Response to reviewers' comments on the manuscript "Geothermal flux beneath the Antarctic Ice Sheet derived from measured temperature profiles in deep boreholes" submitted to The Cryosphere

First of all, we would like to thank the Editor Alex Robinson and both anonymous reviewers for fruitful comments and advices. We tried to consider all mentioned issues and, in order to address comments (only critical ones), you will find here our answers point-by-point. The comments are in brown, and our answers are in black. Because our revised manuscript should not be prepared at this stage, we do not present text edits here. After addressing the issues raised, we believe that the manuscript can be accepted by Editor for further processing.

Anonymous Referee #1

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.

We agree with the reviewer that an exact steady state never occurs in reality and transient model likely would give more precise results instead of steady-state model. It is important to recognize that in both cases these will GHF "estimates", not "measurements". The thermal gradient can be affected by processes other than GHF, creating local anomalies that may coincide with the point estimate (e.g., Lake Whillans – Fisher et al., 2015). To use transient model, we need to know the accumulation rate and surface temperature in the past. For some of the discussed drill sites this data is available from ice-core studies, for some sites is not.

To evaluate possibility of using transient model, we did some more calculations for WAIS Divide site. The accumulation rate and surface temperature in the past were taken from the study of Buizert et al., 2015 (Fig. 1). In calculations, the history of ice sheet in WAIS Divide was assumed to be 68000 years long. The governing equation for transient model was solved by Finite Difference Method (FDM). The equation was discretized by both central difference method and upwind difference method and then solved in Matlab. To find best solution, the genetic algorithm (GA) algorithm was still used. The central difference method and upwind difference method demonstrated the same temperature profile. So, here we present the calculation results obtained via upwind difference method.

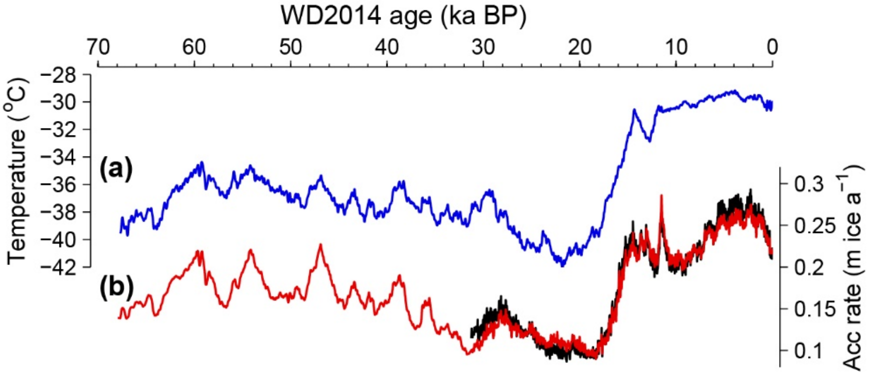

Fig. 1. WAIS Divide ice-core study implications: (a) past temperatures reconstructed from water δD, calibrated to the borehole temperature profile; (b) past accumulation rates as reconstructed by the firn densification inverse model (red), and from the annual-layer count (black) (Buizert et al., 2015)

Unfortunately, the calculation results with transient model showed the best fit GHF value of ~500 mW m^{-2} when m = 1, which seems to be unrealistic. In addition, after running the model, we found that after about 4-8 ka, the influence of initial temperature on temperature profile can be ignored. Later, we assumed the vertical velocity factor m = 0 and a GHF value of 235 mW m^{-2} showed good fit with measured temperature (which is close to our estimations of 251.3±24.1 mW m^{-2} with steady state model and m = 1). The temperature distribution in history was modeled 61.2 ka, 54.4ka, … 6.8 ka ago (Fig. 2). As expected, the modelled temperature in the upper part of the ice sheet grossly changes with time but in the lower portion (~1000 m above ice sheet base) these variations are much smaller. This means the heat disturbance (atmosphere forcing: temperature and precipitation) from the ice sheet surface are gradually decayed with the depth. From all appearances, near-base portion is close to the steady state.

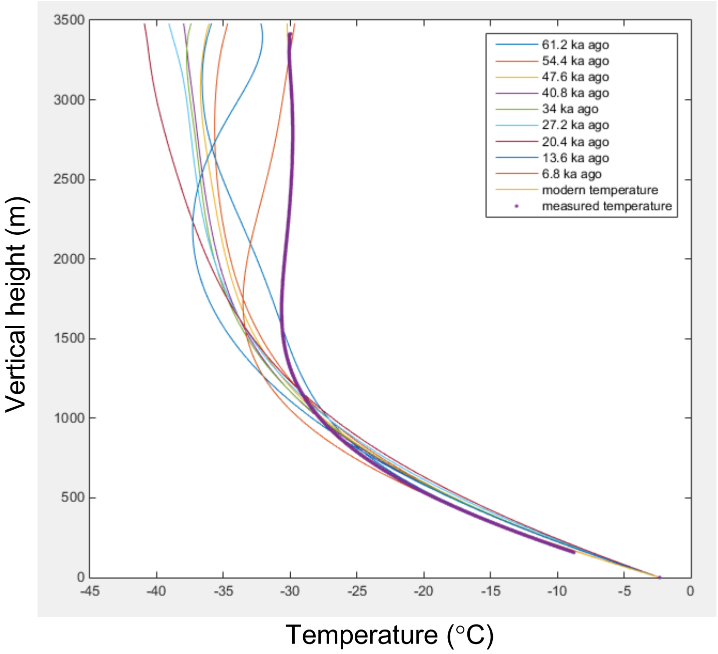

Fig. 2. Paleo temperature profiles based on transient model (m = 0)

Four drill sites (WAIS Divide, Dome C, Dome F, Vostok) are in close vicinity to ice divides (Fig. 3a) where horizontal advection and horizontal heat conduction are assumed to be minimal and the environment approximates a steady state (Cuffey and Paterson, 2010). In areas with a relatively smooth bed, horizontal conduction is much lower than vertical conduction (Hindmarsh, 1999, 2018) and horizontal advection and horizontal heat conduction can also be safely neglected (Van Liefferinge et al., 2018). Therefore, the interior slow-moving areas of the Antarctic Ice Sheet with smooth bed, including the rest two sites – Byrd and Kohnen (Fig. 3b), also can be considered at thermal steady state in their near-base portion.

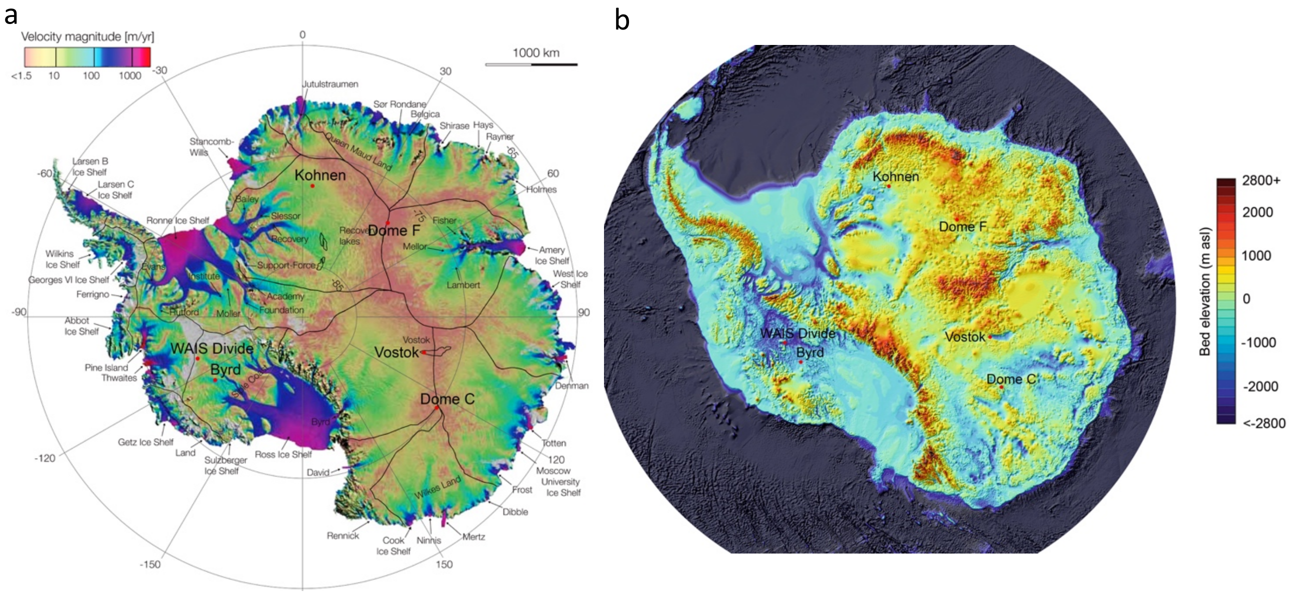

Fig. 3. (a) Antarctic surface ice velocity derived from satellite radar interferometry (Rignot et al., 2011); (b) Antarctic bed topography (Fretwell et al., 2013) and locations of the deep ice-coring drill sites

Steady state model was intensively used in the past and is still used in the recent GHF estimates in Antarctica (Martin and Gudmundsson, 2012; Mony et al., 2020; Parrenin et al., 2017; Price et al., 2002; Zagorodnov et al., 2012 and others). Thus, we are of the opinion that at first approximation, we can use a steady state model for GHF estimations.

In our method, the temperature in the lower portion of the ice sheets is assumed in steady state and can be only well fitted by guessing the four key parameters (the surface temperature, surface accumulation rate, basal melt, and basal temperature gradient). Utilizing of the GA algorithm helps to find the better value of the four parameters. In GA, the four parameters are not constrained in the range of the values they appeared in history because any constraint of the parameters in historical range will show worse fitting.

It is worth to be mentioned that the value of the parameters for best fitting got by GA is not the real parameters in ice sheet history. They can be considered as "equivalent" values for calculating modern temperature profile by eliminating the historical climate change. Namely, the following steady state equation (Eq. 6 in text) is used to describe only the temperature profile form instead of calculating the real value of these four parameters. Consequently, the vertical velocity profile showed in the text is the "equivalent" vertical velocity instead of real one.

$$T = T_s - \left[\frac{\partial T}{\partial z}\right]_B \int_0^z exp\left(\frac{(w_{melt}-Acc)z^{m+2}}{\alpha_T(m+2)H^{m+1}} - \frac{w_{melt}}{\alpha_T} z\right) dz + \left[\frac{\partial T}{\partial z}\right]_B \int_0^H exp\left(\frac{(w_{melt}-Acc)z^{m+2}}{\alpha_T(m+2)H^{m+1}} - \frac{w_{melt}}{\alpha_T} z\right) dz. \qquad (6)$$

The real melt rate is only calculated by the Eq. 7 in text. So, in total, the governing equation for steady state model was used twice. At the first time, it was integrated to a temperature distribution form (Eq. 6 in text) to fit lower portion of measured temperature in ice sheets, and later, the equation was rearranged to calculate real melt rate by derivation of the Eq. 6.

$$w(z) = \left[\alpha_T(\frac{\partial^2 T}{\partial z^2}) - \alpha_T(\frac{1}{k}\frac{\partial k}{\partial T})\left(\frac{\partial T}{\partial z}\right)^2\right] / \frac{\partial T}{\partial z}. \qquad (7)$$

So, the only uncertainties in our fitting model are coming from GA algorithm and from variability of the form factor *m*. For each deep borehole, the fitting experiments were trialed five times to avoid random error of GA. Then, the average value in the five fitting experiments was used as the GHF from bedrock into ice at selected site and the uncertainty ranges came from the difference between the maximum/minimum and the average GHF values.

Choosing of the appropriate form factor *m* is really challenging task. In our manuscript we stated (Lines 101-105):

“Classically, vertical velocity linearly depends on *z*/*H* (Cuffey and Paterson, 2010) and *m* = 0. However, at an ice divide, the downward flow of ice is slower, for the same depth, than at locations away from the divide (Raymond, 1983). This reduces the cooling influence of vertical advection and increases the basal temperature. Within this near-divide zone, the form factor could be from 0.5 (Fischer et al., 2013) to 1.0 (Raymond, 1983). All discussed sites are located at, or near, ice divide, thus, we assume *m* = 1.”

To set up the vertical velocity profile at Dome C, Fischer et al. (2013) performed three runs with *m* = 0.3, *m* = 0.5 and *m* = 0.7 and found that the temperature profile is only slightly affected by this choice. However, the form factor *m* had a strong influence on the age profile of the ice. That was the reason why the authors used *m* = 0.5, which is in good agreement with the EDC3 age scale.

To evaluate influence of *m* in the steady state model, we did some more calculations again for WAIS Divide site. The results are summarized in the table below. The results from the previous estimations that were trialed five times with *m* = 1 are highlighted by grey.

m	1	1	1	1	1	Average value	Error	0,75	0,5	0,25	0
Interval, m	2000-bottom	2000-bottom	2000-bottom	2000-bottom	2000-bottom			2000-bottom	2000-bottom	2000-bottom	2000-bottom
Temperature gradient (℃/100m)	3,98	3,75	3,9	3,92	3,87	3,88		3,93	3,71	3,59	3,69
Melt rate (cm/a)	1,97	1,52	1,85	1,82	1,78	1,75	0,23	1,62	1,30	0,24	-0,05
Conductive flux (mW/m^2)	83,7	79,1	82,1	82,6	81,5	81,4	2,3	82,78	81,55	75,86	77,75
Melt flux (mW/m^2)	191,7	148	179,5	176,3	172,9	169,9	21,9	157,56	125,87	24,22	-4,88
GHF (mW/m^2)	275,4	227,2	261,7	259	254,5	251,3	24,1	240,3	207,4	100	72,8

Decreasing of *m* from 0.75 to 0 leads to reduction of GHF from 240.3 to 72.8 mW m^{-2}. In the latter case, the melt flux is negative meaning that the ice sheet base is frozen to the bed (it is extremely unlikely). Because there are no clear considerations or prerequisites for choosing of the form factor *m*, we still are on the opinion that at the first approximation we can follow Raymond's (1983) arguments for deformation in the vicinity of ice divides and run with $m = 1$.

From the other hand, GHFs for WAIS Divide and Kohnen look really overestimated. The current WAIS team modeling shows that GHF at WAIS Divide is on the order of 105 mW m^{-2} (unpublished as of yet) that corresponds to our GA result with steady state model and form factor $m = 0.25$ (~100 mW m^{-2}). Apparently, there are some other "physical" uncertainties that we did not know and did not account for these sites at the moment. Most likely that horizontal conduction in the bottom of the ice sheet at these sites is quite high and cannot be ignored. Thus, one of co-authors suggested to remove results of our GHF estimates for WAIS Divide and Kohnen from the revised version of the manuscript as some unsolved problems of the applied model and GA are still exist. However, we can try to go further with GHF estimates with GA for other four sites. Our further actions will depend on feedback from the editor, reviewers and final discussion within co-authors.

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.

Section 2.2 of submitted manuscript contains general theoretical computation of temperature distribution in ice sheet at steady state. In our calculations, we do not use time-dependent values of the surface temperature and accumulation rate. These parameters are changed within GA in a wide range to fit the measured temperature. Then the "equivalent" accumulation rates and temperature can be calculated from GA results. The following table shows values of "equivalent" accumulation rates and temperature at ice sheet surface which were derived from our calculations. In all cases, "equivalent" accumulation rates are higher than modern ones while the "equivalent" surface temperature are close to modern ones. "Equivalent" vertical velocities at drilling sites derived from GA results are shown on Fig. 3 of submitted manuscript.

Parameters	**Byrd**	**WAIS Divide**	**Vostok**	**Dome C**	**Kohnen**	**Dome F**
"Equivalent" Acc (cm a^{-1})	64.7	97.4	8.95	3.70	7.22	3.00
Modern Acc (cm a^{-1})	16.9	22.0	2.48	2.84	7.00	2.99
"Equivalent" surface temperature (°C)	-29	-30.8	-56.5	-54.6	-45	-56.5
Modern surface temperature (°C)	-28	-30	-57	-54.6	-44	-57.3

In general, the computational details that need to be captured and shared for reproducible research include: (1) the data that were used in the analysis; (2) written statements in a programming language (i.e., the source code of the software used in the analysis or to generate data products); (3) numeric values of all configurable settings for software; (4) detailed specification of computational environment including system software and hardware requirements, including the version number of each software used; and (5) computational workflow (National Academies of Sciences, Engineering, and Medicine, 2019). All these are extremely extensive. We tried to provide baseline that can guarantee reproducibility of our scientific findings and will be happy to provide other data (if considered necessary).

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 account 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.

In our calculations, the ice sheet thickness was kept at present day height. We agree with the reviewer that the ice sheet thickness at the studied sites varied in history. 3D thermo-mechanical model and the simple 1D model showed that the maximum variation of ice sheet thickness at Dome C and Dome F is less than 250 m in the history (Parrenin et al., 2007). Generally, the typical difference in the ice thickness in the glacial and interglacial periods at Dome C was 150 m (Passalacqua et al., 2017). At the Kohnen site, the local elevation variation is in the order of 100 m (Huybrechts et al., 2007). Located in east Antarctica plateau, the ice thickness variation at Vostok has the similar range as at Dome F and Dome C (Ritz et al., 2001).

The best evidences for ice-sheet elevation change in the interior of the West Antarctic ice sheet come from the Ohio Range, to the south of the WAIS Divide site at a height of 1600 m a.s.l., and from Mt. Waesche to the north of the WAIS Divide site at a height of 2000 m a.s.l. (Ackert et al., 1999, 2007). Moraines at Mt. Waesche were ~50 m higher and trimlines in the Ohio Range were ~125 m higher, between 12 and 10 ka. The ~100 m of thinning throughout the Holocene occurred as the grounding line retreated by hundreds of km and the accumulation rates were relatively stable (Anderson et al., 2002; Conway et al., 1999). The model of Cuffey et al. (2016) suggested that a more likely scenario of 200 m thickening at WAIS Divide when accumulation rises after the last glacial maximum, followed by 300 m of thinning to the mid-Holocene. The elevation change is comparable to the amount of elevation change inferred for interior East Antarctic sites.

Comparing with the modern ice thickness value, the variation of ice thickness is small and its influence on ice temperature distribution can be neglected, especially on lower portion of the ice borehole. For example, assuming a 150 m thickness increase from the LGM to 15 ka changes the reconstructed LGM temperature by less than 0.2 °C compared to a constant thickness in WAIS ice core (Buizert et al., 2015). This is the reason why constant ice thickness is also used by other researchers for GHF estimations (Dahl-Jensen et al., 2003; Engelhardt, 2004; Mony et al., 2020).

To our knowledge, we used GA for the first time to find optimal solution of temperature fitting in ice sheets. GA can solve optimization problems by limiting unknown parameters changing in a predetermined range with any types of constraints, including integer constraints. This is very helpful in our study. In general, GA generates high-quality solutions for optimization problems and search problems.

Answers on the other comments were given hereinbefore.

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.

We will be happy to add corrected figure in the revised version of the manuscript (see Fig. 4 in the current response).

Anonymous Referee #2

... there are crucial aspects that are unclear from the text such as, why the results are important, what is the new gained knowledge, how these results compared with other local GHF values obtained through modeling in the same drill sites by other authors?

The Antarctic GHF is an important boundary condition for ice sheet behavior and associated sea level change (Golledge et al., 2015) since it keeps basal ice relatively warm, and thus less viscous than colder ice above, and helps supply meltwater at the ice sheet base. Typical questions are: What are the basal ice temperature and mechanical properties? How does GHF control basal melt and internal deformation of the ice sheet? How old is ice at different locations? These questions can be answered only by applying reliable GHF measurements or estimates. However, GHF remains poorly constrained, with few borehole-derived estimates, and there are large discrepancies in currently available glaciological and geophysical estimates (Burton-Johnson et al., 2020).

We estimated GHF at six sites – Byrd, WAIS Divide, Dome C, Kohnen, Dome F, and Vostok, which have succeeded in reaching to, or nearly to, the bed in inland locations in Antarctica. Our GHF estimates allow to validate continental and local models and reveal (if so) local geothermal anomalies.

Obtained GHF values are compared with five modellings (Shapiro and Ritzwoller, 2004; Fox Maule et al., 2005 Van Liefferinge and Pattyn, 2013; An et al., 2015; Martos et al., 2017) using bar graphs on the Fig. 1 (or Fig. 4 in the current response). Further comparison with this data and data from other references for specific sites was given in the "Results and discussion" section.

The manuscript lacks of a proper discussion section. The manuscript should separate results from discussion and conclusions. Additionally, a more detailed discussion is necessary.

In case if the manuscript will be accepted by Editor for further processing, we separate "Results and discussion" section into two sections "Results" and "Discussion". We plan to add into "Discussion" the following details: (1) transient model vs. steady state model; (2) uncertainties; (3) comparison studies; (4) implications. In addition, "Conclusions" section will be presented.

In addition, key components of the methods are not adequately described or are missing. In particular, uncertainties are not adequately addressed which makes it difficult to evaluate the results and conclusions of this study.

We applied GA algorithm to fit measured temperature in deep ice-core drilling boreholes by variation guessing of the four key parameters influenced on temperature distribution: the surface temperature, surface accumulation rate, basal melt, and basal temperature gradient. All these parameters are suggested by algorithm in order to get the best-fitting curve. The only uncertainties in our fitting model are coming from GA algorithm itself and from variability of the form factor *m*. Detailed answers for applied method and uncertainties are given to Anonymous Referee #1 hereinbefore.

Below are my comments, suggestions and concerns that I hope will be useful for the authors to improve the manuscript:

- I suggest to change the title as it is not accurately representing the content of the manuscript.

The title can be changed to: "Geothermal heat flux from temperature profiles in deep ice-core drilling boreholes in Antarctica".

- Regarding the discrepancy between the high values obtained in Kohnen and WAIS Divide in comparison with Antarctic-wide maps:

One thing to consider is that the Antarctic-wide geothermal heat flow maps are representing the heat flow of a region, while a heat flow value derived using borehole measurements is representing a specific local value. Therefore, probably these higher than predicted heat flow values obtained for Kohnen and WAIS Divide are only representing local values, not necessarily hot spots. The higher values could be consequence of, for example, a higher concentration of a particular radiogenic material in that spot, or a consequence of some particularity of the subglacial topography or the parameters and assumptions that are involved in the solutions of the model to obtain the local value. For these reasons, understanding the uncertainty sources and quantifying them is extremely important and it is necessary.

We agree with the reviewer that there are a large number of possible reasons for elevated GHF at Kohnen and WAIS Divide (variability of crustal thickness, hydrothermal circulation, high concentration of radiogenic materials in the bedrock, etc.). However, at this stage we are not able to give lucid explanations of this phenomenon. Uncertainty sources and quantifying were discussed above.

- L69: The manuscript should demonstrate the temperature measurement precision in a robust and scientific way

We will add evaluation of temperature measurement precision in the revised version of the paper. Uncertainties of temperature measurements in mechanically drilled boreholes filled with drilling fluids were presented in details by one of co-authors in USGS report (Clow, 2008).

- L78-80: Where is this shown? Quantify the good agreement. This is important for the uncertainties of the estimated local geothermal heat flow

This is shown in Table 1 (the line “Ice thickness according with radar/seismic survey (m)”) and Table 2 (the line “Ice thickness according with depth of pressure melting point (m)”).

- Figure 1: The drill sites as well as other local values are plotted in this figure together with a geological map for the Antarctic continent. However, the geology is not mentioned in the text, there is no discussion about results and the subglacial geology. What is the purpose of the geological map if it is not used in the manuscript? I recommend to either include some discussion about it or select another background data to plot the drill sites and discuss the results in that context.

At the first stage of the paper writing, we planned to connect revealed GHF values with Antarctic subglacial geology but then, because of the insufficiency of data, we dropped this idea. We agree with reviewer that it would be more rational to select another background, for example, with location of the Antarctic ice divides (Fig. 4).

- Regarding uncertainties I have two main comments/concerns:

1. How uncertainties are calculated is not adequately explained and more information and details are needed to evaluate the GHF estimates.

2. A substantial discussion about which parameters are contributing to the uncertainty is necessary. In addition, there are assumptions made in the thermodynamic model and also parameters that are assumed to be constant. These assumptions also carry uncertainties and they need to be properly quantified and included in the final uncertainty budget. For example, one important aspect to quantify would be the contribution to the uncertainty budget of considering steady-state condition.

We will be happy to add uncertainty considerations into revised version of the paper.

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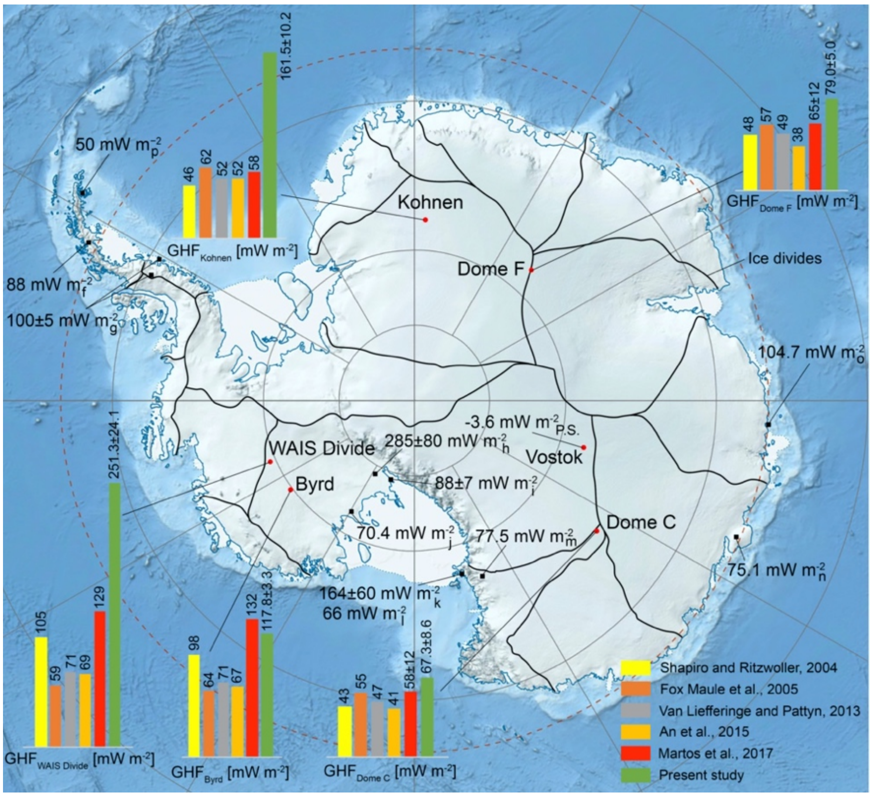

Fig. 4. GHF derived in the present study (P.S.) from basal temperature gradients in deep ice boreholes (green bars) compared with modelling. Location of the Antarctic ice divides is shown according with Rignot et al., 2011.

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