Comments on "Investigating the internal structure of the Antarctic Ice Sheet: the utility of isochrones for spatiotemporal ice-sheet model calibration" by Sutter et al.
Thank you for submitting a revised version of your article. A number of the comments raised by one of the reviewers and the editor have not been fully addressed. These are listed below. Line numbers refer to the most recent non-track-changed version of the article. In cases where an example is given, please check for other instances throughout the manuscript. All points are minor but should be addressed prior to publication.
Pippa Whitehouse (Editor)

We sincerely apologize for omitting some of the reviewer comments and the changes to the manuscript you suggested. We hope we can rectify this embarrassing omission with the newly revised version of the manuscript. Please find point-by-point replies to the remaining comments in Blue and changed text in Red.

RC = reviewer comment
EC = editor comment
non-bold – editor's comment explaining why the points has not been sufficiently addressed

RC: P1L9 (and throughout manuscript). Remove the comma before "that"
Commas have not been removed on lines 9, 259, 273, 288, 302, and 322

Done

RC: P9L222-224. … it's hard to see why this happens here, but not later in the transect where there are significant gradients in topography [comment relates to figure 3]
Please address the reviewer's query about why there is no divergence in modelled isochrones in the region of steep topography between 400 and 500 km on the transect

We rephrased the sentence (now p9l225-226) so that it only refers to gradients in ice flow and not topography as tracers are advected via the 3D velocity field, thus deviations in isochrone elevations for different tracer seeding parameters are due to gradients in the velocity field. The modeled isochrone elevation is affected by the bedrock elevation and gradients in the modelled bedrock contour can deviate from the real bedrock landscape considerably. The region between transect km's 400 and 500 is a good example where high-res radar data shows large local variations in bedrock elevation while the coarse resolution model bedrock elevation is essentially flat (and therefore does not affect the isochrone elevation much for different tracer seeding strategies). A more detailed analysis would be necessary to identify at which point velocity gradients adversely affect computed isochrone elevations for coarse seeding strategies. We will keep this in mind for the future.

RC: P12L276. Remove wayward parenthesis ")"

Done.

RC: Figure 5. Topography color scale could be moved to left panel.
Please do not locate the colour scale for one plot within a different plot, this is confusing

We moved the colour-scale to the corresponding plot.

RC: Figure 6. I didn't understand where the 7 %K-1 scaling came from? Perhaps add a reason why in the caption, or add it to the list of experiments in section 2.2

You note that this point is confusing and provide an explanation in your response to the reviewer. Please also include relevant information in the revised article to explain this point to the reader

We apologize for this omission. We decided to change this figure so it shows the forcing for 6 %K-1 scaling which is consistent with the experiments and hopefully removes the source of confusion. We modified the figure caption accordingly.

RC: comment on spin-up approach: you mention this article is not the place for a detailed discussion of the best approach to ice-sheet model spin-up. However, it would be useful if you could mention in the conclusions why this point is important, i.e. re-iterate your point on line 335 that ice sheet initial state can significantly affect its future behaviour over centennial and decadal timescales.

We amended the 3rd bullet point in the conclusions by the following paragraph:

Even small biases (e.g. due to overfitting against uncertain input fields) in the initial model state can impact ice sheet dynamics and therefore estimates of future ice sheet sea level contributions. We make the case that the paleo-evolution of an ice sheet should be considered both for reconstructions as well as projections of ice sheet changes and that isochrones are ideally suited for this purpose.

RC: P19L412-414. Given your conclusions about the issues with basal friction, can you recommend a more appropriate friction law to use?
You mention that this is a proposed area of future research. It would be useful for the reader if you could briefly outline the alternative approaches that could be adopted

We now mention potential alternative avenues to model basal friction in the conclusions, p25-l510-512:

For example, the impact of different calibrations of basal drag on modelled isochrone elevations, such as inversion methods based on surface elevation and ice flow, could be elucidated in such an intercomparison.

RC: Figure 10. Add y-axis labels to the panels in C)

Done

EC: Ensure that acronyms are defined at their first usage, and that they are used consistently throughout the remainder of the text
For example, 'AIS' is not defined on line 6

Done

EC: Check the format of in-text citations
For example, see line 160

Done

EC: When using the term 'topography', clarify whether you are referring to the surface or the bed of the ice sheet
For example, see caption to figure 1

Done

EC: It is a little unclear whether some of your results are derived from the 2 Ma experiment, or whether this experiment is simply used to initiate the 220 ka experiments and all results shown are derived from the 220 ka experiments. It would be useful to clarify this in section 2.2
No edits were made to clarify this point. In particular, it is unclear whether the 'pal' results are derived from models run over a mixture of 2 Ma and 220 ka, and whether the 'pd-pal' results are based on present-day snapshots of models run over a mixture of 2 Ma and 220 ka

We agree that this is not clear from section 2.2. All simulations were carried out for this manuscript except for the geothermal heat flux ensemble using a 3%/K temperature precipitation scaling which was simply taken from Sutter et al. 2019. We now begin the section with the following paragraph (p6l157-165).:

"In order to compute Antarctic isochrones, time-resolved 3D velocity data as well as the transient ice-sheet geometry (ice thickness and bedrock topography) are necessary. We therefore ran a paleoclimate model ensemble covering the last 220 ka. All 220 ka simulations were initialised from the 220 ka output of a 2 Ma long simulation in Sutter et al. (2019). We also make use of four simulations from Sutter et al. (2019) which are based on four different geothermal heat flux fields (Shapiro and Ritzwoller, 2004; Purucker, 2013; An et al., 2015; Martos et al., 2017). In addition to the 220 ka paleo-ensemble we carried out a present-day equilibrium ensemble to assess the impact of the missing paleo-spinup as well as different model parameterisations on the computed isochrone elevations."

And follow with

"Isochrone elevations (see 2.3) are computed on the basis of: 1) full paleo-ISM runs (called pal) in which model integration starts from the 220 ka time slice of a 2 Ma simulation (Sutter et al., 2019), 2) the present- day snapshot of the 220 ka simulation (pd-pal), 3) a present-day equilibrium ensemble (pd) with an integration time of 2000 years following a thermal spinup using a fixed ice sheet geometry for 200 ka. The 2 Ma simulations in Sutter et al. (2019) are initialised at 2 Ma BP from a present-day ice sheet geometry. Isochrone evolution starts at the isochrone's respective age (see Table 1) in the past and follows the computed transient ice flow. In the present-day snapshot (pd-pal) and present-day equilibrium ensemble (pd) isochrones evolve on the basis of the simulated present-day flow (constant velocity field). "

EC: Your methodology provides an estimate of the normalised elevation of each isochrone above the bed. However, radar systems provide an estimate of the depth of an isochrone below the ice surface. Any uncertainty on total ice thickness/bed elevation will impact on your ability to compare modelled and observed isochrone positions. Please briefly comment on this issue.

No response to this query, consider whether it warrants a comment within the manuscript

This is true and so far, we only shortly mention this matter in the conclusions (see next comment). One could potentially mitigate this issue by tracing the elevation of the individual tracers relative to the surface of the ice which generally better agrees with observations than the bed (at least for present day). In PISM the vertical coordinate is defined relative to the base of the ice and a coordinate transformation would be necessary to track the ice relative to the surface. However, we deemed it to be more consistent to trace the ice trajectories accordingly to the native geometry of the ice sheet model. We added a sentence in section 2.3 (Lagrangian tracer advection) stating:

"Here, it is important to note that observed isochrone elevations are usually defined as relative to the ice surface whereas we compute the isochrone elevation above the ice bed. Any deviations in the modelled ice bed with respect to observations will therefore imprint on the modelled isochrone elevation. Therefore, any comparison between modelled and observed isochrone elevations will be most meaningful along transects with small deviations between the observed and modelled bedrock elevation."

EC: logic of your argument could be clearer in a few places (e.g. lines 491-, 495-)
The logic behind the final sentence of the third bullet point in the conclusions is unclear.

We agree and reformulate the phrase as follows:

"Varying the parameter space relevant for basal sliding for a set of parameters that produce an equilibrium sea-level equivalent ice volume of the Antarctic Ice Sheet within ±2 m of present-day observations cannot remedy this mismatch"

There is a jump in logic between the first and second sentences in the fourth bullet point in the conclusions.

We agree and reformulate the paragraph as follows:

"When using isochrones as a tuning target for paleo-ISMs, two key uncertainties prove difficult to account for: 1) geothermal heat flux fields remain poorly constrained (new, e.g. Stal et al. 2021, and upcoming datasets might reduce this uncertainty) and can have a strong influence on isochrone elevations. 2) Uncertain bedrock elevation in regions with gaps in radar surveys affect modelled isochrone elevations especially for isochrones close to bedrock. However, for areas covered by high resolution radar transects, this aspect can be quantified by comparison to the model bedrock elevation. Combining isochrone elevations, present-day observables and paleo proxy data in the calibration of ice sheet model setups helps to mitigate aforementioned uncertainties and prevent overfitting."

EC: Figures: please check the following points in relation to all figures:

a) Colour scales are included where relevant
for example, figure 1, figure 2, figure 9

Done

b) The caption describes all features shown in the figures please check the accuracy of all captions. In some cases, captions do not agree with information in the figure, e.g. figure 8 refers to Purucker (2013) data which is not shown in the figure, it also refers to 'thin dashed lines' in panel B, which are not visible.

Done. The thin dashed lines described in the caption for figure 8 B) where present in an older version of the figure which we decided not to use. We removed the sentence referring to the thin dashed lines.

c) Somewhere, state the projection used to define the northing/easting values

Done in the caption of figure 1.

d) Ensure that all place names mentioned in the text are indicated on a figure
for example, the reader is referred to figure 1 to locate Dronning Maud Land and George V coast (line 108) but these locations are not labelled on figure 1

Done.

e) Check the location of all transect plots is clear (e.g. this is not the case for figure 3)
in particular, it is not always clear which end of the transect is defined as 0 km

In the caption of figure 3 we note that transect CEA-10 is depicted and refer to figure 1,10,11 for the location. We agree that the location is not given in Figure 11 and a little hard to identify in Figure 1. Thus we now only point the reader to Figure 10 :

"[…] see Figure 10 for the location of transect CEA-10"

The direction of the transect in Figure 3 is identical to the one in Figure 10 and 11.

f) Define all lines in the legend/caption, including the lines representing the ice sheet surface
in several plots multiple lines are plotted at ~3000 m elevation. I think these represent the surface of the ice sheet, but it is not clear what the difference is between the lines

Yes. Different surface elevations refer to different model runs (i.e. for different GHF input fields). Additionally, the observed surface elevation (Bedmap2) is plotted. This is now explicitly mentioned in all relevant figures.

g) Ensure that all sub-plots are labelled
for example, figure 7

Done.

h) Ensure that all axes are labelled and that labels are legible for example, figure 7 (x-axis, right-hand plot), figure 10C (both axes)

Done.

Additional editor comment: it is unclear what some of the numbers refer to in the edits to line 323, e.g. “pal 4.8 and pd 20”

Thank you for spotting this. The sentence now reads:

However, it is relatively small (4.8% vs. 11.4% RMSD) in comparison to the difference between pal (4.8 % RMSD) and pd (20–56% RMSD).