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# *Interactive comment on* "Simulating the internal structure of the Antarctic Ice Sheet – towards a spatio-temporal calibration for ice-sheet modelling" *by* Johannes Sutter et al.

**Anonymous Referee #2**

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Summary: The authors present results from a study focused on utilizing the internal structure of the Antarctic Ice Sheet, as surveyed with ice-penetrating radar, to reveal and validate the paleo evolution of the ice sheet. This approach also has the potential to more thoroughly initialize an ice-sheet model used for future projections of mass loss and sea-level rise.

The new approach simulates the deformation of isochrones using a Lagrangian tracer method. This method uses results from previous ice-sheet model simulations (Sutter 2019) (3D velocity and ice thickness) and therefore by-passes the need to directly incorporate the tracer into the ice-sheet model. Direct comparisons are then made



between the elevation of the modelled and observed isochrones with a number of continuous layers dated between 38 ka and 160 ka.

Multiple processes combine to produce the observed isochrone stratigraphy (surface accumulation, basal melting, ice flow). The authors navigate this complexity by identifying regions of the ice sheet where individual processes dominant the isochrone deformation.

The authors conclude that in areas of slow ice flow far from the coast, such as ice divides, paleo surface accumulation can be determined using this method. Furthermore, isochrones are more accurately reproduced when the ice-sheet model is evolved transiently over the past ∼200 ka rather than maintaining the present-day ice flow and climate configuration. This highlights the importance of correctly simulating the past evolution of the ice sheet for model initialization.

In areas of faster horizontal ice flow, internal vertical flow is overestimated suggesting basal drag or topography is incorrectly characterized in the ice sheet model, possibly a result of the coarse resolution of the ice-sheet model. There are also more substantial difference in stratigraphy in areas where there is more complex historical variations in accumulation, i.e. change in synoptic systems rather than a simple temperature-accumulation relationship.

The authors argue that approaches similar to this, which compare modelled and observed internal stratigraphy, signal a step-change in paleo-ice-sheet modelling and future ice-sheet projections. They suggest a model intercomparison using this data is a possible future direction.

Overview: Although this is not the first time ice-flow models have been used to interpret ice-sheet stratigraphy, most previous studies have be restricted to ice-flow models covering relatively small spatial scales and analyzing a small number of radar profiles. Here simulations covering the whole Antarctic Ice Sheet are used to assess internal stratigraphy across an array of radar profiles covering a variety of locations with differing ice-flow, accumulation and basal conditions. A further novelty of this work is the use of a Lagrangian tracer applied to results from previous ice-sheet simulations. Not only is this efficient, but also has the potential to compare different ice-sheet models used for paleo ice-sheet simulations.

This work is presented as a starting point for more in-depth assessments in the future, and provides an interesting first step which will be of interest to a range of readers within the glaciology community (ice-sheet modellers, radar geophysicists and paleo glaciologists).

I found the work interesting and on the whole well written. I have included below some more substantial points that I believe should be addressed fully before final publication. I also include a commented PDF detailing line-by-line notes.

Main Comments: âĂć I think the authors could be more quantitative with their assessment of how well modelled isochrones match observations. This is mentioned for some cases towards the end of the manuscript, but I think it should be more prominent throughout. After all, one criticism of traditional radar analysis may be it's qualitative nature. Here is a great opportunity to perform a more quantitative assessment, especially given the potential to apply this method further in the future.

âĂć Lines 50-52: "Discrepancies in the initial state with respect to the actual real world ice-sheet can propagate and multiply during the model simulation due to the intrinsic nonlinearities of the system." Some attempts have been made to combat this using transient inversions, see Goldberg, D. N., Heimbach, P., Joughin, I., & Smith, B. (2015). Committed retreat of Smith, Pope, and Kohler Glaciers over the next 30 years inferred by transient model calibration. Cryosphere, 9(6), 2429–2446. https://doi.org/10.5194/tc-9-2429-2015

âĂć Lines 72-73: "englacial isochrones have not been getting the required attention in the context of tuning targets for continental ISMs" - this is a very important point, which I feel should be more prominent in the manuscript. Maybe include some mention of



what these layers are traditionally used for, but their full potential is not being utilized.

âĂć Isochrone stratigraphy is a result of the cumulative effects of surface accumulation, basal melting and ice flow. It would be good to have some comment on how these processes effect the stratigraphy generally and how they can be picked out from the structure of layers.

âĂć Line 95: isochrones covering "38 ka to 170 ka" – is it not possible to trace earlier layers? I'm curious about this choice, wouldn't earlier layers have interesting histories too?

âĂć Section 2.1: I found the inclusion of a detailed section summarizing the formation of isochrones to be well written and a nice addition to the text. It opens up the remainder of the manuscript to those who may be unfamiliar with ice-penetrating radar surveys.

âĂć Section 2.2: âĂć o The results of this work rely heavily on previous ice-sheet simulations from Sutter et al., 2019. It would be really helpful to have more details about these simulations. One particular question is; is GIA included in the model? You mention transient bedrock topography. o o It would also be helpful to have a summary of the differences between the model results in the three different cases used for the Lagrangian tracing; pal, pal-pd and pd. In particular what are the difference in pal-pd and pd with respect to the 3D velocity and ice geometry? Are there any clear differences which result in the different isochrone elevation. With respect to pal, to what extent has the ice flow/thickness varied? o âĂć Fix typo in equation (1)

âĂć Lines 178-180: "Misfits of the ice-sheet model state in terms of elevation and velocity field relative to the true (unknown) ice sheet state at that point in time in the past, will lead to deviations of the modeled isochrone as observed in the ice sheet today." Deviations between the modelled and the observed isochrones are a result of cumulative differences between the model and reality, not at a single point in time.

âĂć Lines 191-193: "From this elevation map we then extracted the computed tracer-

, bedrock- and surface-elevation as well as the melting at the base of the ice and the corresponding geothermal heat flux (which was provided as input data) along the individual radar transects." This statement is a bit confusing. The elevation of the tracer is extracted from the tracing process, but all other parameters are taken from the ice-sheet model results.

âĂć Lines 196-197: "(i) climate forcing, (ii) model parameterisation, (iii) bedrock and geothermal heat flux." I agree with the assessment that these three processes affect ice-sheet internal structure and like the way you have gone about targeting them individually!

âĂć Lines 253-254: "The modelled isochrone elevations discussed above were computed on the basis of transient snapshots of local velocity and topography fields and show a good match to observed isochrone elevations." More details are needed here. What is the initial state? How much does this vary from present day? How does velocity vary in time? I assume very little? I realize these details are probably given in Sutter 2019, but it would be good to give a brief summary here. Especially given the next section of text.

âĂć Use of pd or pd-pd – which one do you want to use?

âĂć Lines 273-276: This is a really interesting point. Details of calibration may vary depending on desired analysis/end product. Most models used for near term projections (100-500 year) tend to use method (a). But clearly for projections over a longer period, and paleo simulations, the ability of the ISM to reproduce paleo-proxies is vitally important.

âĂć Line 295: "ice-sheet model parameterisations" I don't feel this point is sufficient explored in the text. What parameterisations are you referring to? Have you used models with difference ice rheology parameters, etc?

âĂć Lines 303-304: "dominating or confounding effect" - I agree that the combination



of these processes can make deciphering the true history complex. Do you have any insight into how to pick apart these contributing components?

âĂć Figures 7 and 8 – these figures are under utilized and they are very few references to them in the text. I suggest you pick out some more details that the reader may find interesting and include them in the main text.

âĂć Line 348: "Basal melting at the bed of the ice along the radar tracks is unfortunately unknown" Is there any evidence of water in radar profiles, i.e. flat bright reflectors, or isochrones that are drawn down and intersect the bed, that may suggest melting?

âĂć Line 359: "the modelled isochrone" – can additional information be gather from the relationship between isochrones (modelled and observed) and also from the relationship between their misfits? Suggesting possible changes in time not included in the model.

âĂć Lines 373-374: "synoptic activity can dominate the spatial and temporal variability in precipitation" I don't know too much about spatial and temporal patterns in accumulation, but is there significant inter-annual variability in regional climate models in these regions that could be used to give some additional bounds on the changes that could be expected?

âĂć Line 380: "identify past accumulation patterns" How reliant is this on having additional data from ice-cores or good climate models?

âĂć Lines 401-403: "While analysing the match of an ISM simulation with the internal stratigraphy is not as straight forward as using surface observables, it could improve both paleo ice-sheet reconstructions as well as sea level projections due to more realistic initial ice-sheet configurations." It would be good to detail what impacts (if any) an incorrect internal ice-sheet stratigraphy would have on future projections.

Figures: Most figures and captions need some attention to improve their readability. At present they have the potential to be really good, but need a little more work. I have included comments in the attached PDF.

Individual Comments: I include an attached PDF with minor line-by-line comments. One reoccurring issue is the use of compound adjectives: ice-sheet model, present-day accumulation, etc. This should be addressed consistently throughout the text.

Please also note the supplement to this comment:
https://tc.copernicus.org/preprints/tc-2020-349/tc-2020-349-RC2-supplement.pdf

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