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Interactive comment on "Geothermal flux beneath the Antarctic Ice Sheet derived from measured temperature profiles in deep boreholes" *by* Pavel Talalay et al.

Anonymous Referee #1

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The study titled "Geothermal flux beneath the Antarctic Ice Sheet derived from measured temperature profiles in deep boreholes" aims to infer the Geothermal heat flux (GHF) from ice core borehole temperature profiles and heat flow modelling at six ice core sites: Byrd, Dome C, Dome F, Vostok, WAIS Divide, and Kohnen. Talalay et al. apply a thermodynamic model to simulate the temperature of the ice at depth directly against borehole temperature observations to constrain model parameters. A thermodynamic 1D heat flow model was used to infer the GHF at the base of the ice. A least square data-model score of the borehole temperature profiles is performed given four model parameters: surface temperature, surface accumulation rate, basal melt, and basal temperature gradient. A genetic algorithm (GA) is applied to find optimal param-

eter choices and to infer GHF at the base of each ice core site. The study identified anomalously high GHF values at Kohnen and WAIS Divide relative to the literature.

The study targets pertinent scientific questions with respect to the Antarctic basal environment which are within the scope of TC. However, given issues listed below with the experimental design, the claims of the study are not adequately substantiated and require additional development and experiments.

The title and abstract summarize and reflect the content of the manuscript. The paper follows a logical structure; however, the method section lacks crucial information needed to assess the results of this study. Furthermore, the study does not justify and test their assumptions adequately which directly impact the interpretation of their results against the broader literature (see Main Remarks). Finally, the study does not present information that is required if other researchers were interested in reproducing their work. For these reasons, I suggest that the study is rejected given there are several major revisions required to address the outstanding issues discussed below.

Main Remarks:

1. Heat flow model assumptions

The Antarctic ice sheet has an exceedingly long thermal memory and the slowest response time of the ice sheet is on a timescale exceeding 10 kyr (Ackert, 2003). The ice sheet is continuously in a transient state responding to past changes as well as contemporary forcings. The ice sheet is in disequilibrium, therefore, the assumption that the system is in a thermodynamical steady state must be properly justified and quantified. Otherwise, how are the results of this study meant to be interpreted against the literature (e.g. Martos et al., 2017; Passalacqua et al., 2017).

Over the last several glacial cycles, ice thickness, surface temperatures, and accumulation rates have varied across the ice core sites. Within the scope of a 1D time-dependent heat flow model, these boundary conditions (BCs) directly impact the thermal profile of the ice. Many ice core records offer reconstructions of both temperature and accumulation rates through time. These could directly be applied as BCs into a time-dependent heat flow model rather then constant model parameters.

The structural uncertainty affiliated with the assumption of a steady state heat flow model should be quantified. Time-dependent transient experiments should be conducted with proper time-dependent BCs wherever appropriate to assess the impact of a steady state assumption on the GHF results. Supplemented with a proper uncertainty analysis, this would contextualize the results with the literature.

2. Surface forcing of heat flow model

The heat flow model uses four model parameters: surface temperature, surface accumulation rate, basal melt, and basal temperature gradient. This seems to suggest that the surface temperature and accumulation rate are constant values and not time dependent. What are the resultant optimal GA temperature and accumulation forcings for each ice core site and how do they compare to present day observed values? There is a passing mention of the accumulation rate being time dependent in Section 2.2 to calculate vertical velocities at each ice core site. What is this study using, constant surface accumulation rates (model parameter), time-dependent accumulation rates (vertical velocity inference), or both? How does the accumulation rate used in the vertical velocity calculations compare against the optimal rate inferred from the GA? The study should be consistently using time-dependent surface temperature and accumulation rates. No reference is provided for the accumulation time-series mentioned at line 99, rendering this work not reproducible by other researchers.

3. Understated uncertainties

The GHF results come with uncertainty estimates that only represent one source of uncertainty affiliated with the initial parameter choices going into the GA. This significant underrepresents the overall uncertainties in their GHF estimates, which compromises the interpretation of their results with respect to the literature. The study does not ac-

count for structural uncertainties associated with their assumptions (steady state and no horizontal advection). Moreover, it is unclear if the ice thickness in the analysis is kept constant at present day values, this is not explicitly state. It appears the study uses constant ice thickness at each ice core site and does not attempt to estimate GHF uncertainties affiliated with this assumption. The heat flow model does not apply time-dependent surface temperature and accumulation rates, these time-series come with uncertainties which should also be propagated into the uncertainty model of the GHF estimations.

Furthermore, the uncertainty of the power law exponent (form factor) for the vertical velocity profile from Fischer et al. (2013) is not considered. The form factor could be anywhere from m = 0.5 to 1, with the former being favoured by Fischer et al. (2013). The study chooses m=1 without justifying that choice. The analysis should be conducted again using m=0.5 and 0.75 to quantify the impact of the form factor on the GHF estimates. This would propagate parametric uncertainties of the vertical velocity parametrization to the GHF estimates.

The GA manages to identify parameter choices that produce a strong fit to the observed borehole temperatures. However, given the unquantified impact of model assumptions and model weaknesses, it is possible the model is overfitting the data. Therefore, the study would greatly benefit from more robust confidence intervals that incorporate parametric uncertainties and structural errors in the assumptions made in the heat flow model. Upon achieving this, the study would be able to assess the robustness of the anomalous GHF values at Kohnen and WAIS Divide.

Minor comments:

In Figure 1. a GHF comparison is shown at each ice core site. A legend showing which reference is affiliated with which color would clean up the figure and caption. This would remove all the subscript a-e appended onto each GHF bar graph.

References:

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