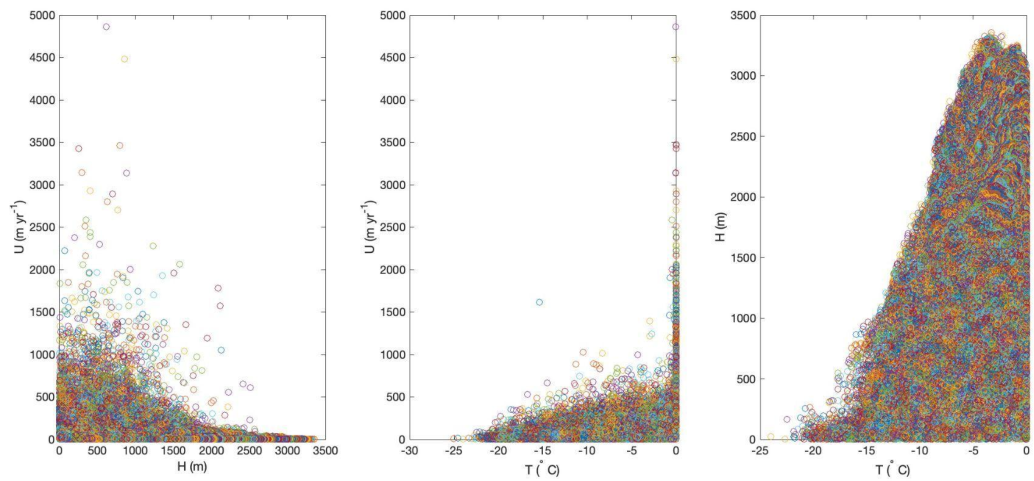

Figure 1: Relationships between surface speed (U), ice thickness (H) and basal temperature (T)

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.

Thanks for the comments. We now add a new paragraph at the end of the Discussion section.

Detailed comments

- Methods: what is the mechanical model used? Does it include both bed-parallel vertical shear deformations as well as membrane stresses?

The momentum balance is computed using the DIVA (depth-integrated viscosity approximation) solver in CISM, as stated at the start of the Methods section. Yes, it is a higher-order solver that includes both vertical shear and membrane stresses. If we neglect membrane stresses, we will have SIA.

- L116: “All floating ice is assumed to calve immediately.” Does this mean that there are no floating ice shelves/tongues?

Yes, that is correct. We added some text to make this clear.

- 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)?

The grounding line parameterization is a sub-grid method of determining the grounded fraction of the grid cell containing the grounding line. By this method we can accurately capture the basal shear stresses near the grounding line on a relatively coarse mesh. We added some text to make this more clear, along with a reference to Leguy et al. [2021], which describes CISM’s grounding-line parameterization in detail.

- 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)?

    Yes, the friction is locally nudged by matching the modeled ice geometry to observations. We added text to clarify that friction coefficients are nudged at each velocity point. The nudging does not depend on the size of different terms in the momentum balance.

    - 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?

    In most of the ice sheet, the thickness and velocity fields are in approximate balance, and thus the spun-up velocities are in good agreement with observations, even though velocity is not a nudging target. The exception would be regions where the velocity has recently changed and the thickness has not had time to adjust. We added text to clarify this point.

    An example of thickness uncertainty at the 10 ka after the spin-up can be seen in Figure 2. Over the majority of ice sheet domains, the thickness difference is pretty small. But at some locations near the ice sheet margin, the thickness difference can reach around 1000 m. The overall RMSE is around 32 m.

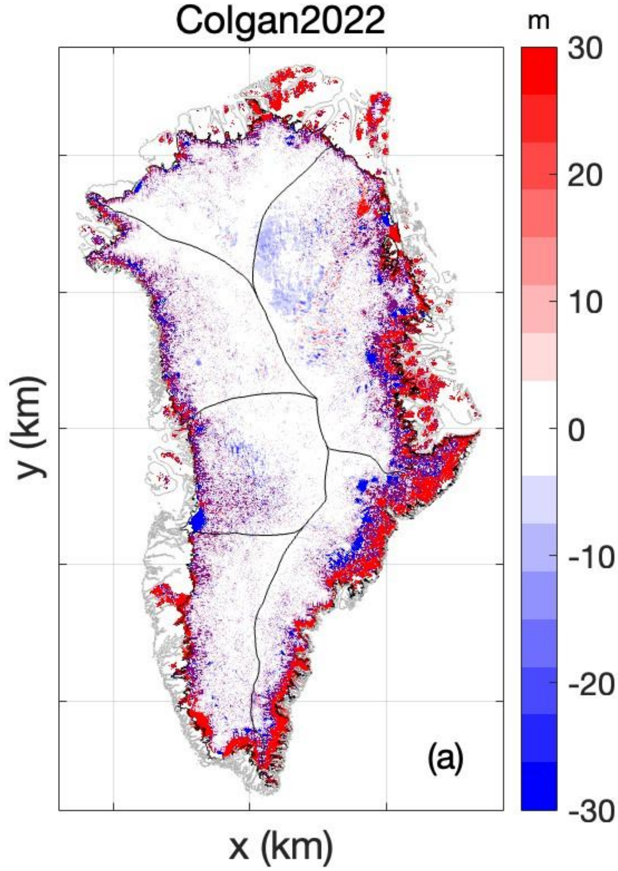

Figure 2: The thickness difference between the modeled values at 10 ka and observations using the Colgan et al. [2022] heat flow model. The colorbar saturates at [-30, 30] m.

- 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.

m=3 (Glen's law exponent) is a commonly used parameter for the Weertman sliding law (Gagliardini et al., 2013)

- L141- 142: What is the idealised vertical englacial temperature profile that is used?

We used the initial temperature profile described by Lipscomb et al. [2019]. This profile is linear where the SMB is negative, and is based on advection–conduction balance where the SMB is positive. We added text to make this explicit.

- 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?

In this study we take the model in transient equilibrium by looking at the ice mass change over time, as shown in the following two figures 3 and 4. Clearly they are nearly at the equilibrium state after 10 ka year runs. The relative volume change at yr 10 ka is around 1e-5 % for Case 1 and 1e-3 % for Case 2. If we look at the basal temperature difference during the last 1 ka, the RMSE across GrIS is only 0.0656 K, 1.17e4 Pa yr m^{-1} and 1.51 yr m^{-1} (Fig 5).

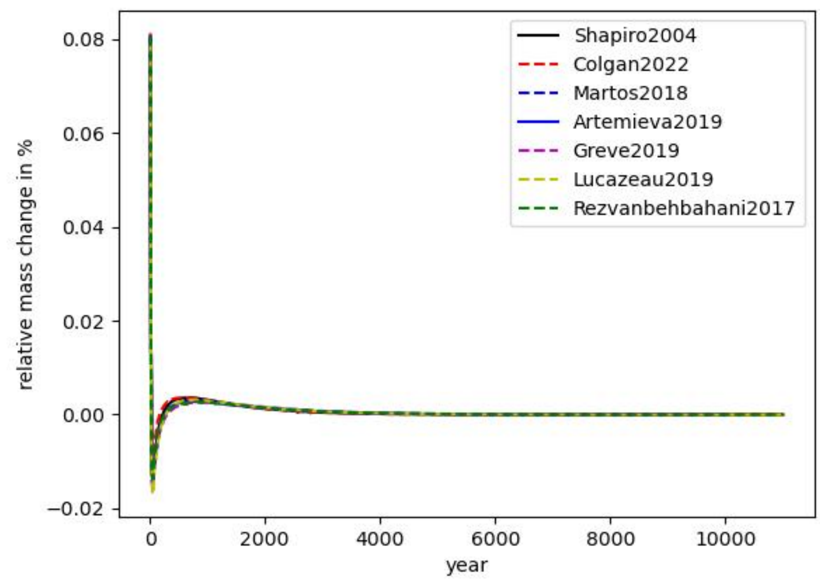

Figure 3: relative mass change in time for Case 1

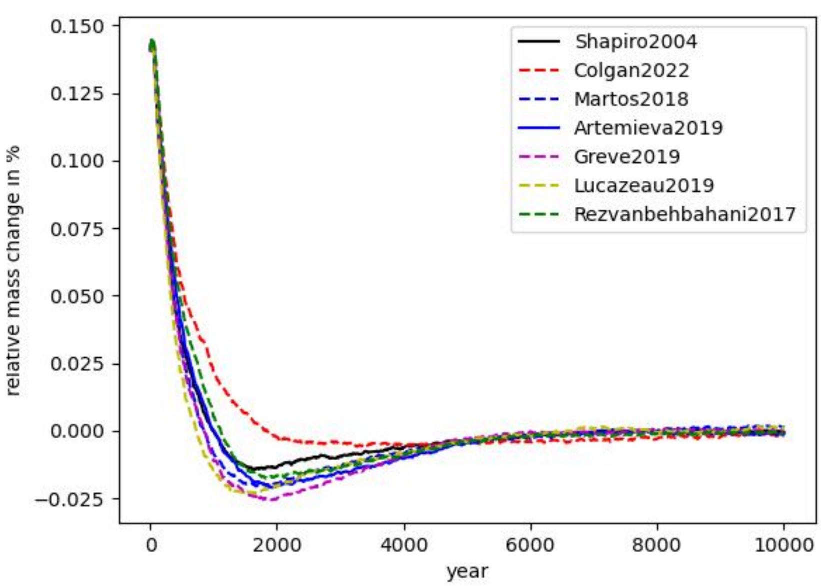

Figure 4: relative mass change in time for Case 2

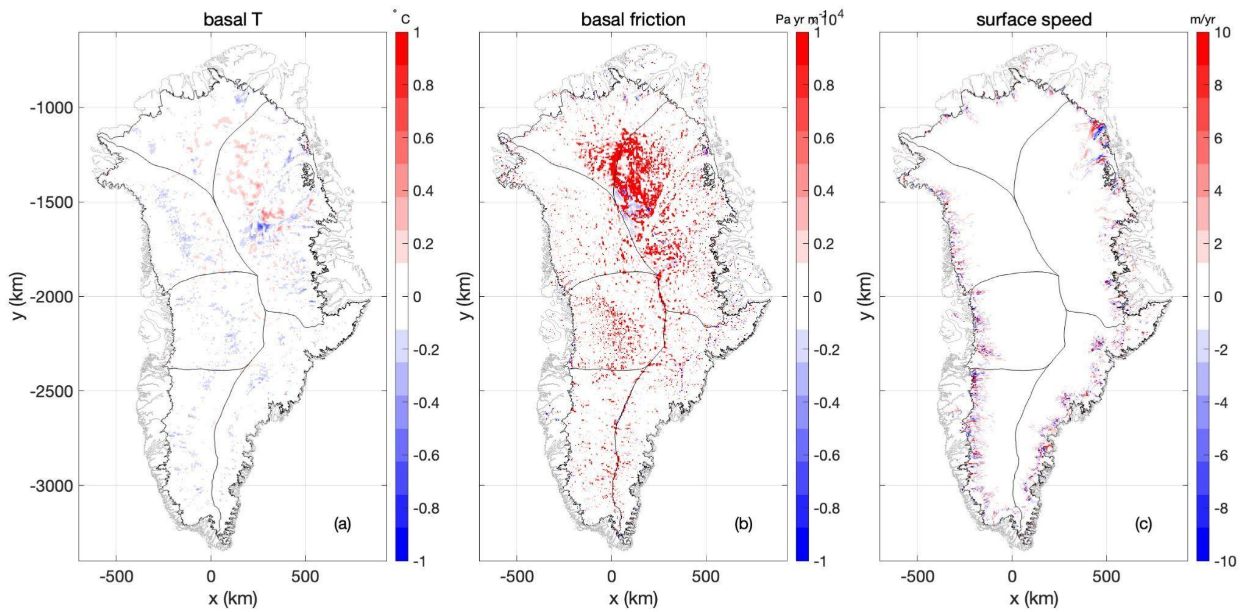

Figure 5: The difference of basal temperature (a), friction (b) and surface speed (c) between yr 9 ka and 10 ka using the Colgan et al. [2022] heat flow model. The colorbar saturates at [-1, 1] deg C, [-1e4, 1e4] Pa yr m^{-1} and [-10, 10] m yr^{-1}, respectively.

- What are the model timesteps

  The time step is ⅙ year, i.e. about 2 months. This is now stated in the text.

- L146: How is the CISM bed interface temperature field calculated?

  Where the bed is frozen ($T_b < T_{pmp}$), the basal temperature is computed by prescribing a balance of geothermal heat flux, vertical conductive flux, and frictional fluxes at the ice–bed interface. Where the resulting temperature would exceed T_{pmp}, we set $T_b = T_{pmp}$ and use the excess energy to melt ice. This is now stated in the text.

- L178: "coldest basal temperature" → " lowest basal temperature"

  Changed

- L181: "warmest basal temperature" → " highest basal temperature"

  Changed

- 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.

We now add more detailed information in Figure 5 in the manuscript.

- 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?

In this place, the original Figure 7 should be for Case 1, and we now update Figure 7 here in the manuscript. The old Figure 7 is now renumbered as Figure 12 in the revised manuscript. Here we see that the low heat-flow anomaly yields a high ice-velocity anomaly, and vice versa. The reason we believe is because we do the nudging in Case 1 where the effect of low ice temperature (ice deformation) is compensated by decreasing basal friction to increase ice flux in order to match the ice geometry.

Regarding the scatter plots, we do not think there will be clear and straightforward (e.g., linear) relationships between dU and dG / dbeta, as shown in the following figure.

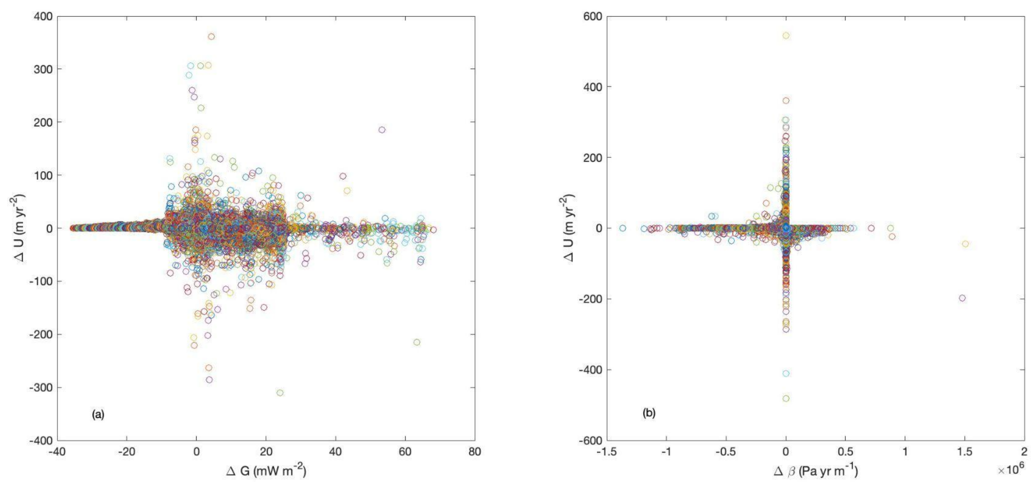

Figure 6：Relationships between the deviation of surface speed, ice thickness and basal friction

- 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?

We believe the high GHF and high friction effect is from the nudging process. It is possible because the nudging will compensate for the low ice velocity from low GHF by decreasing

basal frictions. In Case 2 where we do not constrain basal friction, we do not see this effect. So yes, we think it is the main reason that Case 1 and 2 have different calving flux behaviors.

- 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?

This argument is based on the findings that the thawed area for Case 2 (fully transient) is larger than that for Case 1 (nudging), as listed in Table 2. But we also agree with the reviewer that the dynamic sensitivity depends on a few different factors. We now change it to "may suggest" so that this sentence sounds a bit weaker than before.

- 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.

It might be the case. The basal strain heating might be dominant in some regions. But it would not be an easy task to fully split out their contributions. We probably need to do the following work: (i) set heat flow to zero across the whole GrIS to slip out the contribution from basal heat flow, and (ii) disable all ice dynamics to split out the contribution from strain heating. But as we are spinning up the model, the basal friction and ice flow will also change if we turn off basal heat flow for (i), and for (ii) we can not even do the spin-up simulations due to the lack of ice velocity. I would suggest using a full Stokes or Blatter-Pattyn model for this understanding. It would be another paper, but it is an interesting and also important thought.

- 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).

Thanks for the inputs.

- 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?

Thanks for the comments. We are afraid we could not answer the first question as we do not consider subglacial hydrology in this study. For the second question, we can tell the importance of sliding and deformation by calculating the ratio of basal to surface velocity from the model outputs, just like the following figure.

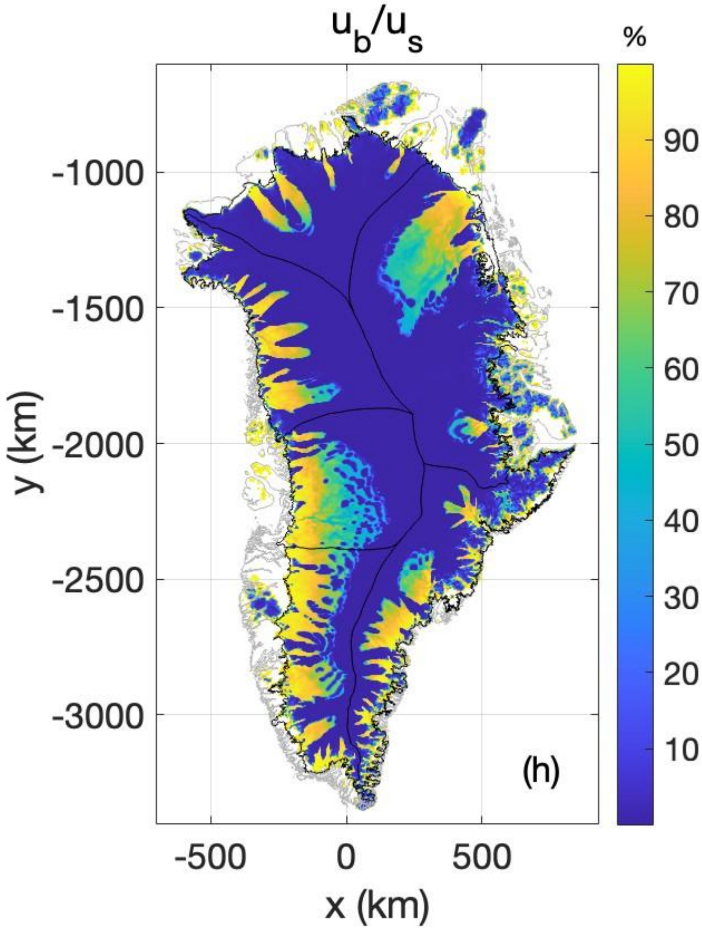

Figure 7: the ratio between basal and surface ice speed

- General question for discussion: how do you expect the results might depend on the choice of mechanical model and flow relation used?

It is a hard question and is also one of the reasons that we want to do this study. If you look at the McGregor et al. (2022) paper, you can see various model results from different ice flow models, and indeed it is hard to tell where the differences are actually from. To split out the impacts of the ice flow model, we here use just one single ice flow model so that we could attribute the model differences to other factors like basal heat flow more clearly.

- 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?

Thanks for this comment. We now change the sentence to “Despite the fact that the spatial resolutions of several basal heat flow models are coarse and can not be compared to that of CISM, this evaluation still appears to provide some insights on which heat flow map or spin up approach is most locally suitable.”

- 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?

Ideally, yes. The unconstrained simulations provide more physically based understandings of ice sheet evolutions. The nudged simulations artificially change important parameters in ice flow and might not be very appropriate if we run the model forward using the nudged basal friction field. We change “generally” to “possibly” in this sentence to make it sound a bit more proper.

- Figures 1-3: panel (h) is missing, but there’s an (i)?

Changed.

- 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?

We now use a different colormap (jet) instead.

- 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.

The lines are improved.

- 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.

Changed.

- All figures: it’d be helpful to add units to the colour bars in each panel

Changed.

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.

We thank the reviewer agian for the support.

References

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