Impact of boundary conditions on the modeled thermal regime of the Antarctic ice sheet

– Response to Editor's Review –

We would like to thank Dr. Benjamin Smith for his insightful and valuable comments, which help us to improve our manuscript. We address his remarks below point by point. The editor's comments are shown in red, and our replies are in black (RC).

TThe KIS temperature profiles are likely from iche new version of the manuscript does a nice job of responding to the referee's concerns with the first version. There's one technical point (about KIS, below) that I'd like to see addressed throughout the study, and I have some edits I'd like to see to improve the clarity of the writing. In general, the manuscript could use another round of editing with an eye towards removing redundant phrases, and towards improving paragraph structure so that the topic sentence of each paragraph gives a clear idea of the ideas that are to be discussed in that paragraph.

The KIS temperature profiles are likely from ice that as moving quickly before the ice stream's stagnation around 1860 CE. As a result, the deeper ice likely came from places where the surface temperature was significantly lower that it is now, and the temperature profiles reflect strain regimes characteristic of basal sliding. This history should be taken into account in evaluating the models, which cannot be expected to know about the wayward behavior of KIS.

☑ Lines 124-132: This paragraph as written is hard to follow (too many specifics to address as lists within sentences). Consider conveying this information in a table.

Rather than discussing every borehole in the main text, we now refer to Table 1. The changed sentence is as follows:

Line 124: To validate the thermal models, we compile all available 15 borehole temperature profiles listed in Table 1. The 10 boreholes in the West Antarctic Ice Sheet region are drilled at Whillans Ice Stream (WIS), Bindschadler Ice Stream (BIS), Engelhardt Ridge (ER), Kamb Ice Stream (KIS), Raymond Ridge (RR), Unicorn (UC), Alley Ice Stream (AIS), and Siple Dome (SD) (Engelhardt, 2004a) (Figure. 1b).

☑ Line 146: Confusing: rewrite as "…except for at Dome Fuji and Law Dome, for which few thickness measurements were available."

Done

☑ Line 154: Too many significant figures in the misfit values. 12.5 and 19.5 are more than enough.

Done

☑ Line 155: "relatively lower" is redundant

This sentence is changed as follows;

> "Line 152: The standard deviation in ice velocity misfit is 0.09 m yr^{-1} for the IVz, and 0.35 m yr^{-1} for the IVz-nosliding group."

☑ Table 2: too many significant figures in velocity misfits.

We updated the table as follows:

GHF	Vertical velocity	
	IVz	IVz-nosliding
SR	SR-IVz (12.4 m yr^{-1})	SR-IVz-nosliding (19.9 m yr^{-1})
Maule	Maule-IVz (12.5 m yr^{-1})	Maule-IVz-nosliding (19.1 m yr^{-1})
An	An-IVz (12.6 m yr^{-1})	An-IVz-nosliding (18.6 m yr^{-1})
Martos	Martos-IVz (12.3 m yr^{-1})	Martos-IVz-nosliding (19.7 m yr^{-1})

☑ 165-75: Consider the above point about KIS in relation to this material.

We appreciate the editor’s comment. It is not easy to determine the exact period when the stagnation of the KIS region started. According to Joughin and Tulaczyk (2002), the ice has been stagnant there for about 150 years. We therefore assume that the start of stagnation year was around 1850 CE (150 years ago from 2002). We have modified the text as follows:

> “Line 173: However, none of the experiments successfully reproduce the temperature profiles at KIS boreholes, where the ice has been stagnant since around 1850 CE (Alley et al., 1994; Joughin and Tulaczyk, 2002). This history cannot be captured by our thermal steady-state assumption. A more detailed description of misfit values for each borehole can be found in the next section.”

☑ 177: “Let’s focus” is too informal.

This sentence is changed as follows:

> “Line 177: First, we focus on the three borehole profiles: SD, RR, and Dome Fuji.”

☑ Line 180: It looks to me like the nosliding groups do quite well for Fuji and SD. Is this a typo?

Thank you for catching the typo. We fixed the typo as follows:

> “Line 180: For these boreholes, the ~~IVz-nosliding~~IVz group does not capture the linear shape of the temperature profiles.“

☑ Line 181 “which of value” –possible typo?

Revise the typo as follows:

“Line 181: The IVz-nosliding group at these boreholes has a misfit value within 2˚C, which is lower than that of the ~~IVz-nosliding~~ IVz group (Figure 3).”

☑ Line 186: “The basal modeled temperature at An is the lowest…” – should be “for An”

Done.

☑ 190: “The borehole of Styx glacier is a shallow ice core”. – Redundant. Please rewrite.

This sentence is revised as follows:

> “Line 190: At the borehole of Styx Glacier, both IVz and IVz-nosliding groups display similar average misfit values of ~0.64°C and ~0.40°C, which show good agreement with the observed temperature profiles. The drilling depth of Styx Glacier is about 210.5 m (Yang et al., 2018), and the ice thickness measured with ground penetrating radar survey is about 550 m (Hur, 2013). While We cannot definitively confirm the basal condition from observations, the thermal model results suggest that none of the experiments reach the melting point.”

☑ 194: UC was likely an area of stagnant ice in the middle of the old ice stream.

We added some information that UC boreholes are located at stagnant ice, and the sentence ice changed as follows:

> “Line 195: <u>The UC boreholes are located in an area of stagnant ice and have a</u> relatively high basal temperature gradient compared to the other adjacent boreholes, such as AIS/WIS boreholes (Engelhardt, 2004b).”

☑ 225: refer to table 3, not figure 3

The temperature misfit value is listed in Figure 3, therefore, we think that this is the right reference.

☑ 227: Don’t need “from MEASURES version 2” (the Rignot citation is enough).

This sentence is changed to

“Line 219: The observed ice velocity at Bruce Plateau is 49 m yr^{-1} according to Rignot (2017),~”

☑ 228-229: Please explain why there is any difference at all between the sliding and nosliding models here (since both are sliding)

Although both the IVz and IVz-nosliding experiments allow for sliding in fast flow regions, the mean modeled ice velocity of the IVz-nosliding group in the AIS/WIS region is generally slower than the one of the IVz group (Figure 1). However, in the BIS region, it seems that the modeled ice velocity for IVz and IVz-nosliding are not significantly different, both consistent with observed ice velocity. The difference between these two cases is the width of the ice stream. When ice streams are narrow, the modeled speed will be sensitive to the no-sliding condition that is imposed along the sides of the ice stream, potentially slowing down ice flow. Wide ice streams, on the other hand, are less affected by the no-sliding constraint imposed on slow moving ice, because the constraints are imposed further away. The modeled temperature profile in the AIS/WIS will be different for the IVz and IVz-nosliding groups because it is a narrow ice stream.

“Line 227: The AIS/WIS and BIS boreholes are located in the fast flow region of the Siple coast, where the ice velocities are 365 m yr^{-1} for AIS/WIS-1991-1, 379 m yr^{-1} for AIS/WIS-1995-4,7, and 376 m yr^{-1} for BIS-1998-4,5 from Rignot (2017). The average misfit value of the IVz group is 1.38°C for AIS/WIS-1988-1, 2.16°C for AIS/WIS-1995-4,7, and 0.86°C for BIS-1998-4,5 (Figure 3). In these regions, both IVz and IVz-nosliding allow for basal sliding. However, there are differences in misfit values between IVz and IVz-nosliding groups at AIS/WIS. The reason for these differences is that the modeled ice velocities of IVz-nosliding in the AIS/WIS region are slower than the ones from IVz because it is a narrow ice stream that is influenced by the no-sliding constraint along its sides , resulting in higher misfit values for IVz-nosliding compared to the IVz group.”

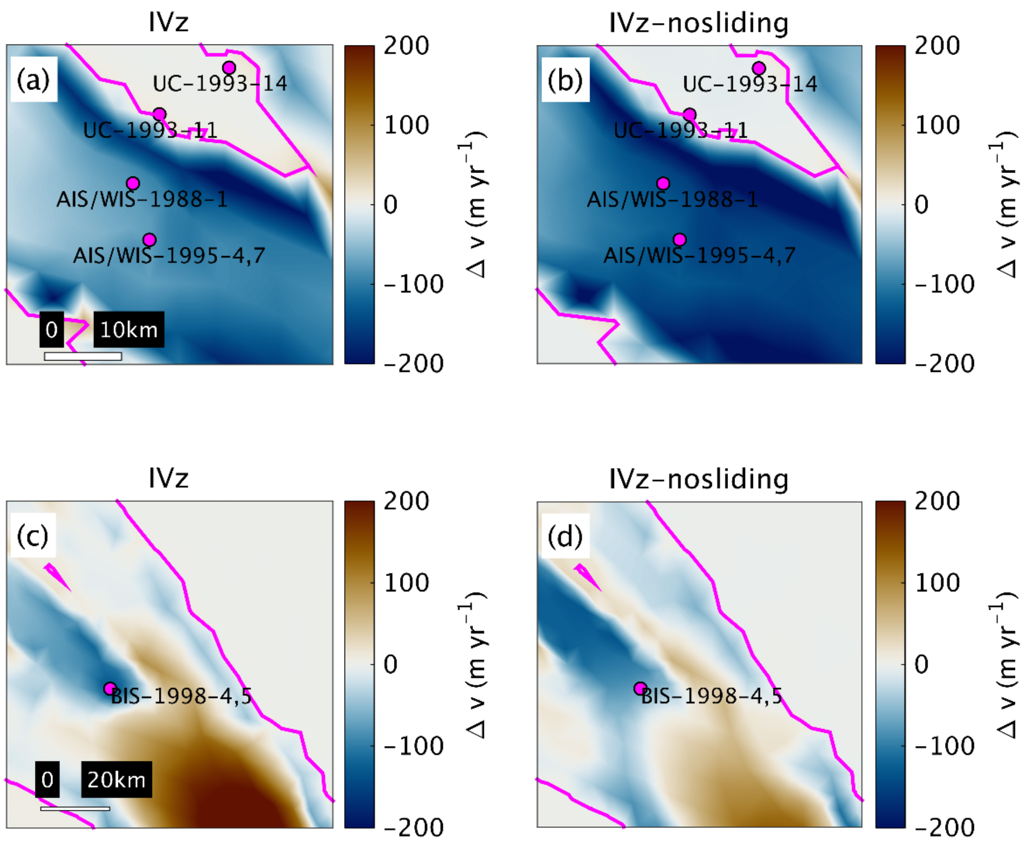

Figure 1. The velocity misfit between mean modeled and observed velocity from Rignot (2017). Each magenta dot indicates borehole location, and magenta contour line indicates observed ice velocity with 10 m yr^{-1}.

☑ 233-36: Please explain why the temperatures depend on the quality of the bed geometry.

This paragraph is changed as follows:

> "Line 234-: The misfit between the modeled and observed temperatures at BIS is lower than that of AIS/WIS. In fast flow regions, the advection, estimated through the stress balance of ice and the ice incompressibility, plays a crucial role in the thermal model compared to diffusion. In these advection-dominated regions, the temperature is sensitive to bed geometry. The primary difference between the BIS and AIS/WIS regions is that the bed geometry in the BIS region is constructed using a mass conservation approach, which relies on the equation of ice incompressibility. In contrast, the bed geometry in the AIS/WIS region was constructed using the stream diffusion method, similar to kriging (Figure S5). This suggests that enhancement in the quality of the geometry and utilizing the mass conservation method in the Siple coast fast flow regions would improve the estimation of the vertical velocity by the IVz

equation with sliding as well as the overall performance of the thermal model. The AIS/WIS-1995-4,7 borehole is located at the center of the ice stream, whereas AIS/WIS-1988-1 is relatively near the margin of the ice stream. Although the bed geometry at AIS/WIS is constructed using the kriging method, IVz reproduces the temperature profile reasonably well at the center of fast ice flow regions."

☑ 256-57: Check this sentence: is "the surplus of" needed? What is "1.08 1.26"?

Revise the typo and revised sentence is as follows;

"Line 261: Compared to IVz, IVz-nosliding suggests a mean total basal melting volume increase of 1.89 Gt yr^{-1} (60%) and 1.26 Gt yr^{-1} (40%) in the slow and fast flow regions, respectively."

☑ 258 "The total melting fraction of the grounded ice, which represents the grounded ice melting area"—This seems redundant.

This value is not particularly important, we have removed this sentence.

☑ 260-265: Please consider whether all of these details need to be spelled out.

Done. Providing site-specific values of total grounded ice melting volume for each basin is not essential in this paragraph. Instead, we highlight that the magnitude of the total basal melting volume is proportional to the geothermal heat flux. The revised paragraph is as follows:

"Line 260-265: The total grounded ice melting volume is proportional to the GHF magnitude. Each basin displays significant differences in terms of the grounded ice melting volume depending on the GHF source. Note that the GHF from An, which is the lowest value among all GHFs, shows the lowest total grounded ice melting volume."

☑ Line 280-94: Please reconsider in light of the flow history at KIS.

To reflect the editor’s comment, we revise this paragraph as follows:

“Line 280-296: 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 the KIS 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). In the past, the KIS and ER region experienced faster ice flow, and the ice stream started to stagnate around 1850 CE (Alley et al., 1994; Joughin and Tulaczyk, 2002). There are hypotheses explaining the stagnation in the KIS region: the water piracy hypothesis (Alley et al., 1994) or the removal of basal water contributing to the loss of lubrication (Tulaczyk et al., 2000; Bougamont et al., 2003). The upper part of observed temperatures in KIS boreholes likely originates from upstream, where the surface temperature was lower than it is now, and the temperature profiles reflect past basal sliding when the ice stream was active. In model experiments, Bougamont et al. (2015) revealed changes in the tributaries at KIS and ER using a plastic till deformation friction law including a simple subglacial hydrology model. In contrast, we employ the Budd type friction law and assume the effective pressure fully connected to the 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.”

☑ 300 “ which of value”—I’m not sure what this phrase indicates.

“which of value” was meant to indicate the original value of total grounded ice melting volume of Llubes et al. (2006) with 16 km yr^{-1}. This description seems redundant, therefore, we remove this sentence.

> “Line 302: It is lower than 65 Gt yr^{-1} from Pattyn (2010) and higher than 14.7 Gt yr^{-1} from Llubes et al. (2006)~~, which of value is converted to volume from total ice volume of 16 km3 yr−1 in ice equivalent~~.”

☑ 305: Shouldn’t a linear vertical velocity profile be appropriate as long as the surface velocity is approximately equal to the sliding velocity? It seems like this should only result in small errors in the melt rate

Thank you for raising this point. Yes, if the basal ice velocity is equal to the surface ice velocity in fast-flow regions, the vertical velocity is proportional to the linear vertical profile. However, its basal vertical velocity is constrained as $v_z(b) = v_x(b)\frac{\partial b}{\partial x} + v_x(b)\frac{\partial b}{\partial x} - M_b$ (where M_b represents the basal melting rate).

Furthermore, Joughin et al. (2009) used a thermal model that was not based on an enthalpy formulation, and its method differs from the one used in this study. It is challenging to determine which procedures contribute to the differences between their study and our work. We have removed this sentence from the revised manuscript to not introduce any confusion.

☑ 314: "does not coincide with physical property"—please edit

Below your comment about "Line 310-315, this paragraph requires concision and English grammar." The revised paragraph is listed in below.

☑ 315 "which of equation"—please edit

Below your comment about "Line 310-315, this paragraph requires concision and English grammar." The revised paragraph is listed in below.

☑ 310-325: This paragraph needs rewriting for concision and English grammar.

Upon reviewing the sentence, we realize that it contains redundant information and lacked concision. Taking this into account, we have revised this paragraph as follows.

"Line 308-317: The thermal models have been employed to explore the thermal regime of ice and estimate basal melting rates beneath grounded ice. In the thermal model's advection term, the horizontal components of the ice velocity are estimated using the stress balance equations, whereas the vertical velocity is recovered from the ice incompressibility. Under kriging-based bed topography, the vertical velocity in fast flow regions leads to large flux divergences (Seroussi et al., 2011). In contrast, mass conservation-based bed geometries, such as BedMachine (Morlighem et al., 2017, 2020), preserve low flux divergence. We confirm that the vertical velocity in bed geometry inferred from mass conservation provides a viable way of computing temperature profiles in the Siple coast fast flow regions, such as the BIS. Additionally, we expect this study to provide a reliable understanding of temperature profiles in the other fast flow regions generated with mass conservation. We should highlight that the good agreement between modeled and observed temperatures in fast flow regions does not guarantee that the magnitude of basal melting volume is accurate, as it depends on both geothermal heat fluxes and frictional heat.”

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