Author response on 'Cosmogenic-nuclide data from Antarctic nunataks can constrain past ice sheet sensitivity to marine ice margin instabilities' by Halberstadt et al.

Here we describe our revisions in response to comments by reviewers. The line numbers refer to the revised manuscript with tracked changes shown.

Reviewer 1

Figure 2: Box in panel (a) is not explained in caption; scale bar is missing; rainbow color scheme is unsuitable.

- The box has been removed, and figure has been corrected
- We have shifted to a colorblind-friendly palette

Figure 3: y-labels for panels (b,c) missing; time slices predate the model start time

- Axis labels have been corrected
- Labeling of the time slices has been corrected

Figure 4: It is unclear how the dashed black line for 'modern ice thickness' is established.

- Fig. 4 caption now refers the reader to Section 6.3 for further discussion on establishing a modern ice thickness

Figure 5: Caption does not describe the difference between the top and bottom scenario

- Caption now includes additional text ("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.")

Figure 7: Label for colorbar is missing; clarification needed regarding the blue dots

- Corrected, and clarification has been added in figure caption

Figures 9-13: Explain double y-axis, specify what 'h' is; add nuclide name to all figures consistently

- Figure captions are now consistent; 'h' is defined in the y-axis label, so it should now be clear (from discussion in Section 2) that 'Cumulative frequency of ice thickness' is an analogous quantity to 'Fraction of time ice-covered', the two y-axes.

Figure 14: Legend and caption are discrepant; white dots should be bigger

- Legend has been fixed to correctly match caption description; white dots adjusted

Clarify that different time periods of interest may exhibit different frequency behavior

- We have added text "...although the details of this frequency behaviour depend on the time period of interest." (L233)

The text states that the desensitized model is more likely to occupy elevations of ~1200m, but Fig. 4 looks like the blue curve spends relatively little time near 1200 m within the last 1-2 Ma

- 1200 m is the average model thickness, but we remove the reference to 1200m in the text to avoid confusion (L255)

Cite the data references for Figs 11 & 12 in main text

- Added (L439)

Consider using Jones et al. (2017) as a reference for the general approach described in this paper

- Added (L84, L95)

The reviewer also made several language suggestions and corrections, all of which have been corrected in the revised manuscript.

Reviewer 2

As described in our Response to Reviewer 2, we primarily address reviewer concerns through three groups of revisions. We also describe our revisions in response to additional specific reviewer concerns, listed below. In addition to these substantive revisions, the reviewer also made several language suggestions and corrections, all of which have been corrected in the revised version.

Revision 1: Clarify our aims and approach

- Additions in italics: “The aim of this paper is to explore how to use geologic data from the Antarctic continent to differentiate between ice sheet model simulations with *end-member instability behaviour* (e.g., Fig. 1b versus 1c). *We aim to elicit the largest possible variation in model ice sheet behaviour in order to test if this difference is resolvable using cosmogenic nuclide data.* We describe end-member simulations as ‘sensitized’ or ‘desensitized’ models based on the idea that stronger positive feedbacks in the form of marine ice instabilities result in model predictions that are more nonlinear, that is, more “sensitive,” with respect to the forcing. Specifically, we investigate the sensitivity of ice sheets *to marine ice cliff instability under stronger and weaker ocean temperature forcing*.” (L42-50)
- Replaced sentence “At these locations, we can compare model predictions to geologic data as a means of gaining insight into whether sensitized or desensitized models are more accurate representations of ice sheet” with “At these locations, we can compare model predictions to geologic data as a means of gaining insight into *past ice sheet behaviour. This methodology therefore can be applied to future ensembles of simulations with more realistic and varied parametrizations to test which model realization most accurately represents the true ice sheet response to warm climate*” (L65-69)
- In abstract: Replace sentence “We identify regions of Antarctica where predicted frequency distributions are diagnostic of marine ice sheet instability parameterizations” with “We identify regions of Antarctica where predicted frequency distributions *reveal*

differences in end-member ice-sheet behaviour"

Revision 2: Properly describe our ocean forcing method as an external forcing rather than an internal nonlinearity

- Clarify that we have mixed our parameterization of nonlinear mechanisms with the amplitude of ocean forcing to elicit the largest possible model response:
    - "Specifically, we investigate the sensitivity of ice sheets to (a) ocean temperatures and (b) *marine ice cliff instability mechanisms under stronger and weaker ocean temperature forcing*." (L48-50)
    - "*To elicit the largest possible difference between these end-member simulations, we further enhance the ice sheet instability mechanisms in the sensitized model with a stronger ocean temperature forcing, whereas the desensitized model experiences weaker ocean forcing.*" (L148-150)
- Ensure that we no longer refer to our varied parameterizations as simply 'marine instabilities'.
    - "The critical difference between sensitized ice sheet models (with strong marine ice margin instabilities *and strong ocean temperature forcing*) and desensitized models (with weak instabilities *and weak ocean forcing*) is the extent of deglaciation of marine basins." (L51-53)
    - "This confirms that our model approach has successfully promoted 'linear' vs.'non-linear' ice-sheet behaviour by varying the parameterized ice sheet sensitivity to marine ice feedbacks *and ocean forcing*." (L239-241)
    - The title is altered to: "Cosmogenic-nuclide data from Antarctic nunataks can constrain past ice sheet instabilities". We realize that this still invokes the presence of instabilities, but we feel that this title still accurately reflects our main point (which is that this methodology can be applied to model simulations to distinguish between instability parameterizations, and this is how we hope that the wider glaciological community will utilize this method in the future).

Revision 3: Provide more detail on the model components and application, input datasets, etc.

- We have added Appendix A (L546-579) to the revised manuscript that includes: (a) description of the long-term forcing scheme we applied here; (b) description of the ocean temperature ramped scaling; (c) explicit citations for input data fields; (d) description of the additional temperature shift added to the Amundsen and Bellingshausen Seas during interglacial time periods in our sensitized simulation; and (e) discussion of the insensitivity of results to model resolution
- This appendix is referenced in the main text on L191-192

<u>Additional specific comments</u>

Could you please elaborate on what you mean by "ambiguous"

- We have removed the word for simplicity (L27)

Maybe a matter of opinion, but I would argue that is the present climate state the one

approaching the peak mPWP states, at least when acknowledging the poor paleorecord, uncertainties, and biases. Perhaps removing this sense of direction altogether?

- We have removed this comparison of modern and mid-Pliocene climate states (L28-29)

This would be a good place to introduce the concepts of ice shelf HF and MICI, after "… ice margins (Fig.1)" and before "Model runs…".

- Added sentence: "Specifically, [these non-linear feedback mechanisms] incorporate meltwater-driven hydrofracture of ice shelves, which can trigger full-thickness calving at the grounding line. Structural failure of exposed ice cliffs can drive rapid grounding-line retreat on a reverse-sloping bed, in a positive feedback loop dubbed 'marine ice cliff instability' (Section 3.1)" (L32-34)

[In places], MICI is mentioned, but not ice shelf HF. Consistency is needed on how you define and utilise these terms throughout the manuscript.

- After introducing these concepts, we refer to the combination of parameterizations (hydrofracturing and cliff retreat) as "marine ice cliff instability" (see L159, L172, L276)

Before such a hypothetical strong implication (L524 in original manuscript) could be trusted, a significant amount of validation would be needed.

- This sentence now reads: "If replicated at multiple sites across the continent, *and under a larger range of model experiments,* this would be an extremely significant result,…" (L540-541)

Figure 1: Needs a way to quantitatively interpret the contours and colormap, including the name of the plotted quantity. Adding the present-day observed grounding line and calving fronts in a distinctive manner, to allow for a quick evaluation of the model's ability to reproduce the present state of the ice sheet, would be useful to the reader as well.

- The caption has been updated to describe the contours (the colormap is redundant) as well as the plotted quantity: "Antarctic ice sheet model simulations with mid-Pliocene boundary conditions… showing ice surface elevation of grounded ice with contour lines at 500 m intervals and ice shelf boundaries as a thick grey line…" The figure has been altered so that subplot (a) shows modern grounding and calving line.

Figure 2: Needs stylistic consistency; black rectangle is unnecessary/inconsistent with panels; panels f and g are counterintuitive in that the linear response shows actually more retreat than the nonlinear one; needs a colorblind-friendly color palette

- Black rectangle is removed
- We now use a colorblind-friendly palette
- The panel with a non-linear (sensitized) response now shows greater advance and retreat than the linear (desensitized) panel

Figure 3: Time slices predate the model start time

- Labeling of the time slices has been corrected