Title: Impact of boundary conditions on the modeled thermal regime of the Antarctic ice sheet
Journal: *The-Cryosphere*
Reviewer: Tyler Pelle (Scripps Institution of Oceanography, tpelle@ucsd.edu)

Overview:
Park et al. present an in-depth analysis of how varying geothermal heat flux fields and vertical ice velocity initializations impact the modeled thermal regime of the Antarctic Ice Sheet (AIS) via comparison to 15 borehole measurements. Using the three-dimensional Ice-sheet and Sea-level System Model to provide 8 modeled thermal AIS states (4 geothermal heat flux fields and 2 vertical ice velocity initializations), Park et al. find that varying vertical ice velocities have the greatest impact on the modeled thermal state and that traditional means of inferring vertical ice velocity perform well in fast flowing regions.

Overall, I find that the paper is very well written and the results will be of wide interest to those within the glaciological community. This work constitutes an important step forward in our understanding of how ice sheet thermal models perform against available borehole measurement and which initialization processes drive the thermal solution. I do have a few general comments about that paper that I would like to see addressed, but these are mostly minor and should be relatively easy for the authors to fix. In particular, I am a bit worried that the conclusion that "GHFs have little influence on the variance in basal temperature fields and grounded ice melting rate compared to the vertical velocities" is not well supported by the work (see line comment L343). I also would like to see a bit more explanation about limitations of the ice sheet model and how it is initialized. Otherwise, most of the remaining comments are grammatical or based on small changes I would like to see to figures (most of which are very well constructed). I think this work would make a wonderful contribution to *The-Cryosphere* and I would like to see it published after addressing my minor comments.

General Comments:

- **Abstract**: Your manuscript is full of really wonderful conclusions that didn't make it into the abstract! For instance, a lot of your results pertain to modeled grounded ice melting rates and how varying spatial distributions of GHF impact this. In addition, you also highlighted that bed topography from mass conservation improved the performance of the thermal model over other methods that are less constrained by data. While it is up to you which results you would like to highlight and I do appreciate that you kept the abstract very straight forward, I think a lot of really great results are buried in the paper and you have the room here to highlight them (same for the conclusions as well).
- **Tense of writing**: When reading, I noticed that you switched between past and present tense a lot. I think the standard is to use the present tense. In the line comments, I tried to point out a few instances of when you used past tense, but I definitely did not catch all of the instances.

- **Assumptions in the ice sheet model**: Will the choice of a Budd sliding law impact the simulated thermal structure of the AIS? Same for the assumption that the effective pressure is equal only to the ice overburden pressure (meaning that you are assuming there is no subglacial water system at the ice-bed interface)? Several studies (e.g. Gustafson et al., 2022) have found a complex subglacial water system underlying the Siple Coast (where many of your borehole measurements are taken), which could certainly impact basal sliding (and thus vertical ice velocities). While I believe that an in-depth analysis of this is beyond the scope of this paper, it would be nice to see perhaps a figure or two in the supplement that show if your modeled thermal AIS states are sensitive to these two assumptions. I would also like to see limitations like this addressed in the discussion section as well.

Line Comments:

- L7: Can you be more specific when saying "vertical velocity plays a more important role in the temperature profile than GHF"? Do you mean that the temperature profiles are more sensitive to vertical velocity than GHF?
- L8: " . . . which consists of combining . . .
- L21: "Several important properties, such as ice elevation and surface ice velocity, . . ." " . . . subglacial properties, such as ice temperature and geothermal heat flux, . . ."
- L25: A little confusing wording, perhaps change to: In order to get reasonable estimates of these englacial and subglacial fields, inversion techniques are routinely employed (citations)."
- L28: "geothermal heat flux" should not be capitalized
- L29-30: " . . . and ice dynamics (citations); yet, large uncertainties . . ."
- L36: " . . . better understanding of subglacial and englacial environments . . ."
- Methods: You use past tense here (e.g. "We used ISSM", "We used a 3D HO model", . . .). I mentioned this above, but please try to switch this to present tense when possible.
- L76-78: Which surface ice velocity map did you use to perform the inversions?
- L102:106: In L102, you state that there are three different vertical velocity profiles, but in the experiment description, you only describe 2. Also, in L105, do you mean IVz-nosliding ignores the inferred basal sliding velocities?
- L115: It would be interesting to see a figure showing these four GHF data sets (with overlaid positions of borehole measurements) rather than only giving the AIS-means. I see you do this for the top row of figure 4, maybe reference that here and add borehole locations onto those maps if possible.
- L127: " . . .between temperature measurements along the borehole profile and triangular mesh were not . . ."
- L156: Add a space between sentences.
- L163: Remove double-comma
- L172: Change LVZ to LVz

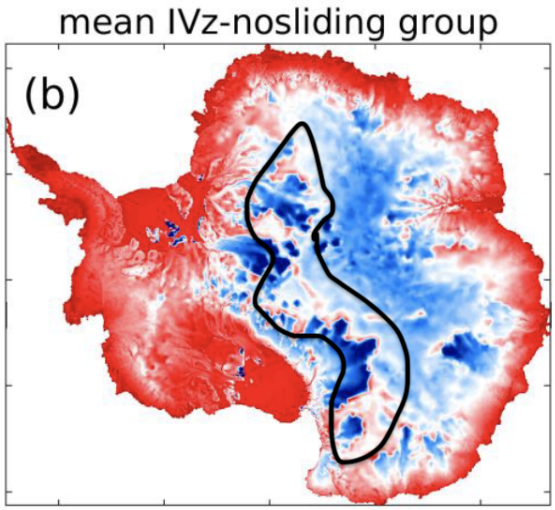
- Table 3: This table is quite large and it is very difficult to comprehend results from it because there are so many numbers. I am wondering if there is a way you could add shading to the table to show greatest to least misfit (almost like a heatmap). Or you could add highlighting to the lowest misfit for each borehole (replacing the bold text, which does not stand out very much). Alternatively, I'm wondering if this data would be best visualized as a figure rather than a table?
- L181-185: Maybe I am confused, but in figure 2, it seems like the IVz-nosliding group captures the linear shape of the temperature profiles quite well (hence the good match between observations and the dotted lines for the first three profiles). Also, are we interested in the sign of R2, or just its absolute value of? Because while it is true that R2 is larger for IVz-nosliding than IVz, they both seem equally close to 0 when only considering the absolute value. Perhaps a description on how to interpret the R2 value in the methods section would help clarify this.
- L229: Degree symbol is not a superscript in 5.1DegC
- L235-240: This finding about bed topography improving the performance of the thermal model is really great! I know it is not a main point of the paper, but I think it is super important and should be highlighted if possible (maybe in the discussion and/or conclusion sections?).
- L243: Do you know why the vertical profile for Maule-IVz shows such high misfit for the AIS/WIS boreholes, whereas it always seemed fairly similar to the other IVz profiles?
- L246: By peripheral region, do you mean coastal regions? It might be helpful to use a more descriptive word here.
- L257: Perhaps here, it would be better to reference figure 3, where you show the basal temperature fields for each experiment. In figure 3, it is easy to tell that basal temperatures are warmer in IVz-nosliding compared to IVz; however, it is hard to distinguish differences in figure 4 e-l (see figure 4 comments below).
- L262-263: Hard to tell differences in grounded ice melt between GHF sources, see figure-4 comments.
- L340: change "velocitiy" to "velocity"
- Conclusions: I think it might be worth mentioning that varying spatial distributions of GHF did have a large impact on the spatial distribution of grounded ice melting rates across the AIS.
- L343: Here, you say that the effects of different GHFs have little influence on the variance in basal temperature, but I would argue that figure-5 shows the opposite. Comparing figure 5c and 5d (the SR-IVz versus Maule-IVz basal temperature), the area of the ice sheet base that reaches the pressure melting point is much larger for the Maule-GHF than the SR-GHF (especially in East Antarctica). In fact, this difference in the hatched-white area is greater than that when comparing SR-IVz to SR-IVz-nosliding in this same figure, possibly showing that GHF has more of an impact on ice basal

temperature than the vertical ice velocity. As it reads now, I think your conclusions underplay the importance of the GHF field in driving variance in ice basal temperatures.

- L353-355: Fix formatting here.

Figure Comments:

- Figure 2: It would be helpful to show visually which borehole measurements were taken in fast-flowing regions. Perhaps in these panels, you could add an asterisk or some identifier.
- Figure 3: This figure is really fantastic!
- Figure 4: Add locations of borehole measurements onto GHF maps if possible. Also, the colormap of the basal melting rate figures is very washed out on the positive side. Perhaps try limiting the colormap to 0.05 m/yr or using a log-scale (with using gray-shading for basal re-freezing since you cannot use log-scale for negative values) to better show regions of grounded ice melt.It could also be interesting to see difference maps in basal melt between respective GHF experiments (e.g. SR-IVz minus SR-IVz-nosliding) as an additional row. Also, it could be helpful to the reader if you include the AIS-integrated grounded ice basal mass balance value in each melt plot so that readers can get a feel for how quantitatively different each result is.
- Figure S2: There are very sharp transitions in B in the IVz-nosliding panel (see annotated figure below), especially along interior sectors of the EAIS. Does this occur because these are the locations where basal sliding cuts off to 0 m/yr? It might be worth addressing this in the manuscript.



Citations:

- Chloe D. Gustafson et al. A dynamic saline groundwater system mapped beneath an Antarctic ice stream. *Science* **376**, 640-644 (2022).