Impact of boundary conditions on the modeled thermal regime of the Antarctic ice sheet
– Response to Review #1 –

In-Woo PARK et al.

September 24, 2023

We would like to thank Dr. Tyler Pelle, the reviewer for his insightful and valuable comments, which have helped us to improve our manuscript. We address his remarks below point by point. To clarify the reviewer's comment and its reply, we have used red for the reviewer's comment and black for the replying comment (RC).

1 Reviewer #1

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).

RC: Thank you for this comment. As mentioned by the reviewer, we have modified the abstract to emphasize the impact of GHF on the modeled grounded ice melting rates, and the use of mass-conservation-based bed topography data in improving the performance of the thermal model.

Modified abstract:

> A realistic initialization of ice flow models is critical for predicting future changes in ice sheet mass balance and their associated contribution to sea level rise. The initial thermal state of an ice sheet is particularly important as it controls ice viscosity and basal conditions, thereby influencing the overall ice velocity. Englacial and subglacial conditions, however, remain poorly understood due to insufficient direct measurements, which complicates the initialization and validation of thermal models. Here, we investigate the impact of using different geothermal heat flux (GHF) datasets and vertical velocity profiles on the thermal state of the Antarctic ice sheet, and compare our modeled temperatures to in situ measurements from 15 boreholes. We find that the ~~vertical velocity plays a more important role in the temperature profile~~ temperature profile is more sensitive to vertical velocity than GHF. The basal temperature of grounded ice and the amount of basal melting are influenced by both

selection of GHF and vertical velocity. More importantly, we find that the standard approach, which consists ~~in~~ of combining basal sliding speed and incompressibility to derive vertical velocities, provides reasonably good results in fast ~~flowing~~ flow regions (ice velocity > 50 m yr^{-1}), but performs poorly in ~~slower moving regions .~~ in slow flow regions (ice velocity < 50 m yr^{-1}). Furthermore, the modeled temperature profiles in ice streams, where bed geometry is generated using mass conservation approach, show better agreement with observed borehole temperatures, compared to kriging-based bed geometry.

- 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.

RC: Revised per the reviewer's comment, we have adjusted all statements to be in the present tense.

- 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.

RC: Thank you for this invaluable comment. This comment also provides an additional insightful perspective on how the basal conditions affect the ice velocity field, including vertical velocity. The general form of Budd type friction law can be written as general form of power type friction law:

$$\boldsymbol{\tau}_b = -CN^r \|\boldsymbol{v}_b\|^{s-1} \boldsymbol{v}_b \tag{1}$$

where C is the friction coefficient, $\boldsymbol{v}_b$ is the basal velocity, N is the overburden pressure, and $r = q/p$ and $s = 1/p$. In this study, we obtain the basal drag using $p = 1$ and $q = 1$. However, previous studies employ other types of friction law to investigate the future behavior of ice (Brondex et al., 2017; Yu et al., 2018). These alternative basal friction laws include:

- Weertman type friction law

$$\boldsymbol{\tau}_b = -C_w |\boldsymbol{u}_b|^{m-1} \boldsymbol{u}_b \tag{2}$$

  where C_w is the friction coeffient for Weertman friction law.

- Coulomb type friction law (Tsai et al., 2015; Brondex et al., 2017)

$$\boldsymbol{\tau}_b = \min(-C_w \boldsymbol{u}_b^m, fN) \tag{3}$$

  where f is the solid friction coefficient.

- Schoof type friction law (Schoof, 2005)

$$\boldsymbol{\tau}_b = -\frac{C_s |\boldsymbol{u}_b|^{m-1} \boldsymbol{u}_b}{1 + (\frac{C_s}{C_{\max} N})^{1/m} |\boldsymbol{u}_b|)^m} \tag{4}$$

  where C_s is the friction coefficient for Schoof type friction law, $C_{\max}$ is the maximum value of $|\boldsymbol{\tau}_b|/N$.

As the low basal velocity is estimated with the above friction laws, the current ice rigidity may not be not sufficient to reproduce the surface ice velocity. Aschwanden et al. (2012) incorporates an enhancement factor in effective ice viscosity to increase the vertical shear in SIA model as given by:

$$\mu = \frac{B}{2E\epsilon_e^{1/n-1}} \tag{5}$$

where E is the enhancement factor. In slow flow regions, high rigidity leads to low vertical shear, hindering the flow of ice. Therefore, it is worth noting that conducting additional experiments with other types of friction laws and rigidity values is a viable option for reproducing the thermal regime of ice.

Additionally, we only consider that effective pressure is fully connected with ocean pressure. The changes in effective pressure due to subglacial hydrology system would affect the estimate basal velocity. While there are several tools available for modeling the subglacial hydrology system, such as GLaDS (Werder et al., 2013) and SHAKTI (Sommers et al., 2018), considering these models for calculating effective pressure is quite complex within the scope of our study.

Your invaluable suggestion expands our understanding of the thermal regime of ice. Therefore, we have included a discussion of your suggestion in the ”Discussion” section.

Added part:

L280: In slow flow regions, we find that IVz-nosliding experiments show a reasonably good agreement with the observed borehole temperature profiles. However, the three-dimensional thermal model occasionally estimates convex temperature profiles, which are not consistent with the observations, such as KIS-1996-2 and KIS-2000-1,2 boreholes. Compared to other boreholes, the ice velocities at KIS and ER gradually decrease from upstream to downstream, and coincide with the presence of a basal ridge (Price et al., 2001; Ng and Conway, 2004) (see also Figure S2). Furthermore, the subglacial hydrology system at WAIS discharging to the Ross Ice Shelf has been explored using magnetotelluric, passive seismic data, and drilling borehole (Fisher et al., 2015; Priscu et al., 2021; Gustafson et al., 2022). The deceleration of tributaries at KIS and ER is attributed to water-piracy hypothesis (Alley et al., 1994) or removal of basal water contributing to the loss of lubrication (Tulaczyk et al., 2000; Bougamont et al., 2003). In model experiments, Bougamont et al. (2015) revealed changes in the tributaries at KIS and ER using a plastic till deformation friction law including simple subglacial hydrology model. In contrast, we employ the Budd type friction law and assume the effective pressure fully connected to ocean part, not including changes in the effective pressure. The variation in effective pressures also changed the basal ice velocity in Budd type friction law. In addition, a selection of other types of friction law, including Weertman (Weertman, 1974), Schoof (Schoof, 2005), and Coulomb (Tsai et al., 2015) types, also influences the initialization and future fate of ice (Brondex et al., 2017, 2019). Further investigation is required, such as the application of other types of friction laws or initialization with paleo spin-up, to better understand temperature profiles.

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?

RC: Yes, this sentence aligns with the reviewer’s point. To clarify the meaning of the text, we have made the following revisions.

Modified part:

L7: We find that the ~~vertical velocity plays a more important role in the temperature profile~~ temperature profile is more sensitive to vertical velocity than GHF.

- L8: ... which consists of combining ...

RC: Revised as reviewer's comment.

- L21: "Several important properties, such as ice elevation **and** surface ice velocity, ..." "... subglacial properties, such as ice temperature **and** geothermal heat flux, ..."

RC: Revised as reviewer's comment.

- 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)."

RC: Revised as reviewer's comment.

Modified part:

L28: In order to get ~~a reasonable estimate of these quantities, such as basal friction or~~ reasonable estimates of these englacial and subglacial fields, inversion techniques are routinely employed to estimate basal friction and ice shelf rigidity~~, are routinely estimated through inversion techniques~~ (MacAyeal, 1993; Khazendar et al., 2007; Morlighem et al., 2010; Gillet-Chaulet, 2020).

- L28: "geothermal heat flux" should not be capitalized

RC: Revised as reviewer's comment.

- L29-30: " ... and ice dynamics (citations); **yet**, large uncertainties ..."

RC: Revised as reviewer's comment.

Modified part:

L32-34: ice dynamics (Pattyn et al., 2008; Seroussi et al., 2017; Smith-Johnsen et al., 2020b); yet, large uncertainties in spatial variation and magnitude of GHFs in Antarctica still remain.

- L36: " . . . better understanding of **subglacial** and englacial environments . . ."

RC: Revised as reviewer's comment.

- 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.

RC: Revised as reviewer's comment.

- L76-78: Which surface ice velocity map did you use to perform the inversions?

RC: We used MEaSUREs version 2 ice velocity map (Rignot, 2017), so we have revised the manuscript as follow.

Modified part:

L82-83: To minimize misfit between modeled and observed ice velocities, the surface ice velocity of MEaSUREs version 2 (Rignot, 2017) is used. The ice rigidity under grounded ice ~~was~~ is estimated using the temperature-rigidity relation (Cuffey and Paterson, 2010).

- 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?

RC: We apologize for the confusion. This is simply a typographical error. Indeed, we conducted two experiments and the latter part also aligns with what the reviewer mentioned. So, we have made the following revisions.

Modifie part:

> L107-111: We ~~computed~~ compute the thermal state of the ice sheet using ~~three~~ two different vertical velocity profiles: 1) vertical velocity computed by solving for incompressibility while accounting for the inferred basal sliding (hereafter IVz), and 2) the equation of incompressibility of ice while not allowing basal sliding when surface ice velocities are below 10 m yr^{-1} (hereafter IVz-nosliding). In other words, ~~IVz~~ IVz-nosliding ignores the inferred basal sliding velocities from the initial inversion and assumes that the bed is frozen when surface velocities are ¡ 10 m yr^{-1}.

- 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.

RC: The manuscript has been revised in accordance with the reviewer's comments. We have added borehole locations to the GHF field and have depicted it in the figure below. In the revised manuscript, this figure is now labeled as Figure 5 for reference.

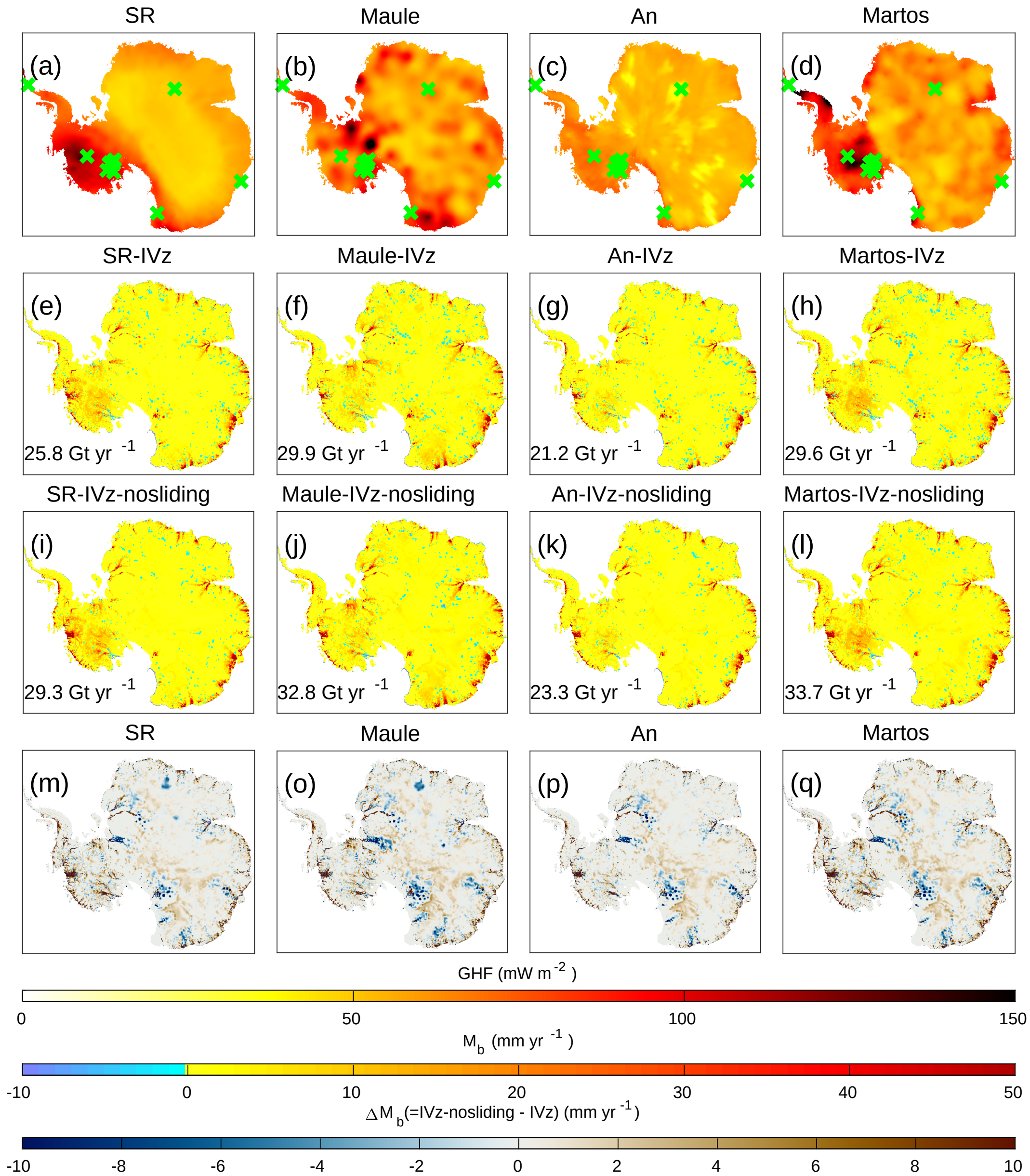

Figure 1: Figure 5(in revised manuscript). Upper panels (a-d) are the geothermal heat flux distributions of each source. Middle panels (e-l) are the basal melting rate distributions, with the value at the bottom left indicating the total grounded ice melting volume for each experiment. The basal melting rate exceeding 50 mm yr^{-1} is truncated. Lower Panels (m-q) are difference in basal melting rate between IVz-nosliding and IVz for each geothermal heat flux. A green cross dot on the geothermal heat flux map indicates the borehole location. The color map for difference in basal melting rates is from Crameri et al. (2020).

- L127: " ...between temperature measurements along the borehole profile and **triangular** mesh were not ..."

RC: Revised as reviewer's comment.

- L156: Add a space between sentences.

RC: Revised as reviewer's comment.

- L163: Remove double-comma

RC: Revised.

- L172: Change LVZ to LVz

RC: Revised.

- 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?

RC: In accordance with the excellent suggestion from the reviewer, we have restructured Table 3 into a figure as shown below. In the revised manuscript, this figure has been designated as Figure 1 for reference.

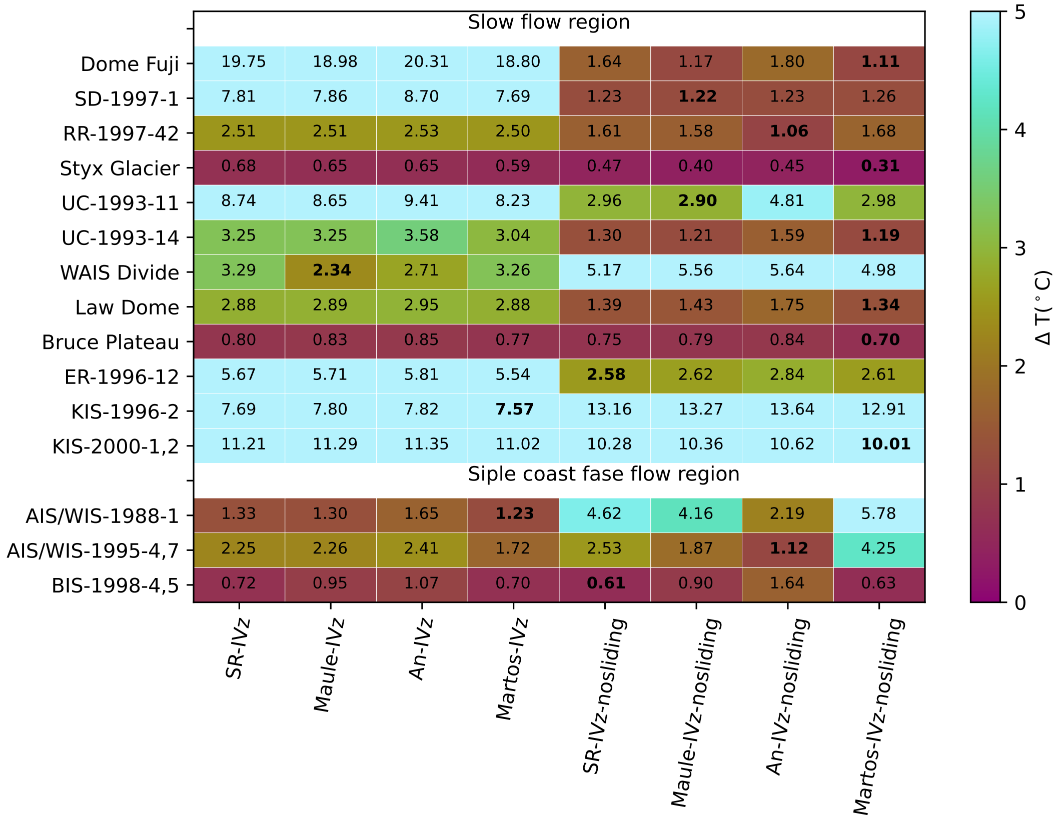

Figure 2: Weighted absolute misfit between observed and modeled borehole temperatures according to each experiment. The absolute temperature misfit is truncated over 5°C. An asterisk in the AIS/WIS and BIS boreholes indicates the fast flow region.

- 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.

RC: We initially use the R^2 value as it typically indicates how well a linear line fits dispersed data. However, based on the reviewer's feedback and additional discussion, we have concluded that the R^2 value may not be a suitable metric for this study. Therefore, in the revised manuscript, we have replaced the use of the R^2 value with the correlation coefficient between the observed and modeled temperatures, as shown in Figure S1 of the revised manuscript (Figure 3).

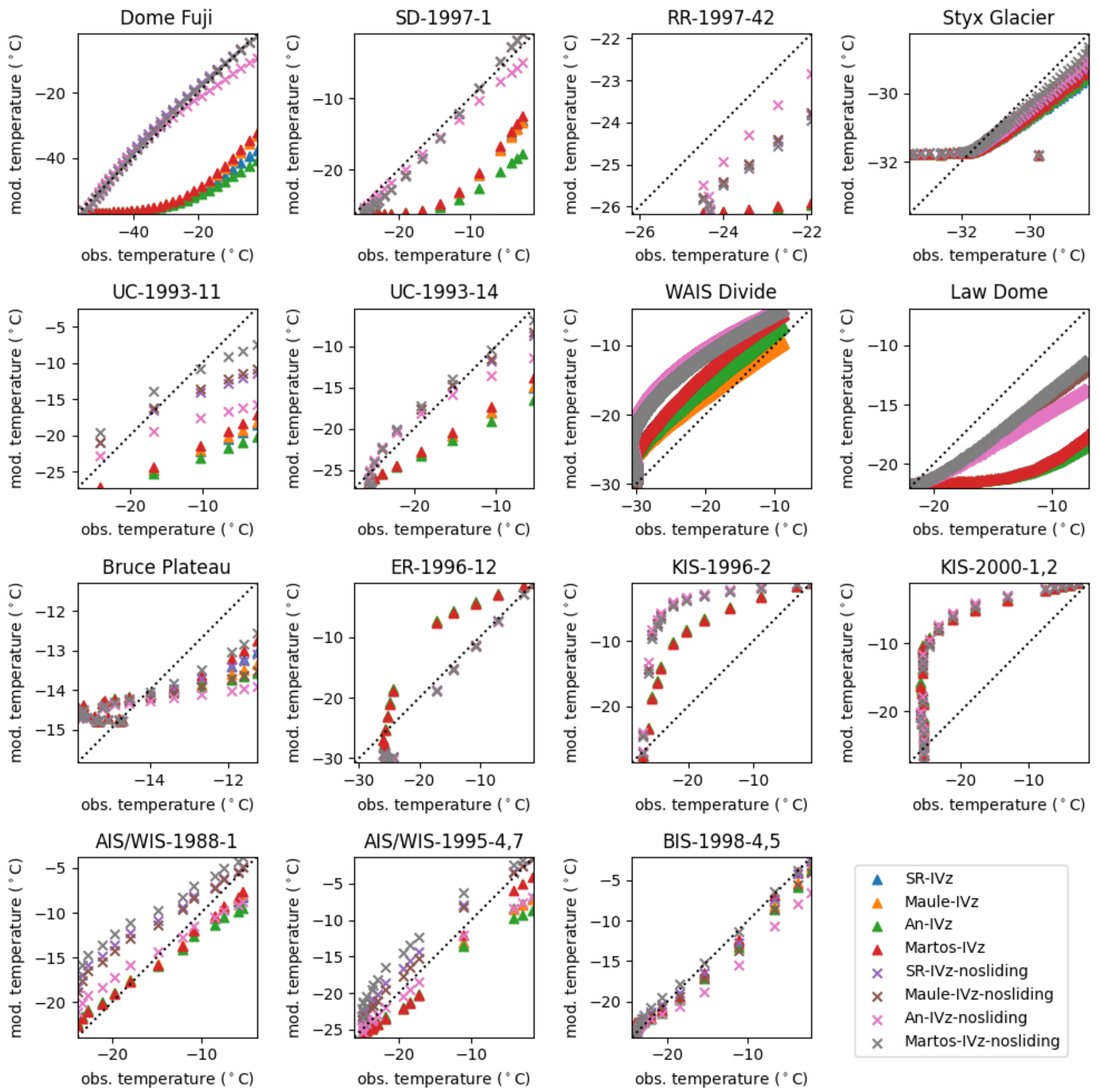

Figure 3: Scatter plot showing the relationship between modeled and observed temperatures at each borehole depending on each experiment. Cross and triangle dot indicate IVz and IVz-nosliding group, respectively. A dashed solid line indicates modeled temperature equal to observed temperature.

- L229: Degree symbol is not a superscript in 5.1DegC

RC: Revised as reviewer's comment.

- 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?).

RC: Thank you for providing an opportunity to emphasize important findings. In response to the reviewer's comments, additional content has been incorporated into the discussion and conclusion sections as follows.

Added part:

L311: Thermal models have been used to reconstruct the thermal regime of ice and estimate the melting volume beneath grounded ice. Regarding the advection term in the thermal model, horizontal ice velocity is estimated with Higher Order or Full Stokes (FS) models, while the vertical velocity is recovered with the ice incompressibility. Under kriging-based geometry, the vertical velocity in fast flow region does not coincide with physical property. In contrast, state-of-the art bed geometry, such as BedMachine (Morlighem et al., 2017, 2020), is generated with the mass conservation, which of equation is based on ice incompressibility. We confirm that using the equation of ice incompressibility to reconstruct the ice vertical velocity provides a viable way of computing temperature profiles that exhibit good agreement with observations in Siple coast fast flow regions, such as the BIS. Given that the geometry of other fast flow regions, such as Thwaites Glacier, is generated using the mass conservation method (Morlighem et al., 2011, 2020), therefore, we expect that this study provides reliable temperature profiles. Note that the good agreement in modeled temperature at fast flow region, not only Siple coast fast flow region, does not guarantee the magnitude of basal melting volume because the basal melting volume at fast flow region is associated with the frictional heat. However, at slow flow region, the basal temperature is mainly affected by the GHF and the vertical advection, rather than the low frictional heat. It is worth noting that the basal melting volume would be reliable with IVz-nosliding.

- 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?

RC: It is true that the modeled temperature profiles are sensitive to advection in ice, which is why the Maule experiment generally appears quite similar to most other IVz profiles.

To address the reviewer's question, upon conducting a more detailed analysis of the existing experimental results, we recognized an issue with the model producing abnormally cold values near the boundaries. In the process of improving this, we also realized that there is room for reducing discrepancies with observations, particularly in the AIS/WIS region, for the Maul-IVz-nosliding experiment.

After making these improvements, we performed additional sensitivity experiments to address the 2nd reviewer's suggestion to conduct additional experiments with different 2-m air temperature datasets (ERA5) and different flow region boundary for IVz-nosliding experiment with vel < 15, 18, 20 m/yr. As a result, while it is true that the modeled vertical temperature profiles in the Maule-IVz-nosliding experiment still exhibit larger discrepancies with observations in the AIS/WIS region, they have been improved to better match the observed profile shapes compared to the previous version (see Figure 2 in the revised manuscript).

Additionally, by considering the cumulative results of these additional experiments, we have concluded that the modeled temperature profiles are sensitive to the ice vertical velocity fields, and ice vertical velocity is also sensitive to ice rigidity.

- L246: By peripheral region, do you mean coastal regions? It might be helpful to use a more descriptive word here.

RC: The term "peripheral region" refers to the main ice trunk, so this sentence has been modified as follows.

Modified phrases:

> L242-244: The mean basal temperature ~~in the peripheral region~~at the main ice trunk, where the ice ~~discharges to~~ primarily discharges into the ocean, reaches the ice pressure melting point.

- 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).

RC: As suggested by the reviewer, we have changed the reference figure from Figure 5 (4 in previous version) to Figure 4 (3 in previous version).

> Line 251: All the experiments generally indicate that most of the regions experiencing basal melting are concentrated in fast flow regions, where basal frictional heat is significant and provides enough heat for the ice to reach the pressure melting point (Figure 4). Since IVz-nosliding displays lower vertical advection than that of IVz, the basal temperature of the IVz-nosliding group in slow flow regions is warmer than that of IVz (Figure 4c-j)

- L262-263: Hard to tell differences in grounded ice melt between GHF sources, see figure-4 comments.

RC: Following the reviewer's feedback, we have incorporated a figure illustrating the difference in basal melting rate between the IVz and IVz-nosliding experiments into Figure 1 (in this manuscript, Figure 5 in revised manuscript).

- L340: change "velocitiy" to "velocity"

RC: Revised as following reviewer's comment.

- 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.

RC: We have incorporated the reviewer's mention of the effect of GHF into the conclusion.

Modified conclusions:

> **Conclusions**
> In this study, we used a three-dimensional thermo-mechanical model of Antarctica with different sources of GHF and vertical velocity fields to reproduce different thermal states of the Antarctic ice sheet, and we compared the results to 15 in situ measured

borehole temperature profiles in slow and fast flow regions. Comparing the modeled to measured borehole temperature profiles, we ~~confirmed~~ confirm that the vertical ice ~~velocitiy~~ velocity based on the equation of incompressibility (IVz) is suitable for fast flow regions, such as BIS, where the bed geometry is constructed with using the mass conservation method, while an IVz that ignores basal sliding (IVz-nosliding) performs better in slow flow regions. Our results show that the vertical temperature profile ~~and basal conditions are~~ is more sensitive to the vertical velocity~~field than the GHF. The effects of different GHFs have little influence on the variance in basal temperature fields and the grounded ice melting ratecompared to the vertical velocities. However, the~~. In addition, the basal conditions, such as temperature and melting rate, are both sensitive to both GHF and the vertical velocity field. The total grounded ice melting ~~rate and average~~ volume and basal temperature are proportional to the magnitude of the average GHF values for the same vertical velocity method. Finally, constraining the basal velocity to zero in slow ~~moving~~ flow regions is a reasonable assumption and leads to a more realistic temperature profile.

- 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.

RC: We have revised the conclusion in line with the reviewer's feedback, and the updated conclusion is included in the attached response to the query above.

- L353-355: Fix formatting here.

RC: Revised as reviewer's comment. We fix formatting the urls.

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.

RC: Thank you for this comment. To enhance readability for readers, we have changed the placement of the AIS/WIS and BIS borehole results to the bottom row. Additionally, we have added blue and red boxes to emphasize and distinguish between slow flow and Siple coast fast flow regions, respectively.

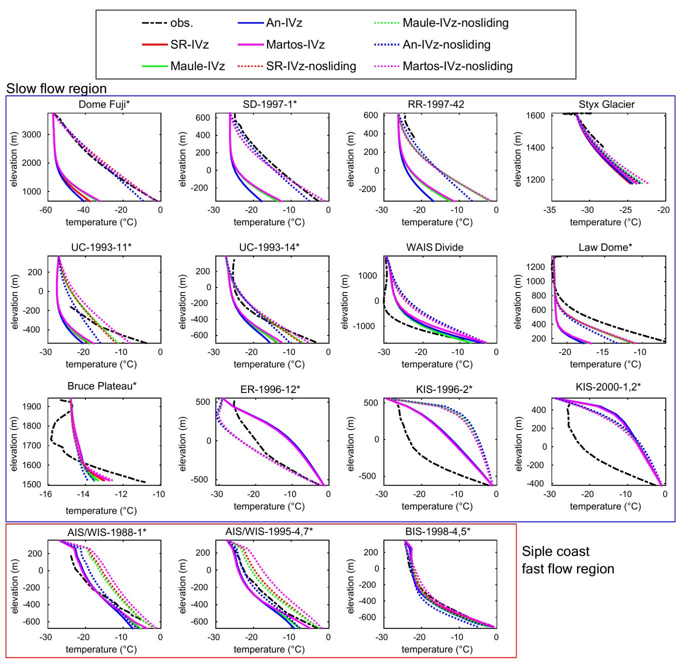

Figure 4: Observed and modeled vertical temperature profiles from eight different experiments at 15 borehole locations. Blue and red boxes indicate slow flow and Siple coast fast flow regions, respectively. The bottom elevation at each borehole is set with considering the ice thickness, as listed in Table 1. An asterisk on borehole name indicates that the drilling reaches the bed rock. RR and Styx boreholes do not reach the bed rock.

- Figure 3: This figure is really fantastic!

RC: Thank you for your appreciation of this figure.

- 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.

RC: Thank you very much for providing suggestions to enhance the readability of this Figure 5. Based on the reviewer's feedback, we have made the following improvements to the figure, as shown in Figure 6 in the revised manuscript.

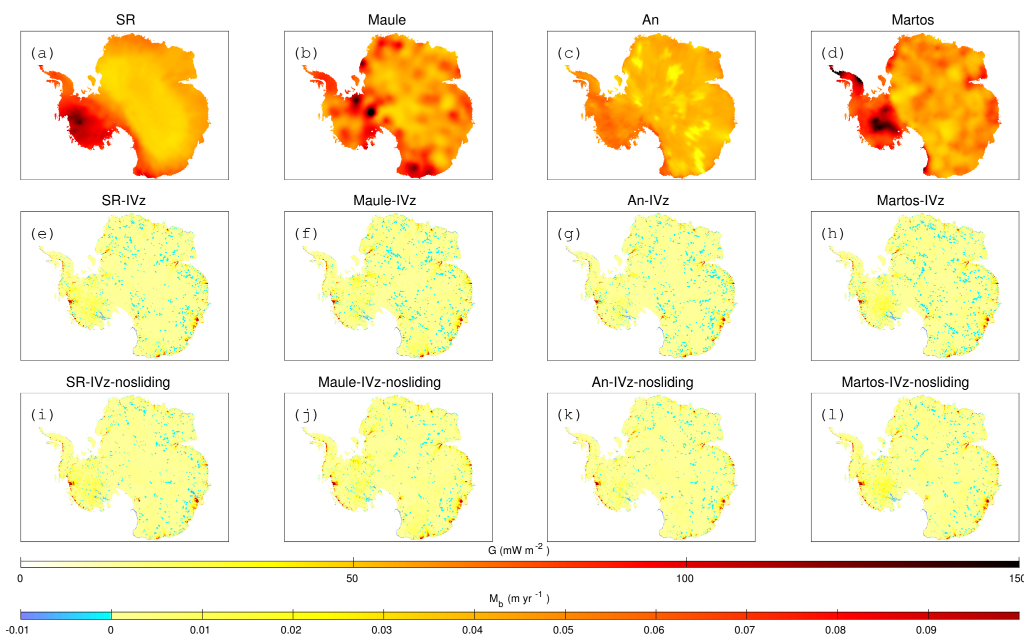

Figure 5: (in previous manuscript) Figure 4

- Add locations of borehole measurements onto GHF maps if possible.

- RC: In accordance with the reviewer's suggestion, we have added borehole locations to each GHF field in the top row of Figure 5 in the revised manuscript.

- 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.

- RC: Thank you for this suggestion. To improve the readability of the basal melting rate for each experiment, we have changed the unit of basal melting rate from m yr^{-1} to mm yr^{-1}, and set an upper limit 50 mm yr^{-1}. Due to the presence of negative values of basal melting rate, we could not use a logarithmic scale.

- 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.

- RC: Revised as reviewer's comment. We have added total grounded ice melting volume to the middle panels of grounded ice melting rate figures (Figure 5 in the revised manuscript).

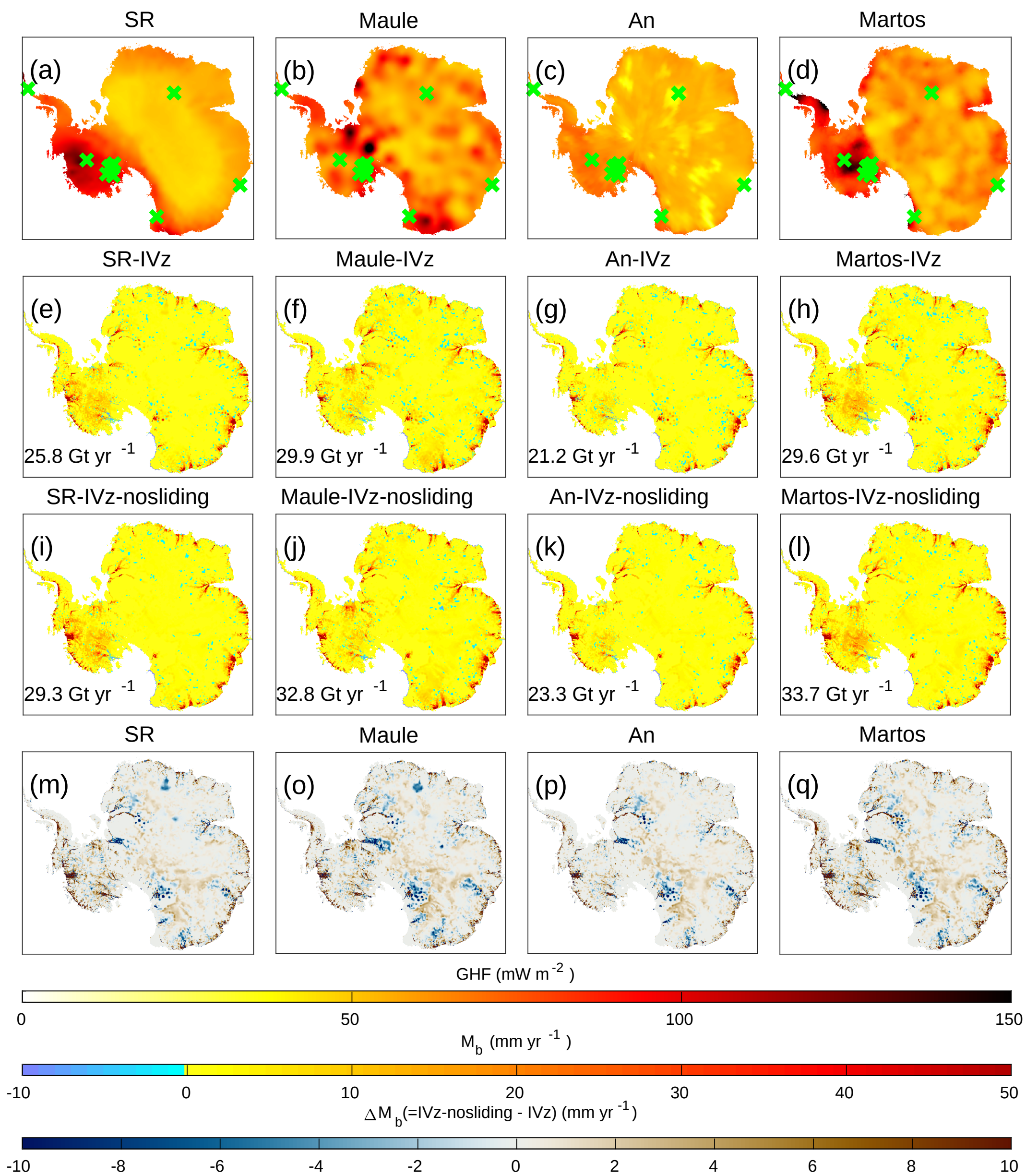

Figure 6: (in revised manuscript) Figure 5. Upper panels (a-d) are the geothermal heat flux distributions of each source. Middle panels (e-l) are the basal melting rate distributions. The basal melting rate over 50 mm yr^{-1} is truncated. Lower Panels (m-q) are difference of basal melting rate between IVz-nosliding and IVz for each geothermal heat flux. Colormap for difference in basal melting rate is from Crameri et al. (2020).

- 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 10 m/yr? It might be worth addressing this in the manuscript.

RC: As you mention, the sharp transition in B (ice rigidity) is related to where basal sliding cuts off to 10 m/yr. We mention this sharp transition zone and some futher works on this problem.

> L340:Furthermore, the adoption of no-sliding in specific regions results in a sharp transition zone in ice rigidity, B. This occurs because the basal velocity near the transition zone does not smoothly changed from no-sliding to sliding (Figure S4). Therefore, additional work is required to address and resolve the transition between no-sliding and sliding.

References

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