We would like to thank the reviewer for their comments, suggestions, and feedback. This response aims to address any comments raised by the reviewer. Our responses are embedded below and are shown in orange. Sections of text taken from the manuscript are shown in quotation marks “” while revisions/additions within these sections are underlined.

Response to referree comments #2

This study presents an ensemble of coupled ice sheet–2D Glacial Isostatic Adjustment (GIA) simulations applied to the Antarctic Ice Sheet over the last two glacial cycles. The authors conducted 9,293 simulations and employs history matching techniques using Markov Chain Monte Carlo (MCMC) sampling and Bayesian Artificial Neural Networks (BANNs) to efficiently explore parameter space and refine model estimates. They selected a sub-ensemble of 82 simulations that best align with the bounds of past and present GIA and relative sea-level (RSL) observations. The selected sub-ensemble aims to provide improved constraints on past and present ice sheet evolution and the associated GIA response, contributing valuable insights into uncertainties in Antarctic mass balance assessments. The results indicate that the uncertainty in present-day GIA is greater than previously estimated by IJ05_R2 (Ivins and James, 2005), W12a (Whitehouse et al., 2012b), and ICE-6G_D (Peltier et al., 2015), particularly in the Amundsen Sea Embayment.

General Remarks

This study holds significant value for the scientific community. The analysis is well executed, and the figures are effectively presented. However, the methodology section is too concise and the section often refers to manuscripts in preparation and a preprint. Therefore, additional methodological details should be described within this manuscript. The interpretation of specific areas requiring additional explanation are outlined in the detailed comments below.

This manuscript is already lengthy and builds on part 1, hence why we rely on citations and opted to exclude an exhaustive model description and data scoring methodology section. The first part of this study is published and includes an abbreviateddescription of the history matching scoring and sigma thresholds in the methodology section (https://doi.org/10.5194/tc-19-919-2025). There are a variety of approaches to data-model scoring (e.g. Briggs et al., 2013; Ely et al., 2019) and the one applied in this study is broadly described in Tarasov & Goldstein (2019) (https://doi.org/10.5194/cp-2021-145). We are fine to have this paper not accepted until the history-matching methodology egusphere preprint becomes publicly available. Moreover, the GSM description paper is now available (https://doi.org/10.5194/gmd-2024-175). For these reasons, a mention in the introduction now explicitly states:

“<u>This study is the second part of a two-part study, and should be considered in conjunction with part one for a complete understanding of the research (Lecavalier and Tarasov, 2025).</u>”

The sensitivity test often cited to explain differences between the model ensemble and the dataset examines the effect of lateral Earth structure. However, using 2D structures with a relatively low mantle viscosity results in significantly different ice sheet evolution, bedrock uplift and sea level change than using 3D Earth structures (Gomez et al., 2018; van Calcar et al., 2023). Additionally, the test employs an uncoupled GIA model, where lower viscosity affects ice sheet dynamics differently than in a coupled model, as the stabilizing GIA effect is absent. This likely leads to an overestimation of uplift between 15 and 5 ka due to stronger ice mass loss in the uncoupled model compared to a coupled model. Since the test does not fully assess the impact of lateral structure in the original coupled model ensemble but rather the effect of globally lower viscosity in an uncoupled model, its limitations should be acknowledged. While coupled 3D GIA–ice sheet simulations are not expected, the methods section should clarify these constraints, and the results should discuss potential uplift overestimation and its implications.

These limitations are explicitly stated in section 3 and 4 for the simulations that are part of the sensitivity analysis.

"The ice load chronologies from the 18 members of the NROY sub-ensemble HVSS were subject to repeated GIA post-processing over a range of Earth models. This involved applying each individual ice load chronology in the HVSS as input to the gravitationally self-consistent sea level solver using alternate Earth models. Specifically, the lithospheric thickness and upper mantle viscosity was progressively decreased from 146 km and $5\cdot10^{21}$ Pa·s to 46 km and $5\cdot10^{18}$ Pa·s (146, 120, 96, 71, to 46 km; $5\cdot10^{21}$, $5\cdot10^{20}$, $5\cdot10^{19}$, to $5\cdot10^{18}$ Pa·s), respectively, to evaluate the impact of an anomalously low upper mantle viscosity on isostasy (Fig. S1 and S2). This experimental design isolates the Earth model sensitivity at the cost of lost dynamical self-consistency between the ice history and Earth model."

"To better address this question will require a more involved specification of the structural uncertainty attributed to lateral Earth structure and/or a history matching analysis with a coupled 3D GIA Earth model. Moreover, the upper mantle viscosity sensitivity analysis shows that regions with a low viscosity zone can exhibit significant sensitivity to recent loading or unloading. Additionally, the sensitivity analysis does not consider coupled GIA feedbacks with these anomalously low upper mantle viscosities. Even though the NROY sub-ensemble is consistent with the entire AntICE2 database and represents a wide range of ice loading chronologies, 3D Earth GIA models could produce responses to ice loading that are not bracketed by the NROY sub-ensemble due to GIA feedbacks caused by lateral Earth structure. Thus, the NROY sub-ensemble GIA predictions likely underestimate the uplift and geoid rate bounds in specific regions with anomalous viscosity structure."

The history-matching analysis does perform a joint history matching of the AIS using an asynchronously coupled ice sheet and GIA model which results in a wide range of chronologies that are broadly consistent with the AntICE2 database. However, the sensitivity analysis is used as a secondary evaluation of remaining outstanding data-model discrepancies to assess the impact of a low viscosity lateral structure. Even though the simulations in the sensitivity analysis are not coupled, the ice load history being tested represent a wide range of loading scenarios.

A range of loading scenarios was applied in the sensitivity analysis to hopefully bracket the magnitude and timing of loading changes that would be represented by the GIA feedbacks in a fully coupled ice sheet and 3D Earth model. We recognize that the sensitivity analysis has limitations as stated in the text and the simulations aren't intended the reproduce the 3D Earth model GIA feedbacks but it represents an important evaluation that attempts to isolate the impact of lateral structure on remaining data-model misfits. Three sentences were added (see above edits) to emphasize the lack of GIA feedback that might produce loading changes that are not bracketed by the full ensemble.

Last, the conclusion now consist of a short summary of what has been done and of recommendations for future work. This section would be improved by including more detail on the performance of the NROY subset and the 2sigma subset. Conclude which subset performs best in which region and the corresponding uncertainty ranges.

This is quite nuanced because the NROY sub-ensemble of simulations was approximately history matched against the entire AntICE2 database. Therefore, a given simulation can misfit paleoRSL data but achieve a good fit to paleoExt data. There are direct trade-offs when maximizing fits to only one data type over another. It is not as simple as stating the full ensemble has outstanding data-model misfits in a given region since typically it achieves a decent fit to several data types with the exception of some data. It is best framed in terms of the model limitations that might manifest in outstanding discrepancies rather than identifying regions where the NROY sub-ensemble struggles with a subset of data. For these reasons, this discussion is best left to section 4 results. Text was added to the conclusion to specify which model limitations are generally attributed to the remaining outstanding discrepancies and which regions are most impacted.

"The full ensemble of simulations broadly brackets the AntICE2 database with a few outstanding data-model discrepancies likely attributed to model resolution limitations, insufficiently climate forcing degrees of freedom for certain sectors, and insufficient accounting for uncertainties in the basal environment. In particular, this manifest in a few outstanding data-model discrepancies in regions with inadequately resolved complex topography such as the Transantarctic Mountains or regions with many subgrid pinning points that can help stabilize an ice shelf and grounding line."

Line-by-Line Comments

L123: The expanded climate forcing scenarios are known to be of high influence on the ice sheet model and is later in this manuscript mentioned as an important source of uncertainty. It would therefore be useful mention which expanded climate forcing scenarios have been applied.

This study aims to focus on Antarctic GIA and opted to instead cite the GSM description paper which offers a more comprehensive description (Section 2.10 of Tarasov et al., 2025; https://doi.org/10.5194/gmd-2024-175). Additions to the text were made to address this comment:

"From the total 38 ensemble parameters, 10 are associated with ice dynamics (ice deformation, basal sliding), 11 with ice-ocean interactions (calving, sub-ice-shelf melt), 14 with ice-atmosphere interactions (atmospheric climate forcing), 3 with ice-solid Earth interactions (solid Earth rheology) and shown in Table 1 of Lecavalier and Tarasov (2025). Some of these ensemble parameters are applied to blend climate forcing schemes (parameterized PD climatologies, glacial index PMIP3 LGM climatologies, coupled energy balance climate model) to explore a wide range of plausible climate histories (Lecavalier and Tarasov, 2025; Tarasov et al., 2025)."

L126-128: Please explain how the PREM density structure is applied to the layers of in the model.

The Preliminary Reference Earth Model density structure defines the radial elastic structure. This is standard practice for 1D GIA models with spherically symmetry earth rheology. The text was expanded as follows:

"The Earth model rheology has a standard Preliminary Reference Earth Model (PREM) density structure (Dziewonski and Anderson, 1981) which defines the radial elastic structure. The density structure is depth parameterized by volume averaging the values into shells with thickness of 10.5 km in the crust and 25 km in the mantle. Moreover, an ensemble parameter-controlled three-shell viscosity structure defined by … "

L130-131: Please mention explicitly what the GIA component in post-processing modelled ice sheet chronologies is.

We do not entirely understand the request. The text was party revised to hopefully provide clarity:

"The GSM is fully coupled to a GIA model of sea-level change based on a self-gravitating viscoelastic solid-Earth model which calculates GIA due to the redistribution of surface ice and ocean loads (Tarasov and Peltier, 1997) using a pseudo spectral solution for a spherically symmetric Earth rheology (Mitrovica and Peltier, 1991)."

What is described above represents the GIA component in the GSM. However, during a transient ice sheet simulation the GIA calculations do not compute the full gravitationally self-consistent solution. Only at the end of a transient simulation, a post-processing step computes the full gravitationally self-consistent solution as described:

"Given typical GIA response timescales, the GIA calculations are computed every 100 simulation years. To minimize the considerable computational cost of solving for a complete gravitationally self-consistent solution coupled with an ice sheet model (Gomez et al., 2010, 2013), a zeroth order geoidal approximation is used to account for the gravitational deflection of the sea surface. This approximation sums all ice sheet contributions to the local geoidal deflection from the global mean as detailed in Tarasov et al. (2025). However, upon completing the simulation, a gravitationally self-consistent solution is computed using the AIS simulation in combination with interim GLAC3 chronologies for the other last glacial cycle ice sheets (e.g. Tarasov et al., 2012; Kageyama et al., 2017; Kierulf et al., 2021) as per the methodology of Mitrovica and Peltier (1991)."

Or perhaps there is confusion associated with the fact that Whitehouse et al 2012 did not have coupled GIA in their ice sheet model. Just in case, we've added

"The GIA component shares many similarities to that used in Whitehouse et al. (2012b) for post-processing modelled ice sheet chronologies but in contrast to the GSM, their ice sheet model did not have this component coupled (but instead used a simple local relaxation response parametrization)."

which clarifies that their GIA calculations are conducted after their ice sheet simulation finishes as part of a post-processing step.

L135-136: Explain in detail what is meant by zeroth order geoidal approximation and how this is applied.

The following revisions were implemented to address this comment:

"Given typical GIA response timescales, the GIA calculations are computed every 100 simulation years. To minimize the considerable computational cost of solving for a complete gravitationally self-consistent solution coupled with an ice sheet model (Gomez et al., 2010, 2013), a zeroth order geoidal approximation is used to account for the gravitational deflection of the sea surface. This approximation sums all ice sheet contributions to the local geoidal deflection from the global mean (as per the imposed eustatic sea level chronology) as detailed in Tarasov et al. (2025)."

It is a method that accounts for approximate geoidal changes due to GIA and ice load changes by scaling spatial geoidal deflection according to ice sheet volume. The deflection fields are from previously history matched full gravitationally-self-consistent GIA solutions and the resultant deflections are then applied to the mean sea-level forcing. A detailed description along with a sample comparison against a complete sea level solution can be found Section 2.15 of Tarasov et al. (2025).

L136-138: At this point in the text, it is not clear what is meant by "full transient simulation" and why the simulations in section 4 are different from the simulations in the other sections. Please elaborate in the text which method is used for which simulations exactly. It would be useful to end the introduction with a short overview of which simulations are discussed in which section so that the reader has got an overview to which you can refer to lines 136-138.

This was corrected, instead here we only refer to the "simulation" since two sentences later we specify what is meant by a full transient simulation (205 ka to present). Effectively, all the simulations in the history-matching analysis are full transient simulations using the GSM. Except that the sensitivity analysis are subject to only GIA post processing with an alternate Earth model.

"The full continental scale transient Antarctic simulations over 205 ka have a 40 by 40 km horizontal resolution with the full sea-level solution having a spherical harmonic degree and order of 512."

L148-149: Please indicate why these ranges for viscosity and lithospheric thickness have been chosen and discuss the implications of this choice on the results. As mentioned later in the manuscript, it has been shown that the upper mantle viscosity can regionally be orders of magnitude lower than 0.1*10^21 pa s (e.g. Barletta et al., 2018). Furthermore, it has been shown that using a uniform upper mantle viscosity of, for example, 10^19 pa s better represents a laterally varying Earth structure than a uniform viscosity of 10^21 pa s because most ice mass changes have occurred over the West Antarctic Ice Sheet and the average viscosity of the West Antarctic Ice Sheet is an order of magnitude lower than 10^21 pa s (van Calcar et al. 2023).

Revisions to the text have been made to emphasize that future work should apply a broader range of upper mantle viscosities. The Antarctic continent represents a large region and given that we are using a spherically symmetric GIA model, the chosen range for the Earth viscosity ensemble parameters for the lithospheric thickness, upper mantle viscosity, and lower mantle viscosity is between 46 to 146 km, $0.1 \cdot 10^{21}$ to $5 \cdot 10^{21}$ Pa·s, and $1 \cdot 10^{21}$ to $90 \cdot 10^{21}$ Pa·s, respectively. The literature suggests this is a sufficiently wide range for the studied domain size (e.g. Whitehouse et al., 2019). Indeed there are small regions with anomalous viscosity deviations that exceed this range but our focus was on full continental scale simulation. The low viscosity Earth model GIA simulations (upper mantle viscosities as low as $5 \cdot 10^{18}$ Pa s) were relegated to the sensitivity analysis to quantify their uncoupled impact.

"A future history-matching analysis should apply a broader range of upper mantle viscosity Earth models to include values down to 10^{19} pa·s (van der Wal et al., 2015) as applied in our sensitivity analysis given that WAIS rests atop several anomalously low viscosity zones and this region experienced the greatest mass change since the last interglacial. However, it remains unclear to which degree it is appropriate to use such low viscosity values for glacial cycle simulations given that model-based support for use of such a low viscosity in visco-elastic models coupled to ice sheet models without lateral earth viscosity variation has only been shown for contemporary load change contexts (van der Wal et al., 2015). "

Whitehouse, P.L., Gomez, N., King, M.A. and Wiens, D.A., 2019. Solid Earth change and the evolution of the Antarctic Ice Sheet. Nature communications, 10(1), p.503.

van der Wal, W., Whitehouse, P.L. and Schrama, E.J.: Effect of GIA models with 3D composite mantle viscosity on GRACE mass balance estimates for Antarctica. Earth and Planetary Science Letters, 414, pp.134-143, 2015.

L212-216: It is not clear how the 5% error estimate for RSL was chosen. Additionally, the range of bias error for present-day uplift rates needs further clarification. Is this range site-dependent, and if so, what parameters influence its variation?

The text was revised to provide clarity on this comment:

"This includes a 5% structural bias error for RSL and a +1 mm/yr and -0.5 mm/yr bias error for PD vertical uplift both due to the use of a spherically symmetric global 1D Earth rheology instead of a 3D Earth rheology. These values were chosen on the basis of discrepancies between corresponding results for regional 1D and 3D Earth rheology modelling of Fennoscandia (Whitehouse et al., 2006; Whitehouse, 2009). However, a similar analysis for Antarctica is lacking and needs to be addressed by the community."

L220: The concept of multi-million-point Markov Chain Monte Carlo (MCMC) sampling should be explained.

The following was included in the text to address this comment:

"MCMC sampling uses a sequence of dependent autocorrelated samples generated through a Markov chain to approximate high dimensional probability distributions. Each sampling step in each chain requires a comparison of GSM predictions against the constraint data."

L220: Please also mention how many simulations were included in the original Glacial Systems Model (GSM) ensemble.

These details are described later on in this section of this study:

"Previous ensembles of simulations were evaluated against the AntICE2 database and PD observations to verify that the observations are adequately bracketed by the GSM given uncertainties (Lecavalier and Tarasov, 2025)." … "These enhancements, along with broader parameterizations of marine basins and other model components, led to an increase in the number of ensemble parameters, process additions to the GSM, and revisions to certain boundary conditions. Leading up to the final waves of ensembles, over 30,000 model simulations were performed as part of previous experimentation, sensitivity analyses, Latin Hypercube, and Beta fit sampling of ensemble parameters. In the results section, we present the latest iterations of large-ensemble results based on the history-matching analysis which consists of the final 9,293 simulations."

The text was revised to improve the overall clarity on this topic:

"This final waves of ensembles (N=9,293) is henceforth referred to as the "full ensemble" (see Table 2 in Lecavalier and Tarasov, 2025)."

L221-226: For improved readability, consider moving the sentence "The BANN targets… for data-model comparison" to line 222 before "The BANNs were trained…"

Corrected.

L226-227: The term "MCMC converged sampling chains" requires further explanation. How was convergence assessed? Additionally, more context is needed on the role of the Bayesian Artificial Neural Network (BANN) architectures prior to this sentence.

We are not clear on what is meant by context on the role of the BANN architecture. The specifics on the internal structure of the BANN is well beyond the bounds of this submission. In case the confusion is in regards to BANN, we have added:

"A BANN emulator is a probabilistic surrogate model with a specific architecture of interconnected layers of artificial neurons that approximates the behaviour of a complex system by learning from an ensemble of simulation outputs."

Additions to the text have been made to clarify how MCMC convergence is assessed:

"In the high-dimensional non-linear glacial system, it is challenging to ensure that all not implausible parameter space sectors have been identified. Consequently, this study utilized hundreds of MCMC sampling chains that are initiated from widely dispersed points in the parameter space. A sub-sample of parameter vectors from the converged part of at least100 MCMC sampling chains is in turn used to create an ensemble of GSM simulations. Convergence is assessed according to MCMC diagnostics as well from examining the evolution of a few of the state variables over the chain steps. (Neal, 2012)"

Neal, R.M.: Bayesian learning for neural networks (Vol. 118). Springer Science & Business Media, 2012.

L245-247: What measures have been taken to address the potential issue of overfitting? Could the discrepancies be due to deficiencies in the climate model rather than model overfitting? Please provide a discussion on overfitting control.

Overfitting occurs when forcing a model to fit data without (or with insufficient) accounting for uncertainties, thus effectively fitting the model to the noise in the data. History matching is therefore the complete opposite given its emphasis on complete uncertainty assessment/specification, lack of parameter tuning/optimization, and focus on ruling out model configurations that are clearly inconsistent with the chosen constraint data set. So we do not understand why overfitting is being raised here. If the referee's question is motivated by the dimension of the ensemble parameter space, aside from the above points, this dimension is still limited compared to the uncertainty and degrees of freedom of the ice and climate system over the last glacial cycle.

We are confused as to what is meant by discrepancies possibly being due to over-fitting as the contrary would ensue. The line context for this question is also strange, as the discussion in L245-7 is about inadequate fits to data constraints, overfitting would cause the opposite. As such, we see no point in modifying the relevant text.

The discrepancies discussed in this part are likely due to a host of model limitations (including grid resolution, input data sets, process representation, ...). As we explicitly stated in the original submission, these discrepancies were reduced by adding processes, ensemble parameters, and updating some input boundary conditions. Compared to other paleo ice sheets, uncertainties in atmospheric climate forcing are much less critical (given the negligible amount of present-day surface melt), however uncertainties in the ocean temperature forcing and associated submarine melt are a challenge. Expanding the degrees of freedom in the ocean temperature forcing was therefore a significant part of the GSM updates carried out in this iterative process of history matching as stated:

"<u>To address any persistent data-model discrepancies following history-matching waves, the GSM underwent major model updates. A key refinement involved expanding the degrees of freedom in the ocean temperature forcing. Sub-ice-shelf mass balance in the GSM is computed using an ocean-temperature-dependent parameterization at the ice–ocean interface (Tarasov et al., 2025), encompassing the ice front, grounding line, and sub-shelf regions. Ocean temperature forcing is derived from transient TraCE-21ka simulations (He, 2011), bias-corrected using PD ECCO reanalysis data (Fukumori et al., 2018). For periods prior to 21 ka, a glacial index scheme is applied to the bias-corrected TraCE-21ka outputs. The temperature field beneath ice shelves is extrapolated with a depth cut-off based on minimum sill height to account for deeper continental shelves. To avoid extrapolating TraCE-21ka temperatures under warmer-than-present conditions, particularly relevant for Last Interglacial simulations, a separate ensemble parameter (rToceanWrm) was introduced. This parameter scales glacial-index-derived atmospheric warming and adds it to the PD ocean climatology, leveraging the empirical relationship between Antarctic δ^2H and mean ocean temperature (Shackleton et al., 2021). These enhancements, along with broader parameterizations of marine basins and other model components, led to an increase in the number of ensemble parameters, process additions to the GSM, and revisions to certain boundary</u>

conditions. Leading up to the final waves of ensembles, over 30,000 model simulations were performed as part of previous experimentation, sensitivity analyses, Latin Hypercube, and Beta fit sampling of ensemble parameters."

L248: Clarify which previous ensembles of simulations are being referred to.

We've added a citation to part 1 of our study to make clear where the verification of ensemble bracketing of key data constraints was verified. Going beyond this would likely confuse the issue (what benefit would there be from cataloguing each of the 10 ensembles used in the course of this project?)

L255: The selection process for the 9,293 simulations is unclear. Additionally, where did the 30,000 model simulations originate? Are there references supporting this methodology? A step-by-step description of how simulations were filtered and refined would be beneficial.

This is detailed in part 1 of this study in Section 4 (Lecavalier and Tarasov, 2025), the ensembles are summarised in Table 2, the history matching data-type thresholds are listed in Table S1, and the history-matching methodology is diagramtically illustrated in Figure S8. For these reasons, no revisions to the text are necessary since the focus of this study is predominantly on Antarctic GIA.

L263-267: Define how "high variance" is measured in the subset. What parameters exhibit high variance? What criteria were used for selection? List all key metrics of interest and the minimum scores to which relevant data types.

The text was expanded to include some of this information to address this comment:

"Each metric of interest (LIG deficit and LGM excess relative to present) and AntICE2 data type scores were respectively normalized, and a simulation was chosen from the NROY subensemble to initialize the HVSS sampling (e.g. a NROY simulation with minimum total score across all data types). Each subsequent sample added to the HVSS is selected by identifying which simulation in the NROY subensemble maximizes the multidimensional distance (square root sum of squares) between all the normalized metrics and scores against the simulations already populating the HVSS. This method extracts a subset of simulations which exhibit a wide range of behaviours across the NROY sub-ensemble."

L268: Clarify how the repeated GIA post-processing has been done.

We want to provide some clarity on what is meant by GIA post-processing. We partly address this with the revisions made to address comments linked to L130-131. Regardless of whether an ice sheet model is coupled to a GIA model or not, the resulting ice load chronology can be used as input to a GIA model. This is what we mean by GIA post-processing, we apply an existing ice load history as input to do several GIA simulations using alternate Earth models, hence GIA post-processing. An additional sentence is added which clarifies this step:

"The ice load chronologies from the 18 members of the NROY sub-ensemble HVSS were subject to repeated GIA post-processing over a range of Earth models. This involved applying each individual ice load chronology in the HVSS as input to the gravitationally self-consistent sea level solver using alternate Earth models."

L269: Also include the upper limits for lithospheric thickness and upper mantle viscosity, as well as the step size used in the sensitivity analysis.

This is illustrated in the legend of both Figure S1 and S2. The text was revised to explicitly specify this information:

"Specifically, the lithospheric thickness and upper mantle viscosity was progressively decreased from 146 km and $5 \cdot 10^{21}$ Pa·s to 46 km and $5 \cdot 10^{18}$ Pa·s (146, 120, 96, 71, to 46 km; $5 \cdot 10^{21}$, $5 \cdot 10^{20}$, $5 \cdot 10^{19}$, to $5 \cdot 10^{18}$ Pa·s), respectively, to evaluate the impact of an anomalously low upper mantle viscosity on isostasy (Fig. S1 and S2)."

L271: Figures S1 and S2 are referenced but not discussed. A brief summary of their implications should be included in the main text to guide the reader.

No revisions are made given there are 8 references to Figure S1 and S2 that discuss the implication of these figures in the Results and Discussion section.

L289-290: Please elaborate on how GPS measurements are elastically corrected. Could this correction method contribute to the discrepancies in the model fit for West Antarctica? A brief discussion on the limitations of the elastic correction approach would be valuable.

Addressed with the following additions:

"With regards to the latter, the GPS measurements have to be corrected for the elastic response due to recent ice mass changes to isolate the viscous signal due to past load changes (Martín-Español et al., 2016; Sasgen et al., 2017). We rely on the validity of the elastic corrections which are dependent on the inferred contemporary ice load changes which have their own explicit and some ill-defined implicit uncertainties. Thus, only GPS data that is minimally impacted by a contemporary elastic signal are considered."

L322: Can the required upper mantle viscosity for data consistency in this region be quantified?

Partly, the challenge is that this is a joint ice and Earth model history-matching analysis. The sensitivity analysis attempts to evaluate if a lower upper mantle viscosity can address an outstanding misfit in the region. Simply because it does in this region does not imply that we have constrained the regional viscosity structure since this is a non-unique problem and we simply demonstrate that these alternate Earth models can help rectify the last remaining misfits at site 9101. The sensitivity analysis suggests that for a given loading history and Earth model pair, you might be able to address these final misfits with a GIA component that includes lateral variations in Earth viscosity. However, this does not necessary imply that the upper mantle viscosity in this region is $0.05 \cdot 10^{21}$ Pa·s. The following additions to the text were made:

"Therefore, lateral Earth structure that corresponds to a lower upper mantle viscosity can produce a RSL fall consistent with the data which corresponds to an upper mantle viscosity of $5 \cdot 10^{19}$ Pa·s. However, there is limited evidence of lateral structure in this region (Whitehouse et al., 2019). This suggests the unloading history and magnitude of ice loss could be responsible for the discrepancy with the sea-level high-stand data in this area."

L323-324: The manuscript lacks a clear definition of "lateral structure" and whether is or is not a lateral structure in a certain region. Lateral variations in viscosity depend on spatial scale, and the sensitivity of RSL measurements depends on the extent of ice (un)loading. For example, at the Syowa Coast, viscosity varies by one to two orders of magnitude over 300 km (e.g. Ivins et al., 2023). The inferred average viscosity of ~10^20 Pa·s for this region appears reasonable. Additionally, while inconsistencies could stem from climate forcing, the possibility of errors in the Earth structure model should not be dismissed.

An addition to the text was made to explicity quantify what we mean by lateral Earth structure.

"In this study, reference to lateral Earth structure in the upper mantle is broadly defined wherever there is a gradient in upper mantle viscosity that exceeds approximately one order of magnitude on 100 to 1,000 km length scales (e.g. Figure 4 from Whitehouse et al., 2019)."

Generally we refer to lateral Earth structure as motivation for considering alternate Earth models as part of the sensitivity analysis to explore its potential impact to isostasy. Even though some regions have considerable, limited, to no evidence of lateral Earth structure, we agree that we cannot dismiss this impact even though other sources of uncertainty has the potential to address remaining data-model discrepancies.

L454-455: Provide a clearer explanation of the distinction between nominal ranges and Gaussian confidence intervals.

The 2 sigma range for a Gaussian distribution is based on the 0.02275 and 0.97725 quantiles which represents the 95.45% interval. We apply these same quantiles on the ensemble results rather than the exact 95% interval, hence why we refer to them as the nominal 95% interval. At L285-287 we define the nominal intervals but revisions were made to provide clarity:

"The 2σ and 1σ ensemble ranges shown across several figures (e.g. Fig. 2-7) are the nominal 95% and 68% ensemble intervals based on the equivalent Gaussian quantiles (95.45 % = 97.725 - 2.275 % Gaussian 2σ quantiles and 68.268 % = 84.134 - 15.866 % Gaussian 1σ quantiles)."

L455-456: Briefly justify why the reader should consider the complete NROY sub-ensemble. How do the results of the full NROY sub-ensemble compare to those within the nominal 2σ range? A short discussion on the added insights from the complete sub-ensemble would be beneficial.

In the supplementary we show the min and max of the NROY sub-ensemble spatial fields, while in the main text we only show the 2sigma ranges. The strength of the history-matching analysis is to establish plausible bounds that are consistent with the data. However, when looking at spatial fields, the visualization can be dominated by a single outlier, hence why we show both in this study. The discussion in the text reflects those from the NROY sub-ensemble min/max and only mention the nominal 2sigma uncertainties with regards to spatial plots but for completeness include the spatial min/max figures in the supplementary section. We state the following in the manuscript which covers these points:

"History matching on its own does not produce a probability distribution of chronologies. Throughout this study, we present the NROY sub-ensemble nominal 2σ range since studies that apply GIA corrections are typically interested in accounting for nominal 2σ uncertainties. Moreover, by visualizing 2σ ranges one avoids any one outlier simulation from dominating the visualization. However, these nominal ranges should not be confused with traditional Gaussian confidence intervals and the reader is encouraged to also consider the complete NROY sub-ensemble min and max GIA and RSL ranges shown in Figure S3-S6. When evaluating the spatial RSL, uplift rates, and geoid NROY sub-ensemble plots (Figure 4, 5, 6, and 7), the min/max and -2σ/2σ plots differ primary by magnitude where the NROY sub-ensemble min is broadly more negative than those of the -2σ field (conversely true for the NROY sub-ensemble max and 2σ field). The difference between the min/max and -2σ/2σ plots illustrate the impact of edge case simulations that made it within the NROY sub-ensemble which can be considerable in certain regions (e.g. >10 m difference in WAIS RSL at 10 ka between the max and 2σ field as shown in Figure 4f and S3f)."

L466-467: The phrasing suggests that uncertainties in regional RSL measurements are large. However, given the relatively small error bars in Figure 2, the uncertainty appears to stem from the model fit to all Antarctic RSL measurements rather than the measurements themselves. The sentence should be reworded to emphasize model uncertainty sources, including the choice of climate and GIA models (2D instead of 3D).

We are indeed referencing the modelled RSL predictions based on the NROY sub-ensemble which is data-constrained by the AntICE2 database. Regions in the spatial plots of Figure 4 and S3 with a large min/max and 2sigma range represent regions that are poorly constrained by the data and/or large structural errors in the GSM. The text was revised to explicitly specify that we are discussing modelled RSL uncertainties:

"This emphasizes the large NROY RSL range due to competing observational constraints and structural errors in the entire glacial system."

L469-471: Provide examples of specific regions where this effect occurs. Do these correspond to areas with the largest RSL uncertainty ranges?

These regions have smaller modelled RSL uncertainties because they are physically constrained by the maximum ice load that can expand across the continental shelf. The text was revised to mention two examples:

"The maximum ice load was also physically constrained in some regions during the LGM because of a limited continental shelf, particularly along the Dronning Maud - Enderby Land and Wilkes – Victoria Land sectors. This directly limits the maximum possible ice load in certain regions which impacts the subsequent deglacial GIA response."

L570: GLAC3 is mentioned for the first time here. Please include an explanation in the method section.

We've expanded the text that discusses the GLAC3 model to provide some concise background information.

GLAC3 mentions in the manuscript:

Abstract

"This yielded a NROY sub-ensemble of simulations consisting of 82-members that approximately bound past and present GIA and sea-level change given uncertainties across the entire glacial system. The NROY Antarctic ice sheet chronologies and associated Earth viscosity models represent the Antarctic component of the "GLAC3-A" set of global ice sheet chronologies over the last glacial cycle."

Introduction

"Part two of this study presented below aims to quantify bounds on the evolution of Antarctic GIA. This is carried out via an approximate history-matching methodology that explicitly accounts for data and model uncertainties. As part of the history-matching analysis presented in this 2 part study, a sub-ensemble of AIS simulations are chosen to represent the Antarctic component of the in progress GLAC3 (specifically version A denoted as GLAC3-A) global set of approximately history matched last glacial cycle ice sheet chronologies."

Model description

"Given typical GIA response timescales, the GIA calculations are computed every 100 simulation years. To minimize the considerable computational cost of solving for a complete gravitationally self-consistent solution coupled with an ice sheet model (Gomez et al., 2010, 2013), a zeroth order geoidal approximation is used to account for the gravitational deflection of the sea surface. This approximation sums all ice sheet contributions to the local geoidal deflection from the global mean as detailed in Tarasov et al. (2025). However, upon completing the simulation, a gravitationally self-consistent solution is computed using the AIS simulation in combination with interim GLAC3 chronologies for the other last glacial cycle ice sheets (e.g. Tarasov et al., 2012; Kageyama et al., 2017; Kierulf et al., 2021) as per the methodology of Mitrovica and Peltier (1991). The complete solutions are those that are compared against the GPS and RSL observations in Section 4."

Conclusion

"The NROY sub-ensemble of AIS results represent a collection of not-ruled-out-yet Antarctic components for the in progress global GLAC3 set of last glacial cycle ice sheet chronologies."

Figure 1: The caption should briefly define the abbreviations used in the legend (e.g., paleoExt, paleoH, paleoRSL).

Corrected.

Figure S1 & S2: Ensure consistency between the legend and caption regarding viscosity values. The notation should be clarified, and redundant legends should be removed for clarity. The caption states that UMV varies from 5·10^21 to 0.005·10^21 Pa·s, but the legend lists values of 0.05 and 0.005, presumably referring to 5·10^19 and 5·10^18 Pa·s. Clarify this discrepancy and ensure consistency in notation.

The upper mantle viscosity (UMV) in the legend goes from $5 \cdot 10^{21}$ Pa·s (Ref Earth with UMV=5) to $0.005 \cdot 10^{21}$ Pa·s (RefEarth with LT=46 UMV=0.005) which is consistent with the caption.

References E. R. Ivins, W. van der Wal, D. A. Wiens, A. J. Lloyd, L. Caron, 2023. "Antarctic upper mantle rheology," The Geochemistry and Geophysics of the Antarctic Mantle, A. P. Martin, W. van der Wal.

Citation: https://doi.org/10.5194/egusphere-2024-3268-RC2