

Authors Final Response to Reviewers

Re: Future Antarctic bed topography and its implications for ice sheet dynamics

We thank both anonymous reviewers for their positive reviews. Constructive comments, particularly by the second reviewer, are carefully considered in the revised manuscript. All technical corrections suggested by both the reviewers are also implemented.

This document summarizes our answer to each of the second reviewer's concerns in a point-by-point fashion. It also explains how we have made necessary amendments in the revised manuscript (find RED texts in the attached document).

S. Adhikari et al.
surendra.adhikari@jpl.nasa.gov
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General comments

As the general comments, the reviewer has raised two major concerns. The first one is related to the treatment of ice/ocean loading in the ISSM/GIA model and its consistency with reference to the grounding line (GL) migration. The second one questions the use of present-day ice thickness for calculation of GIA effect on the ice sheet dynamics. Here we address these two major issues, along with several other comments raised by the reviewer.

1. *On the treatment of ice/ocean loading in the ISSM/GIA model*

We agree that we probably did not describe the “ice load” in a clear manner. Assuming the equilibrium sea level at its present-day value, we define the height of ice load as differential ice height (DIH) with reference to the present-day configuration of the Antarctic Ice Sheet (AIS). We now add a whole new section (Sect. 2.2 Differential ice height) on page 8 (line 5 onwards) to explain how the change in Antarctic ice thickness is translated into the height of ice load. This new section has also been outlined on page 5 (line 27).

We mistakenly included non-zero future DIHs even in the areas occupied by the present-day ice shelves in our previous calculations. Fortunately, however, this only affects the SiCoPollIS model solutions to some extent (Supplement Fig. S5c). As we employ the ensemble approach for computing future GIA solutions (page 13, lines 13–19), the model-average solutions are altered only minimally. Nevertheless, we upgrade all relevant plots both in the main text and the supplementary materials, although all of these figures essentially depict the similar order-of-magnitudes and similar spatial patterns as before. Therefore, no major changes are to be made in the main text; a few changes include: page 13 (line 21) and page 14 (lines 7, 8). It does not affect the Abstract and Conclusions at all, thus illustrating that the upgraded results do not alter the overall story of the paper.

Amendments are made on page 12 (lines 17–21) where we describe how future DIHs are computed; associated figures (Supplement Fig. S3) are updated. Now notice in the figure that there is mostly zero DIHs around the ice shelves.

To clarify the fact that GIA solutions are computed at the lithosphere surface (ice/bed and ocean/bed interface) within the present-day outline of AIS, but it perturbs the ice sheet only within the area of grounded ice, we amend on page 7 (lines 10–13).

2. *Why do we use present-day ice thickness in all calculations of Section 4?*

As stated in the beginning of Sect. 4 (from page 17 line 17 to page 18 line 7), the major objective of all the calculations presented there is to evaluate the “potential effect” of the predicted bed uplift, not the predictions of the total GIA effect, on the future dynamics of the AIS. Toward this objective, we need to isolate the rock bed motion GIA effect as cleanly as possible. In order to minimize the potential compounding effects on the ice sheet dynamics, we therefore keep the present-day settings (particularly, ice thickness and thermo-mechanical boundary conditions) fixed for these calculations.

3. *On GIA account in SeaRISE participating models*

While the SeaRISE experiments employed state-of-the-art numerical treatments of ice flow, it should be noted that the majority of these models were not coupled to the comprehensive solid Earth model. Furthermore, the SeaRISE experiments do not capture the paleo-evolution of the AIS since the LGM, thus limiting the possibility for the participating ice sheet models (with GIA capability) to perform similar analysis presented in this study. This is now mentioned on page 6 (lines 17–19).

4. *On possible overestimation of EAIS uplift*

It is true that our predictions might slightly overestimate the GIA solutions in the EAIS, as the modeled lithosphere thickness (i.e., 65 km) is much thinner than more common value (115 km, as reported in Sect. 2.3). Nevertheless, the general findings that – Amery Ice Shelf may rise moderately, the interior of the EAIS may remain mostly unperturbed, and minor subsidence may occur along the coastal EAIS – should remain unaltered. This is now mentioned on page 14 (lines 22–27).

5. *On use of the terminology - 'first-order'*

We now drop this term (e.g., page 6, line 12), or replace it by the suitable word (e.g., page 13, line 15), both in the main text and the Supplementary Materials.

Specific comments

1. *Section 2.1: The label ISSM/GIA somehow implies that the ice sheet model is capable of GIA modeling. If I understand it correctly, the current mutuality of ISSM and ISSM/GIA is the mesh on which they operate. If this is correct, I suggest to put more emphasis on this circumstance in the Introduction and when introducing ISSM/GIA in Section 2.1. Additionally, I suggest, that the authors include a figure in the supplement (for example, in the context of Fig S1a and b) that shows how the discs are situated in the ISSM mesh and how by that the ISSM resolution directly affects the GIA resolution and accuracy.*

We are working toward the full dynamic coupling of ice sheet and solid Earth models. Although presently these models' mutuality, rightly noted by the reviewer, is the mesh on which they operate, ISSM will soon be capable of solving for both the ice sheet dynamics and solid Earth deformation altogether. For the sake of future reference, we therefore want to label our model ISSM/GIA to imply the GIA capability of ISSM. No amendments are made in the revised manuscript in this regard.

2. *Section 2.3: From Bindshadler et al. (2013), I understand, that the described scenario is labeled as 'R8'. Please refer to that label during the description.*

Agree. We now define R8 scenario on page 11 (line 9) and use it consistently both in the main text (e.g., page 11, line 13) and the Supplementary Materials (e.g., page 1, line 12).

3. *P200 L13 / Fig 2: How have the GPS stations and their data been chosen from the set of Thomas et al. (2011)? The authors of the respective study offer viscoelastic uplift*

1 *rates at many more sites. How are the misfits in case of higher/lower values for mantle*
2 *viscosity? Please consider to include respective data in Fig 2b.*

3 It is true that a comprehensive list of GPS data is provided by Thomas et al. (2011).
4 Following Ivins et al. (2013), we however use 18 high-precision data to tune our model.
5 These 18 data are selected as follows. We first eliminate records from the Antarctic
6 Peninsula north of 72° S due to the associated difficulty of dealing with large elastic and
7 transitional viscoelastic signals present there. We then average the values from stations
8 located within 100 km of one another and eliminate some stations with reported errors
9 greater than the signal amplitude. This is all explained in Ivins et al. (2013); we
10 summarize it on page 9 (lines 12–17).

11 As mentioned on page 10 (line 22–24), the mantle viscosity is optimized by minimizing
12 the chosen cost function. For other values of mantle viscosity (higher/lower), the fit is
13 obviously rather weak. So, no amendment is made in the manuscript in this regard.

14 For the reason explained in the first paragraph, we opt not to include other additional
15 data provided by Thomas et al. (2011) in Fig. 2b.

- 16 4. *P200 L19: Please name the values for upper and lower mantle viscosity that have been*
17 *found optimal by Ivins et al (2013) in case of the 65 km lithosphere.*

18 These are now reported on page 11 (lines 1, 2).

- 19 5. *P203 L13-P204 L03: It would be interesting to relate the numbers for uplift/subsidence*
20 *with some average value of DIH in the respective regions.*

21 Agreed, but we leave this important comparison for future when we run the coupled
22 simulation of the ice sheet dynamics and solid Earth deformation. Due to the employed
23 ensemble approach (i.e., use of four ice sheet model results for defining future DIHs),
24 we are reluctant to confidently report the accurate magnitude of uplift rate in basin-
25 or regional-scales. As clearly mentioned on page 13 (lines 14–19), however, our study
26 should provide the correct order-of-magnitude estimates and the likely spatial patterns
27 of the future bed uplift. Note that our Abstract (page 2, lines 9–12) and Conclusions
28 (page 23, lines 20–25) are also consistent in this regard. So, no amendment is made in
29 the revised manuscript.

- 30 6. *P205 L18: ... by perturbing the steady-state response of solid Earth to present-day*
31 *AIS loading through imposition of the future ice load changes. I think, this is unnec-*
32 *essarily complicated. Please consider re-formulation with a focus on the difference to*
33 *the previous experiments that included past loading or were restricted to past loading.*
34 *For example, the description of the experiment with only past loading is much more*
35 *straightforward: ... thus imposing $\Delta h(x, y, t) = 0$ for all $t \in [0, 500]$ (P205 L08).*

36 OK, we rephrase it. See page 15, lines 24–25.

- 37 7. *P207 L10-12: I do not think that changing slopes beneath floating ice at some distance*
38 *from the GL will have an impact on GL migration.*

39 Agreed that changing slopes beneath the floating ice at “some distance” from the GL
40 may not have an impact on GL migration. But in the present context where GL

advances by tens of kilometres, change in bed slopes “around” the GL beneath the ice shelf should affect the magnitude of GL migration. We rephrase the sentence on page 17 (lines 13–15).

8. *P207 L22-23: What are these relevant boundary conditions?*

While calculating ice surface velocities, for example, we update basal boundary condition (basal friction) in the areas previously floating that become grounded due to the GIA effect. We provide this example on page 17 (lines 25–26).

9. *P208 L09-10: It would become very clear how bedrock slopes alter the driving stress, if α_{si} was expressed as the sum of ice thickness gradient and bedrock slope.*

True; excellent point. We rewrite lines 13–17 on page 18.

10. *P208 L13-15: Although the maximum changes in driving stress are about three orders of magnitude smaller than the driving stress itself, large changes are predicted at positions of larger bed uplift. I do not see how the first part of the sentence relates to the second one. Please re-formulate.*

OK. We reformulate the sentence on page 18 (line 20).

11. *P210 L02: 2800 flowlines: Would it be possible to include at least some of them in a figure?*

Sure. We however decide to keep it in the Supplementary Materials as Fig. S8. This figure has been cited in the main text on page 20 (line 5). We also add a sentence on page 1 of Supplementary Materials (lines 18–19) to introduce this figure.

12. *P210 L12-25: Extensive observation of the GL advance ... Observation makes the reader think of a sudden switch to actual remote sensing data or something similar. Also, I find the expression reverse topography confusing. Please consider re-formulation. I can see no evidence of GL migration in the Shackleton Ice Shelf in Fig. 7a and only minimal evidence in the Getz Ice Shelf. In general, a zoom to the respective parts in Fig 5a and c would help the reader to follow the discussion.*

12.1 “observation”: This sentence is reformulated on page 20 (line 14).

12.2 “reverse slope”: We now use “reverse bedslope topography” (not “reverse topography”), which is common terminology in glaciology (e.g., Ross et al., 2011, Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica, *Nature Geoscience*), consistently. See, for example, page 20 (lines 15–16).

12.3 “Zoom-in of figures”: Now provided as Fig. 7b (page 36) and cited in the main text on page 19 (line 26) to page 20 (line 1).

13. *Fig. 4: Just a suggestion: Wouldnt it be more intuitive for the message (small effect of past load; large effect of future load) to exchange Fig S7 and Fig 4 in terms of the colorscaling. Then the small response to past loads would be obvious from the very first glimpse.*

1 Agreed. We now use the same color scale in Fig. 4 to facilitate easy comparison between
2 the past and future ice loading. Necessary amendments are made in the figure caption
3 (page 33). As for Supplement Fig. S7, we use different color scales to better illustrate
4 the spatial distribution. Necessary amendments are made in the figure caption.

- 5 14. *Time conventions: I suggest to make the convention for temporal reference more uni-*
6 *form in the main text and in the Figures (omission of AD in several figures; varying*
7 *reference to $t = 0$ and to years AD).*

8 On page 9 (lines 1–2), we state the general time convention that $t < 0$ is used to denote
9 the past and $t > 0$ for future. However, for results that are actually the “predictions”
10 (e.g., bed uplift) are presented in “AD”. This is clarified at the beginning of Sect.
11 3 (page 13, lines 3–4). Results discussed in Sect. 4, which are actually NOT the
12 “predictions”, are again presented in general time convention. This is noted at the
13 beginning of Sect. 4 (page 18, lines 5–7).

14 **Technical corrections**

15 Only those that need some explanation are listed here. Rest are implemented as advised.

- 16 1. *P192 L24: I think it is worth writing Antarctic Ice Sheet once in the main text; same*
17 *for grounding line on P193 L05.*

18 We opt to redefine all abbreviations again in the main text. See, for example, page 2
19 (line 22) and page 6 (lines 6–7).

- 20 2. *P205 L17: Cancel 'model'? Or exchange 'model' and 'average'?*

21 We define “model-average solution” on page 13 (lines 14–15) to imply that the solution
22 is the average of model solutions. Necessary amendments are made both in the main
23 text (e.g., page 14, line 4) and the Supplementary Materials (e.g., page 1, line 14).

- 24 3. *P208 L23: 'but in out of phase': Cancel 'in', or rather re-formulate without using*
25 *'phase' as the issue is only about positive and negative signs.*

26 We reformulate the sentence (page 18, line 27).