Response to review 1 of 'Cosmogenic-nuclide data from Antarctic nunataks can constrain past ice sheet sensitivity to marine ice margin instabilities' by Halberstadt et al.

This is a well-written and interesting manuscript comparing long-term ice cover histories derived from multiple cosmogenic nuclides measured in slowly eroding Antarctic bedrock surfaces with two ice-sheet model parameterizations. The manuscript suggests a novel way of testing these ice-sheet model parameterizations by use of empirical data. The paper is of wide interest and convincingly written. My comments below mainly contain suggestions to improve/clarify the figures and figure captions.

We thank the reviewer for the supportive comments and helpful suggestions. Below we respond to reviewer suggestions and concerns in detail; for typographical errors or small corrections, the * symbol indicates our intention to enact these corrections in a revised manuscript. We appreciate the reviewer's attention to both the large and small aspects of our manuscript.

Figures

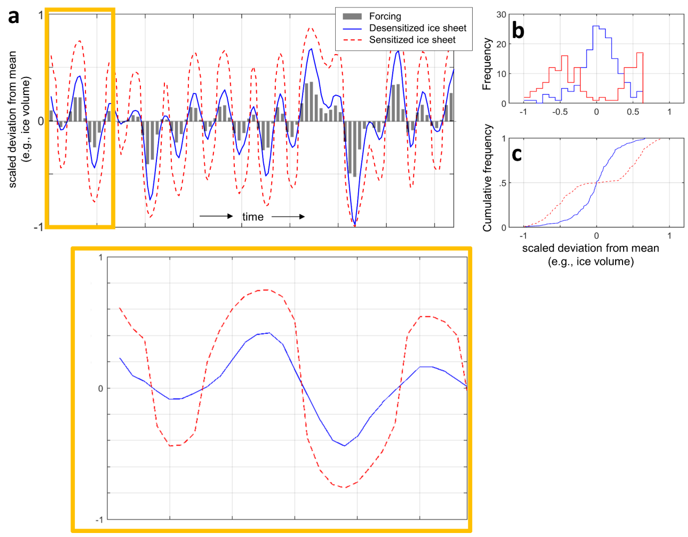
Fig. 2:

- The box in panel (a) is not explained in caption, I assume it is outlining the extend of boxes in (d) and (e), but if so, the blue curve in (d) is lacking an initial and partially a final 'plateau' (horizontal part) similar to the red curve in (e). Even though it is a conceptual figure, I think this way of exaggerating the difference is misleading.

Thanks for pointing this out. Boxes (d,e) were intended to be conceptual, but we agree that the box in (a) is not representative of these blue and red curves in (b,c) and doesn't make a lot of sense in this context - we will remove the box, leaving the rest of (b,c) as is.

- Are you sure the blue curve in panel (b) is reflecting the blue curve in panel (a) correctly? Comparing the curves in panel (a), the blue and red curve shapes are similar – the blue curve has lower amplitude, but still quite steep slope around zero crossings. I would therefore expect the blue curve in (b) to be bimodal, but with less sharp peaks located closer to zero compared to the red line (approximately +- 0.25).

The frequency distributions in (b,c) are indeed calculated directly from the red and blue curves in (a). "Steep" is relative, and the red curves are many times steeper than the blue curves at the zero crossings, which gives rise to the difference in the frequency distributions. For example, zooming in to just a few "glacial cycles" (shown below in yellow) reveals that the blue curve indeed does spend more time closer to zero.

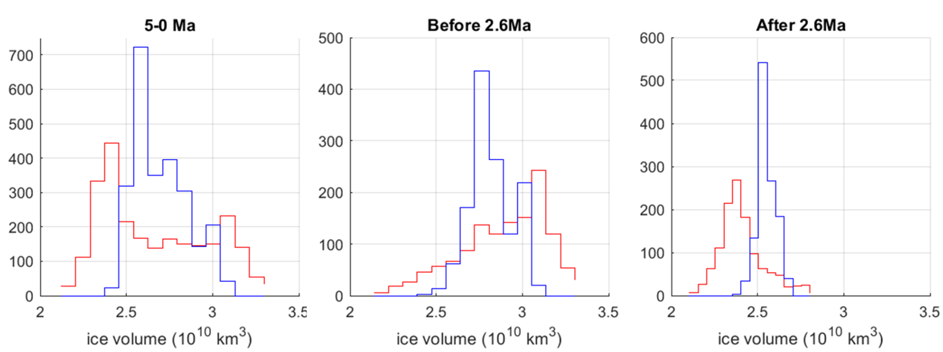


- Scalebar for panel (b) is missing a number (-0.5) or a white box is partially covering it.*
- Avoid rainbow color palette for panels (f) and (g), when the figure is printed in grey both ends of the scale has the same color. *

Fig. 3:

- y-labels for panels (b) and (c) missing *
- Note that the histograms in panel (b) reflect a composite of two quite different responses before and after the Quaternary. I think this makes the blue/desensitized curve look ‘artificially’ unimodal because of the remarkable stability prior to the Quaternary, while the Quaternary period shows a bimodality very similar to the red/sensitized scenario but with a smaller amplitude.

This observation is entirely correct that the ice volume PDFs are not stationary and are different for different integration time periods. However, the blue (desensitized) ice volume PDF is unimodal for both the full time period and for the Pleistocene alone (see frequency distributions plotted by time period below), so this specific concern is not supported.



More broadly, the above plots highlight that the bimodality of the red (sensitized) PDF for the full model run is, in part, due to the tendency of the model to occupy a "small" end-member state during the early part of the model run (before 2.6 Ma) and a "large" end-member state during the later part of the model run (after 2.6 Ma). Thus, if a short period at the beginning of the model run were chosen, the sensitized ice volume PDF would be unimodal at a "small" state with a long tail to "large" states, and if a short period at the end of the run were chosen, it would be unimodal at a "large" state with a long tail toward "small" states. The important thing is that this behaviour clearly highlights the tendency of the sensitized model to occupy end-member states, and the tendency of the desensitized model to occupy intermediate states. In other words, we think this property of the model ice volume comparison is a feature, not a bug.

- Panels (d) and (e): why did you pick these two time slices that both predate the max time (5 Ma) shown in panel a? Are these (7.68 Ma, 9.42 Ma) even within the modelled time range?

This is a labeling error - they should be in ka (768 and 940 ka) rather than Ma. We apologize for this messy error and will correct it in the revisions.

- Check formatting of 'd18O' in caption *

Fig. 4:

- Panel (a): you state in the caption that "The sensitized model (red) displays larger variation in ice thickness and is more likely to occupy extreme values, whereas the desensitized model (blue) is more likely to occupy intermediate values". To me it looks like the truth of this statement depends on what period you look at. For the last million years for example (most important for cosmogenic nuclides) both curves appear to occupy extreme values most of the time. Between 1-3 Ma, the blue curve seems to stabilize at an intermediate thick stage before thinning again in most glacial cycles, but the transition between stages still appears to be rapid. I wonder how sensitive the distinction between curves in (b) and (c) is to the choice of timescale.

Yes, as described in our response above (regarding Fig 3), these blue/red (desensitized/sensitized) curves are different depending on the timescale. The purpose of this figure is to demonstrate that ice thickness patterns at this site generally follow the same behavior as the continent-wide ice volume curves in Fig 3: ice thicknesses tend to occupy extreme end states in the sensitized model versus intermediate states in the desensitized model. We show the dependence of the ice thickness CDFs for this site on the integration time period later in the manuscript, when we compare them to observational data at this site in Fig. 9 and section 6.3 of the original draft.

- Caption: you refer to grey shading in (b) which is not there. *
- You refer to dashed black line in (b), which is really shown in (c). You appear to have two definitions for this line, see two last sentences. It is not obvious to me what you mean by "modern ice thickness… is chosen to approximately align the range of ice

thickness in the model simulation with that inferred from geologic evidence" (last sentence). How can you choose a modern ice thickness?

This is an important question, and is discussed in detail in lines 386-404 of the original manuscript. We will direct the reader to this discussion section in a revised manuscript.

Fig. 5:

- I expected a brief explanation in the caption of the difference between the top and bottom scenario. I can see that D varies between the two but consider spelling out why these two examples have been chosen.

These examples are intended to provide a visual representation of how we calculate the metric that we introduce in this manuscript (the CDF difference metric 'D'). The upper column denotes a scenario that would result in a higher value of D, and the lower column shows a small D. A revised manuscript will modify the caption with the underlined addition: "Method of quantifying difference between model ice thickness CDFs. Upper panels represent a hypothetical site with large differences between sensitized and desensitized models, and lower panels represent a hypothetical site with similar ice thickness behavior between models. Red and blue curves exemplify output from desensitized (blue) and sensitized (red) ice sheet model runs, displayed as histograms (left) and CDFs (right)."

Fig. 7:

- The green dots represent sites with >1 Ma histories, is that also the case for the blue dots?

Some blue dots denote sites with exposure ages > 1 Ma, but others are representative rather than exact locations, as described in the caption. We propose the underlined addition to this caption in a revised manuscript: "The green dots are locations where cosmogenic-nuclide data from bedrock at interior nunataks indicate exposure histories longer than 1 Ma... The surrounding plots (a-l) display ice thickness CDFs… at selected sites (azure blue dots) where some cosmogenic-nuclide data with ages > 1 Ma exist. The upper and lower Lambert Glacier, Beardmore Glacier, and Byrd Glacier (l) sites are representative rather than exact data locations, because the coarse resolution of the model means that existing exposure age datasets collected adjacent to these glaciers do not fall into the model grid cell corresponding to the glacier location."

- Label for colorbar is missing *

Fig. 8

- What nuclides are these apparent ages calculated from? Apparent ages depend in part on the half-life of the measured nuclide (e.g., 14C vs 21Ne in the same sample could yield wildly different app. ages). Are there any patterns in what nuclides are measured at different elevations/distances from coast? I would guess not but this may be worth addressing if you are mixing ages derived from nuclides with different half-lives.

The apparent ages are computed from a variety of nuclides, mainly ^{10}Be and ^{21}Ne. Although the reviewer is correct in pointing out that only certain nuclides are capable of indicating very old apparent ages, this issue is not a critical element in the figure, because the figure is designed to make a distinction between exposure ages < 50 ka and exposure ages > 1 Ma and this distinction does not correspond with the saturation time of any particular nuclide. The distinction could be equally well observed in ^{3}He, ^{10}Be, ^{21}Ne, or ^{26}Al data. The exception, as pointed out by the reviewer, is that ^{14}C data cannot indicate apparent exposure ages greater than about 30 ka, but ^{14}C data are a small minority (5%) of the Antarctic exposure-age data set. For this reason, we kept the figure as simple as possible by not indicating which nuclide was measured. Certainly this is an interesting data set that is not completely explored by this relatively simple figure, and a more elaborate analysis might give more detailed insight into the geographic patterns of weathering and erosion in Antarctica beyond the first-order observation that surfaces higher and farther from the coast are more stable, but that analysis would be a different paper.

Figs. 9-13

- Would it be worth explaining the double y-axes and specifying what ‘h’ is? *
- The legends vary between the different figures – I suggest you add nuclide name to all (missing in fig. 9 and 12). *
- You state in the paper that “26Al data can provide no information about events prior to ~3 Ma”, so why did you choose to show 26Al/10Be and 26Al/21Ne ratios in the left panels (5 Ma to present)?

We decided to show all the available data in all figures simply so that all the data would always be there for the reader to see, and not cause confusion by conflicting with other publications of the same dataset. Certainly this is an editorial decision, but we think it’s a better approach than selectively editing data in a complicated way.

Fig. 14

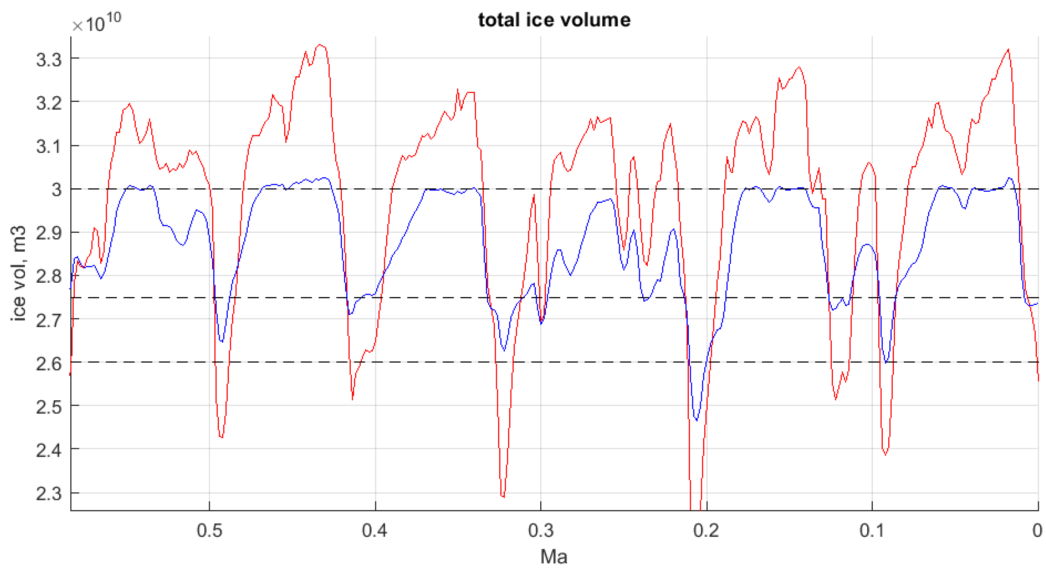
- There is a discrepancy between white and green dots in legend and caption. Legend has white dots as ‘Any age >1 Ma’ whereas caption describes white dots as ‘long-exposed bedrock surfaces are not likely to exist’. Conversely green dots are ‘All ages < 50 ka’ in figure legend, but caption has them as ‘long-exposed bedrock surfaces are likely to exist’ and ‘ages >1 Ma have been observed’. *
- I find it hard to distinguish the white dots on the inset panels, can they be made bigger? *

Manuscript

- l. 52 and 55: Since subglacial data has been gathered in recent years, perhaps state that this type of data is (yet) too sparse rather than saying that ‘it is not possible at the moment’ and ‘In contrast to subglacial basins, it is possible…’. *

- l. 121: patterns in plural *
- l. 213-217: The described difference between the red and blue curve is not representative for the last 1 Ma. For this period, the blue curve also appears to switch abruptly between states, although the endmembers are closer together.

As with Fig. 2, "steep" is relative and the blue (desensitized) curve does indeed switch between states slightly less abruptly than the red curve, when we expand the time axis enough in to see (zooming in to the last few glacial cycles in Fig 3a, which is what this text describes):



Although this detail is important, we feel that it is more important to show the full model run in Fig. 3a, and that the histogram in Fig 3b adequately represents the unimodal behaviour of the blue desensitized curve (tendency towards occupying intermediate values).

As cosmogenic nuclides are increasingly sensitive to the most recent period due to decay (and erosion, although not considered here), I think you should comment on why that is the case and whether it has an impact on your interpretations.

We plan to clarify the text on lines 217-220 regarding the differences in ice behavior through time: "...the desensitized ice sheet is normally distributed (more frequently has an intermediate value) whereas the sensitized ice sheet is bimodally distributed (more frequently occupies extreme maximum or minimum configurations), <u>although the details of this frequency behaviour depend on the time period of interest</u>."

- l. 240-241: You state that 'the desensitized model is more likely to occupy intermediate values near 1200 m'', however, it looks to me like the blue curve spends relatively little time near 1200 m within the last 1-2 Ma.

The original text states: "...the sensitized model is more likely to occupy minimum (ca. 1000 m 240 for this example) or maximum (ca. 1500 m) values, whereas the desensitized model is more likely to occupy intermediate values near 1200 m." The 1200m value is an

average model thickness across the entire desensitized model run; however, a revised manuscript will remove the actual elevation values since this is not necessary to support the point of the sentence, and may confuse readers as evidenced here.

- l. 313: should this only refer to Lower Beardmore (Fig. 7i) since Upper Beardmore fail this criterion? *
- l. 370: Would it be worth also mentioning that the exposed bedrock would need to contain minerals where production rates are well-calibrated for nuclides with half-lives that cover the relevant timescales?

Yes, this is a necessary consideration for moving forward with model/data comparison, but it's mostly not of critical importance -- as a practical matter, there are almost no lithologies outcropping in Antarctica that don't permit measurements of at least a couple of useful nuclides.

- l. 415: Do you need a reference for the ICE-D:Antarctica database according to journal guidelines?

We believe this reference should be acceptable, but will defer this issue to copy editors.

- l. 425-430: consider citing data references in this and the following sections, I see them in the figure captions, but not in the main text. *
- l. 466: specify 40-km resolution model *
- l. 498: change 'there do exist rock outcrops' to 'rock outcrops do exist' *
- The approach in this paper regarding constraining long-term ice-sheet cover based on an elevation transects of cosmogenic nuclides seems comparable to the one in "Jones, R. S., Norton, K. P., Mackintosh, A. N., Anderson, J. T. H., Kubik, P., Vockenhuber, C., ... & McKay, R. (2017). Cosmogenic nuclides constrain surface fluctuations of an East Antarctic outlet glacier since the Pliocene. Earth and Planetary Science Letters, 480, 75-86." Would it be worth a citation?

This is definitely a relevant citation for our approach - this omission will be rectified in a revised manuscript.

- Consider spelling out MPWP since you only use the abbreviation a few times. *