Referee’s comments are in blue, our reply in black, quotes in the revised manuscript in purple.

William Colgan posted a new Referee comment.

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This study explores geothermal heat flow in the Lambert-Amery sector of East Antarctica. A complex system of coupled models (shallow ice, full stokes, and subglacial hydrology) are initiated by six available geothermal heat flow maps to estimate basal temperature distribution across the sector. The basal temperatures are generally realistic and conform to expectation, with their differences being informative. Basal heat conduction is also presented and discussed, although the value of this field is less clear to me at the moment. Below, I provide some comments from this article.

Surface Accumulation – The surface accumulation field is used in the balance flux model, and presumably ultimately influences vertical velocity profile. I do not see any description, or citation, documenting the source of the surface accumulation field. It would be helpful to have better description of the accumulation field, including how possible biases in accumulation (or “recent” versus “steady” temporal variations) may manifest in the parameterization of vertical velocity field from the balance flux model, and ultimately in the simulated basal thermal state.

Reply: We note in Section 3: The surface accumulation rate we used in the thermal model was the mean of Arthern et al. (2006) and Van de Berg et al. (2005). Both were accessed through the ALBMAP_v1 dataset (Le Brocq et al., 2010).

We add in the Discussion section of the revision.
We expect that the present-day accumulation rate field will be higher than the long-term average, because of lower accumulation rate during glacial periods. This will tend to increase the downward advection of cold ice in our model, lowering the basal temperature in comparison to reality. On the other hand, we also expect that the modern-day surface temperature will be higher than the long-term average temperature, again because of lower temperatures during glacial periods. This will tend to increase our modeled basal temperature in comparison with reality. It is unclear which of these competing biases is stronger.

References:

Arthern, R. J., Winebrenner, D. P., & Vaughan, D. G. Antarctic snow accumulation mapped using polarization of 4.3-cm wavelength microwave emission. Journal of Geophysical Research: Atmospheres, 111(D6), D06107, 2006. https://doi.org/10.1029/2004JD005667

Le Brocq, A. M., Payne, A. J., & Vieli, A. An improved Antarctic dataset for high resolution numerical ice sheet models (ALBMAP v1). Earth System Science Data, 2(2), 247–260, 2010. https://doi.org/10.5194/essd-2-247-2010

Van de Berg, W. J., Van den Broeke, M. R., Reijmer, C. H., & Van Meijgaard, E. Characteristics of the Antarctic surface mass balance, 1958-2002, using a regional atmospheric climate model. Annals of Glaciology, 41(1), 97-104, 2005. https://doi.org/10.3189/172756405781813302

Topographic Effect – We discuss the topographic effect on geothermal heat flow in https://doi.org/10.1029/2020JF005598. Specifically, we highlight how subglacial topography in the subglacial Gamburtsev Mountains, East Antarctica, can strongly influence geothermal heat flow at kilometer scale. Whereby subglacial ridges can receive 50% less heat flow and subglacial valley can receive 50% more heat flow, in comparison to the regional average. I suspect that explicitly acknowledging the influence of subglacial topography on geothermal heat flow, by applying such a topographic correction field to the GHF input field used by the 2D SIA model, might further improve the realism of simulated hydrology.

Reply： Thanks for your comments. We agree that subglacial topography has influence on geothermal heat at kilometer scale. But we do not know if this effect is positive or negative. It depends on rock type underneath the ice. We had a similar discussion about the influence of subglacial topography on geothermal heat flow in the paper Wolovick et al. (2021b) https://doi. org/10.1029/2020JF005936 as below: “Heat tends to follow the path of least resistance to the surface, so if the thermal conductivity of ice is greater, then heat will be conducted into local valleys and away from local peaks, giving the classic topographic focusing result; but if the thermal conductivity of rock is greater, then the opposite will occur, and heat will tend to be conducted into local peaks and away from valleys (Willcocks & Hasterok, 2019). The thermal conductivity of rock varies with lithology, and can be either greater or less than the thermal conductivity of ice (Willcocks & Hasterok, 2019).”

Therefore, it is unknown how to make the right correction to the GHF input field.

We add these sentences in the Discussion section of the revision: “Subglacial topography has influence on geothermal heat at kilometer scale. Typically, it has been assumed that subglacial ridges receive less heat flow and subglacial valleys receive more heat flow, in comparison to the regional average (e.g., van der Veen et al., 2007; Colgan et al., 2021). However, the effect depends on subglacial rock type. Heat tends to follow the path of least resistance to the surface, i.e. thermal conductivity. The thermal conductivity of rock varies with lithology, and can be either greater or smaller than the thermal conductivity of ice (Willcocks & Hasterok, 2019), thus the sign of topographic effect on GHF can be either negative or positive. Without knowing a priori whether the topographic effect will be positive or negative, it is hard to apply a topographic correction field to the GHF input field.”

References:

Wolovick, M. J., Moore, J. C., & Zhao, L. Joint inversion for surface accumulation rate and geothermal heat flow from ice-penetrating radar observations at Dome A, East Antarctica. Part II: Ice sheet state and geophysical analysis. Journal of Geophysical Research: Earth Surface, 126, e2020JF005936, 2021b. https://doi. org/10.1029/2020JF005936

van der Veen, C. J., Leftwich, T., von Frese, R., Csatho, B. M., & Li, J. Subglacial topography and geothermal heat flux: Potential interactions with drainage of the Greenland ice sheet. Geophysical Research Letters, 34(12), 2007.

Colgan, W., MacGregor, J. A., Mankoff, K. D., Haagenson, R., Rajaram, H., Martos, Y. M., et al. Topographic correction of geothermal heat flux in Greenland and Antarctica. Journal of Geophysical Research: Earth Surface, 126, e2020JF005598, 2021. https://doi. org/10.1029/2020JF005598

Willcocks, S., & Hasterok, D. Thermal refraction: Impactions for subglacial heat flux. ASEG Extended Abstracts, 2019(1), 1–4. Taylor & Francis. https://doi.org/10.1080/22020586.2019.12072986

Temperate Ice – I understand how the basal state is parameterized as either melting (Dirichlet; Eq 6) or freeing (Neumann; Eq 5), but the reader would benefit from knowing whether a thicker temperate basal ice layer is permitted. Temperate basal ice layers can form at the convergence of outlet glacier flow, even with tremendous downstream advection relatively cold inland ice (https://doi.org/10.3189/172756502781831322). The presence or absence of a temperate basal ice layer clearly influences the vertical temperature profile, which here seems critical to presented basal heat conduction (i.e. whether temperature gradient simply pinned to the pressure-melting point at the bottom, or the temperature gradient effectively becomes the Clausius–Clapeyron gradient). Allowing ice to become temperate general requires assumptions about liquid pore water content, which I do not see stated here.

Reply: Yes, a thicker temperate basal ice layer is permitted in our model. We add in Section 3.1

In the case that the modelled basal ice temperature reaches pressure melting point, T_m, a temperate basal ice layer is permitted in our model. The model works with englacial melting and a temperate ice layer. We do not make assumptions about liquid pore water content. We use a weak-form solution instead of a strict limit. The temperature is allowed to exceed the melting point, but temperature rise is limited by the latent heat absorbed by englacial melting. So, the melt rate rises exponentially as temperature passes the melting point, and the pre-factor for the melt rate comes from the strain heating.

Heat Conduction – I am confused by Figure 8. I would expect that, in the absence of basal hydrologic processes, basal heat conduction is effectively equivalent to geothermal heat flux. Yet inland areas, where basal hydrology is not active, have a very different heat conduction from the forcing geothermal heat flux. The sign of basal heat conduction is also negative, in comparison to the positive sign/direction of geothermal heat flux. Finally, should there not also be “opposing signed” pockets where the basal heat conduction is opposite over subglacial areas where basal water is refreezing (i.e. Vostok in https://doi.org/10.5194/tc-14-4021-2020)? Right now, the axis stops at zero. For these reasons, I find Figure 8 (and associated discussion) difficult to follow.

Reply: The figure about heat conduction is Figure 6. So we assume you are confused by Figure 6 rather than Figure 8 in the previous submission (We add new plots in the revision and the numbering of figures is changed). We checked both figures. Both geothermal heat flux and englacial heat conduction have the same direction, which is upward. It is confusing to use different sign for them.

In the revision, we change “heat conduction” in figure caption of Figure 6 to “modelled heat change of basal ice by upward englacial heat conduction”, and add more sentences “The negative sign means that the upward englacial heat conduction causes heat loss from the basal ice as defined by the color bar with cooler colors representing more intense heat loss by conduction.”

We note there is a sign typo in Eqn (19), it should be as below

$$M = \frac{G + \vec{u}_b \tau_b + k(T)\frac{dT}{dz}}{\rho_i L}$$

where the term $k(T)\frac{dT}{dz}$ is negative, representing heat loss of basal ice by upward englacial heat conduction.

Our modelled heat change of basal ice by englacial heat conduction is all negative, i.e., there is no places where the basal heat conduction is downward.

The conductive heat flux does not necessarily change sign above subglacial freezing zones. Subglacial freezing happens anywhere that water is available and the basal cooling terms (conduction into the overlying ice sheet and supercooling within the water system) are larger than the basal warming terms (geothermal heat flow, friction heating, and viscous dissipation within the water system). Thus, there is no reason why conduction should change sign at freezing zones; if anything, we would expect conductive cooling to be stronger at freezing zones than at other locations.

We also checked Figure 8. There are three places with negative values of basal melting rate, i.e. refreezing. Therefore, we change Fig. 8 to show modelled freeze-on (see the figure below), and add the text “There are negative values of basal melt rate, which means basal refreezing at three local places (Fig. 9), where there are large gradients in ice thickness typically thinning by 700 m across a distance of 2 km. Radar surveys have not yet been done to confirm these freeze-on locations.”.

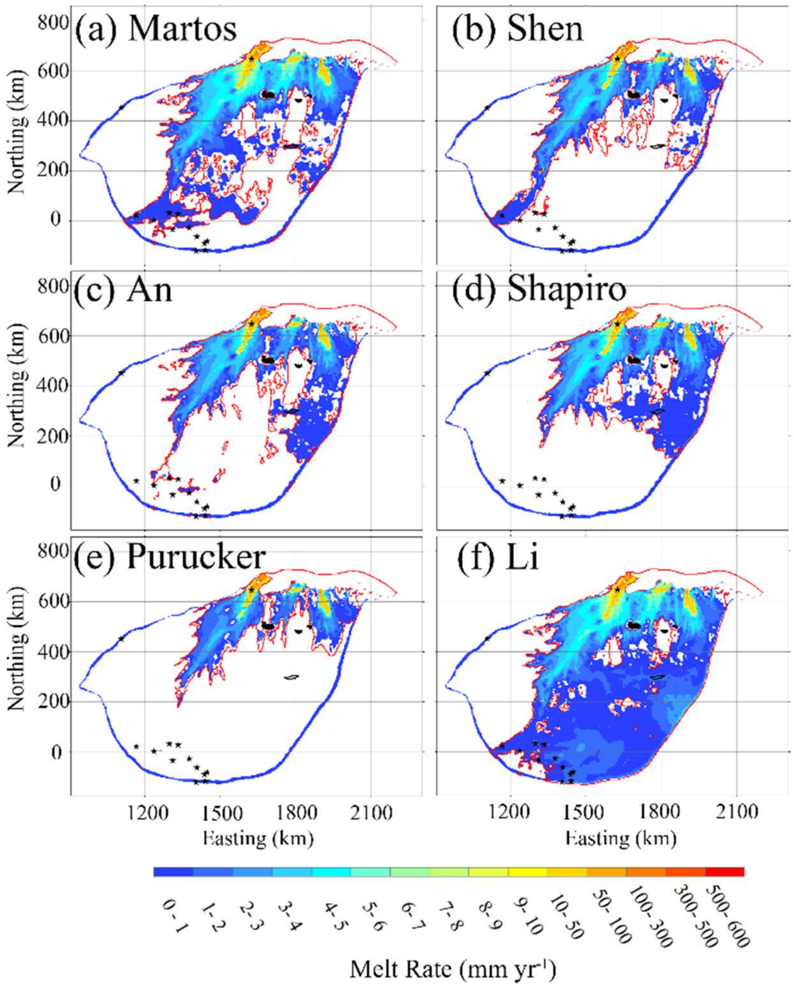

Fig. Modelled basal melt rate (unit: mm yr^{-1}), (a) to (f) correspond to the GHF (a) to (f) in Fig. 2. The ice bottom at pressure-melting point is surrounded by a red contour. The stars denote the locations of observed subglacial lakes, and the area surrounded by the black line is the likely second largest subglacial lake in Antarctica. There is modelled basal refreezing at three local places painted in black.

Subglacial Lakes – Here, subglacial lakes are being used as an indicator of basal ice at the pressure-melting point. The subglacial lake literature, however, now has suggestions that melting temperatures can be depressed significantly lower than pressure-melting point by salinity (https://doi.org/10.1126/sciadv.aar4353) and that radar-derived subglacial water indications can be false positives (https://doi.org/10.5194/tc-14-4495-2020). I think these caveats should be mentioned.

The L511-515 discussion should also use the terminology "false negative" to describe the "one-sided" aspect constraint.

Reply: Agreed, although the Devon Island lake complex is the only known sub-glacial lake that has significantly lowered freezing point temperatures due to dissolved salts, and this is not observed to be the case for Lake Vostok in Antarctica. We add the related discussion as below in the revision. "A lake complex beneath Devon Island ice cap in Canada exists at temperatures well below pressure melting point due to large concentrations of dissolved salts (Rutishauser et al., 2018), and while no similar ones are known to exist beneath the Antarctic ice sheet, direct measurements of ice temperatures above water bodies are rare. Furthermore, relatively high electrical conductivity beds such as water saturated clays can give rise to false positives in radar detections of subglacial water bodies (Talalay et al., 2020)."

References:

Rutishauser A., Blankenship, D. D., Sharp, M., Skidmore, M. L., Greenbaum, J. S., Grima, C., Schroeder, D. M., Dowdeswell, J. A., Young, D. A., Discovery of a hypersaline subglacial lake complex beneath Devon Ice Cap, Canadian Arctic, Sci. Adv.2018; 4: eaar4353

Talalay, P., Li, Y., Augustin, L., Clow, G. D., Hong, J., Lefebvre, E., Markov, A., Motoyama, H. and Ritz, C., Geothermal heat flux from measured temperature profiles in deep ice boreholes in Antarctica, The Cryosphere, 14, 4021-4037, 2020

Consensus Map – Given the time and interest that the authors have clearly expended with this study, it would seem that they are in a very good position to produce a consensus geothermal heat flow map of the Lambert-Amery sector. My final thought would be asking why the authors simply stop with saying the Li and Martos geothermal heat flow maps are most suitable for this region, and do not provide an accompanying data product of a geothermal heat flow map that is self-consistent, or optimized, with an ice flow model (i.e. https://doi.org/10.20575/00000006)?

Reply: Unfortunately, we don't think we can do this. We note in the Conclusions: We cannot make our own GHF map from our analysis since while we can pick the GHF where Li and Martos geothermal heat flow maps are consistent and both agree with the observation, we do not know which (if either) are correct where the Li and Martos GHF datasets disagree and there are no observations. We would need additional observations of measured basal temperature from deep ice cores, or observed refreeze-on, but neither are available in the region.

We read your suggested reference (Greve, 2019). Ralf Greve presented an improved distribution of the geothermal heat flux for Greenland. He did a paleoclimatic simulation carried out with the ice sheet model SICOPOLIS, and modified the GHF values at five deep ice core locations such that observed and simulated basal temperatures match closely. However, there is no deep ice core drilling site in our study region.

References:

Greve R., Geothermal heat flux distribution for the Greenland ice sheet, derived by combining a global representation and information from deep ice cores, Polar Data Journal, 3, 22–36, 2019