

Answer to EGU sphere-2026-2640-CC1

We thank Dr. Han for her careful and constructive comments, which includes helpful suggestions for rephrasing, and additional references. Below, the comments are reproduced in blue and our answers follow in black.

The manuscript presents a useful and timely benchmark of FastIsostasy against a full 3-D GIA model. The results convincingly demonstrate that FastIsostasy closely reproduces the response of the full model while remaining computationally efficient. Providing FastIsostasy as a publicly available tool capable of representing realistic 3-D Earth structure in a computationally inexpensive framework is a significant contribution that lowers the barrier for incorporating GIA feedbacks into ice-sheet models.

We thank Dr. Han for her positive feedback on the potential impact of the paper.

While the study is comprehensive and scientifically valuable, the abstract, introduction and discussion of the manuscript emphasize the need for capturing 3D GIA in the context of centennial scale projection of Antarctic Ice Sheet contribution to sea level (e.g., ISMIP7), while emphasizing the advantages of representing continental-scale 3-D Earth structure over simplified Earth models such as ELRA, ELVA and 1-D GIA. However, demonstrating that a physical process is represented more realistically is fundamentally different from demonstrating that the added realism materially changes the quantities for which Antarctic projection models are ultimately used, and the current manuscript does not establish the latter in a broader sense.

In particular, the manuscript could be improved by distinguishing the following three related, but distinct, statements:

1. 3-D Earth models provide the most physically realistic representation of solid-Earth and sea-level feedbacks.
2. Continental-scale 3-D Earth structure can greatly influence Antarctic ice-sheet evolution under certain retreat geometries.
3. Representing continental-scale 3-D Earth structure materially changes projected Antarctic ice-sheet contributions to sea level over centennial timescales.

We agree that the distinction between these three statements is important, and we state our position on each explicitly in the following. Statements (1) and (2) are established in the existing literature (e.g. Gomez et al., 2018, 2024; Coulon et al., 2021; van Calcar et al., 2025); the present manuscript is not intended to provide further evidence for them. Statement (3) we do not claim as a general result, and we agree that our experiments do not establish it across the full range of retreat geometries relevant to centennial projections. Our claim is narrower: where retreat occurs across regions of contrasting Earth structure, FastIsostasy reproduces the 3-D GIA response at a small fraction of the computational cost of a full 3-D GIA model, and such retreat patterns cannot be excluded from the scenarios ISMIP7 will consider. We will make this distinction explicit in the abstract, introduction and discussion, and the answers below detail how.

The experiments mainly presented in this manuscript are designed to examine a scenario in which substantial retreat occurs across both West and East Antarctica over a 500-year simulation period under RCP8.5 scenario with Marine Ice-Cliff Instability (MICI). Under these conditions, it is scientifically

important and expected that lateral variations in Earth structure exert a strong regional influence on Antarctic ice-sheet evolution. The manuscript therefore provides convincing evidence for Statement (2).

However, the broader applicability of these conclusions to the range of scenarios typically considered within ISMIP6/7 is less clear. It is worth noting that ISMIP6/7 extend through until 2300, and most of the Tier 1 experiments conducted in ISMIP6 – even under the most aggressive RCP8.5 and SSP5- 8.5 scenarios – have shown ice mass loss largely limited to West Antarctica (Seroussi et al., 2024).

We agree with Dr. Han along the following line: laterally variable Earth structure is generally important, but choosing a homogeneous viscosity value for a 1-D GIA or an ELRA model can give results that are similar enough to those of a 3-D GIA model, if the retreat is limited in its extent (e.g. only in the Amundsen Sea Embayment), as was shown by Han et al. (2025), which we will include as an important reference for our discussion, and by van Calcar et al. (2026). We agree that highlighting year 2500 might overstate the importance of our results, and we will add further discussion of results at year 2300 in the revised manuscript. As shown by Fig. 4, this does not change the overall picture: FastIsostasy consistently yields lower error metrics compared to ELRA, even at year 2300 (error in mean ice thickness using the weak Earth model: FastIsostasy ~10 m, ELRA500 ~30 m, ELRA3000 ~40 m; error in mean ice thickness using the strong Earth model: FastIsostasy ~10 m, ELRA500 ~20 m, ELRA3000 ~35 m). We will make this clearer.

Even though the manuscript makes a conditional statement as to when 3-D GIA is needed (e.g., “laterally-constant Earth structure is not well-suited for AIS projections if retreat occurs in both West and East Antarctica”; L333) and stresses that “the aim of this work is not to provide estimates of future sea level rise but rather to demonstrate that FastIsostasy can accurately approximate the 3-D GIA response, even under extreme ice loss scenarios...” (L357), it repeatedly motivates and discusses the implications of this work in the broader context of future Antarctic projection efforts (ISMIP7). In that context, the manuscript naturally leads readers to interpret the results as evidence for the practical importance of representing continental-scale 3D Earth structure in centennial Antarctic projections.

We agree that the manuscript motivates its results in the context of ISMIP7, and we consider this framing appropriate: the ISMIP7 protocol explicitly includes a set of experiments dedicated to representing GIA in ice sheet models. Furthermore, ISMIP7 does not focus solely on ice sheet projections but also aims to advance model development and intercomparison, making it timely to introduce FastIsostasy as an option for improving the representation of GIA in ice sheet models. Our purpose in invoking ISMIP7 is not to claim that capturing continental-scale 3-D Earth structure will be critically important in centennial Antarctic projections but, instead, to make a computationally tractable representation of the 3-D GIA response available to the groups that will run those experiments.

While the introduction broadly motivates the need for continental-scale 3D Earth structure in Antarctic projection studies, the discussion ultimately recognizes that the importance of 3D Earth structure depends on the location of ice retreat and the underlying mantle viscosity.

In this context, it would also be valuable to discuss previous work examining the sensitivity of Antarctic projections to Earth structure. For example, Han et al. (2025) investigated Antarctic Ice Sheet projections using a coupled ice-sheet–1-D GIA framework under the ISMIP6 Antarctica-2300 protocol experiments (Seroussi et al., 2024). Although that study did not explicitly incorporate laterally varying Earth structure, it explored sensitivity to contrasting Earth structures representative of the mantle

structures beneath West and East Antarctica. Across the Tier-1 ISMIP6 Antarctica-2300, the largest projection sensitivity occurred in the Amundsen Sea Embayment, where most projected retreat remained concentrated through 2300. These results further suggest that comparing the effects of 3-D GIA with those of a 1-D GIA model based on a global- or Antarctic-wide average mantle viscosity can overemphasize the importance of lateral Earth structure when projected ice retreat remains largely confined to West Antarctica.

Dr. Han highlights the importance of the pattern of ice retreat for assessing the relevance of 3-D Earth structure. Along those lines, it should be noted that:

- For high-emission scenarios at year 2300, Seroussi et al. (2024) simulate a retreat over most of West Antarctica, which shows a substantial intraregional lateral variability of solid-Earth parameters (Fig. 1 and S1 of our manuscript). This pattern of retreat is very close to what we obtain for year 2500 under RCP8.5 and excluding the possibility of MICI (Fig. S6.c). In this case, the error in ice thickness is negligible when using FastIsostasy (Fig. S6.f) and much higher when using ELRA models (Fig. S6.j & l).
We note that the retreat pattern simulated at 2500 under RCP8.5-MISI is reached after a longer loading history than the corresponding ISMIP6 pattern at 2300, so the comparison should be read as indicative of the spatial distribution of unloading rather than as an equivalence of the GIA state itself.
- For high-emission scenarios at year 2300, Seroussi et al. (2024) also show the onset of a Wilkes Basin retreat, which is characterised by a solid Earth structure that is distinct from West Antarctica and, therefore, cannot be comprehensively modelled with a homogeneous viscosity value calibrated for West Antarctica. Although smaller in surface area than its WAIS counterpart, this retreat represents a large sea-level contribution due to the large ice thickness and associated volume above flotation in this region.
- Processes like damage (Lhermitte et al., 2020; Blasco et al., 2026), ice shelf collapse due to hydrofracturing (Scambos et al., 2000 and 2004; Lai et al., 2020), realistic subglacial hydrology (Kazmierczak et al., 2022 and 2024), regime shifts in ocean cavity circulation (Mathiot and Jourdain, 2023), climate variability (Moreno-Parada et al., in rev.; Blasco et al., in rev.), and tidal water intrusion beyond the grounding line (Robel et al., 2022; Juarez-Martinez et al., in rev.) are still largely underrepresented in ice-sheet models and could drive a larger retreat than what was simulated in ISMIP6.
- Independent of model-based projections, geological evidence indicates that marine-based sectors of East Antarctica have retreated during past warm periods. Uranium isotopes in subglacial precipitates from the Wilkes Basin record ice loss during MIS 11, around 400 ka (Blackburn et al., 2020), and combined ice-core, sedimentological and modelling evidence point to an extensive retreat of the Wilkes Subglacial Basin around 330 ka and a more limited one around 125 ka (Crotti et al., 2022). Reviewing this evidence alongside present-day observations, Stokes et al. (2022) conclude that high-emission scenarios beyond 2100 could generate several metres of sea-level contribution from the East Antarctic Ice Sheet within a few centuries. Retreat patterns extending beyond West Antarctica therefore cannot be excluded from the range of behaviours that ISMIP7 models may exhibit.

We acknowledge that this was not discussed in the manuscript and will include it in the revised version, which will state our message more clearly: *The pattern of retreat dictates the importance of using GIA models that can represent lateral variability for the multi-century projection timelines considered here. Using an ELRA or 1-D GIA model is a sufficiently good approximation for cases of limited retreat within*

the ISMIP experiments, whereas experiments producing extensive retreat across regions of contrasting Earth structure require a model that resolves such variability. In addition, we will refer to Han et al. (2025).

Additionally, in the original manuscript, we already state in a number of places that RCP8.5 including MICI does not aim to produce a sea-level projection but rather to serve as the most demanding test when it comes to accurately representing the GIA response. Figs. 5 & 6 demonstrate that FastIsostasy provides an accurate approximation of the GIA response of a 3-D model.

Taken together, Han et al. (2025) and the present study provide complementary evidence that the importance of continental-scale Earth structure depends strongly on retreat geometry, projection scenario, and the projection quantity being considered. Accordingly, I believe the criticism of van Calcar et al. (2026) and Adhikari et al. (2025) in L322–341 would benefit from additional context. The criticism implicitly extends the present results from Statement (2) to Statement (3), whereas the broader applicability of these conclusions across the range of retreat behaviors relevant to Antarctic projection studies is not clearly established or discussed.

The discussion (l. 323-334) of using Green's function (Adhikari et al., in rev.) or 1-D GIA models (van Calcar et al., 2026) is not written or intended as a criticism. It simply points out the limits of the applicability and usability of these approaches as compared to FastIsostasy.

A second, independent consideration concerns the projection quantities analyzed. The analysis in the current manuscript is focused on quantities directly related to local changes in Antarctic Ice Sheet, such as ice thickness at grounding lines, grounded ice areas, relative sea level (RSL) in the ice model domain defined as the height difference between geoid and bedrock. While local quantities analyzed in this study are appropriate metrics for the purpose of model benchmark between FastIsostasy and full 3-D GIA model, and they show big differences between the simple Earth model cases and the 3-D GIA model cases, it is less clear how these local differences translate into differences in the quantities that motivate many Antarctic projection efforts, namely Antarctic ice- sheet contribution to global and regional sea level. Local ice-dynamic sensitivity and integrated sea-level sensitivity are not necessarily equivalent, and I believe this distinction deserves greater emphasis throughout the manuscript.

We will include the sea-level contribution in Fig. 4.

In summary, the present manuscript convincingly demonstrates that FastIsostasy reproduces 3-D solid Earth deformation captured by full 3-D GIA model. The experimental design and analyses also establish that 3-D Earth structure can matter under the particular retreat geometry considered here.

The manuscript appropriately concludes that laterally uniform Earth models become less suitable if retreat occurs in both West and East Antarctica. However, because this conditional statement forms an important part of the motivation for future Antarctic projection efforts such as ISMIP7, I encourage the authors to more explicitly discuss how the importance of continental-scale 3-D Earth structure varies across the range of retreat scenarios considered in the manuscript, and how those scenarios relate to the ISMIP7 core experiments. More broadly, the manuscript would be strengthened by more clearly distinguishing the three statements outlined above and, ultimately, by distinguishing improvements in process representation from improvements in projection outcomes.

We thank again Dr. Han for her comments and believe that the rephrasing outlined above will address them.

Specific locations for recommended refinement

1. L5-6: This statement asserts a universal requirement for "accuracy." Consider qualifying this by noting that the necessity of this coupling depends on the spatial scale of retreat and the degree of rheological heterogeneity in the affected basins.

We agree that this statement would benefit from a conditional form: If ice thinning occurs over regions with laterally varying Earth structure, accurately capturing changes in bedrock and sea-surface elevation then requires a GIA model that resolves this variability.

2. L39: While true, the discussion could more clearly acknowledge that for many Tier-1 ISMIP experiments, these approximations remain a robust and "fit-for-purpose" approach, particularly when uncertainties in climate forcing and ice-sheet initialization dominate the error budget.

We will add a sentence acknowledging that ELRA/ELVA-type approximations remain a reasonable approximation for some applications, especially where ice sheet retreat is confined to specific regions.

3. L52: This sentence exemplifies the tendency to frame 3D-GIA as the singular "best" choice. I suggest replacing "best option" with "highest-fidelity" or "most physically comprehensive" option.

We will replace "best option" with "most physically comprehensive representation," per the suggested wording.

4. L333-334: This is a vital conditional statement. It would be good to elevate the importance of this caveat throughout the manuscript to ensure readers understand that the "need" for 3D GIA is a function of the retreat geometry rather than an inherent failure of simpler models.

As stated above, we will do this while stressing that West Antarctica does have substantial lateral variability in solid Earth structure.

5. L322-344: The current tone implies that these 1D-based approaches are largely inadequate. It would be useful to have a more balanced discussion—perhaps by discussing Han et al.'s work—that acknowledges how such models can capture first-order sensitivities. Framing FastIsostasy as a high-fidelity alternative—rather than implying 3D GIA is the only viable path forward—would provide a more nuanced perspective. Furthermore, it is important to acknowledge that global integrated quantities (such as global mean sea level) may exhibit different sensitivities to Earth structure than the local quantities (grounding line position, local ice thickness) analyzed in this manuscript. Distinguishing between local ice-dynamic sensitivity and integrated sea-level sensitivity would provide the reader with a more complete understanding of when the overhead of 3D complexity is truly justified by the projection objective.

We emphasize that we do not state anywhere that 3-D GIA is the only viable path forward in all applications. In the line of our answers above however, we will add the sea-level contribution to Fig. 4, which directly addresses the distinction between local and integrated sensitivity.

References:

- Lai et al. (2020). Vulnerability of Antarctica's ice shelves to meltwater-driven fracture. *Nature*.
- Kazmierczak et al. (2022). Subglacial hydrology modulates basal sliding response of the Antarctic ice sheet to climate forcing. *The Cryosphere*.
- Kazmierczak et al. (2024). A fast and simplified subglacial hydrological model for the Antarctic Ice Sheet and outlet glaciers. *The Cryosphere*.
- Blackburn et al. (2020). Ice retreat in Wilkes Basin of East Antarctica during a warm interglacial. *Nature*.
- Crotti et al. (2022). Wilkes Subglacial Basin ice sheet response to Southern Ocean warming during late Pleistocene interglacials. *Nature Communications*.
- Stokes et al. (2022). Response of the East Antarctic Ice Sheet to past and future climate change. *Nature*.
- Lhermitte et al. (2020). Damage accelerates ice shelf instability and mass loss in Amundsen Sea Embayment. *PNAS*.
- Scambos et al. (2000). The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *Journal of Glaciology*.
- Scambos et al. (2004). Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophysical Research Letters*.
- Mathiot and Jourdain (2023). Southern Ocean warming and Antarctic ice shelf melting in conditions plausible by late 23rd century in a high-end scenario. *Ocean Science*.
- Robel et al. (2022). Layered seawater intrusion and melt under grounded ice. *The Cryosphere*.
- Blasco et al. (2026). Fracture-driven weakening amplifies projected ice loss from West Antarctica. *PNAS*.
- Blasco et al. (in rev.). Climate variability eases West-Antarctic Ice Sheet collapse and opens new retreat paths. [Preprint](#).
- Moreno-Parada et al. (in rev.). Climate variability accelerates Thwaites Glacier collapse. [Preprint](#).
- Juarez-Martinez et al (in rev.). Parameterizing tidal-water intrusions in long-term Antarctic ice-sheet projections. [Preprint](#).