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 #1

The work of Lecavalier and Tarasov assesses uncertainties in the solid Earth's response to loading and unloading of ice (and consequently the oceans) in the Antarctic. The authors show that there is a much larger uncertainty and different spatial patterns than previously estimated by the more popular Glacial Isostatic Adjustment (GIA) models, which are used to estimate the present-day AIS mass balance. Their assessment is done by history-matching a large ensemble of simulations using the Glacial Systems Model (GSM), producing a Not-Ruled-Out-Yet (NROY) subset that is further used as input to *adhoc* simulations of GIA using a more faithful solid-Earth model. The GSM ensemble is the same presented in a companion paper. They further use the NROY ensemble results to discuss implications for the climate and GIA (including when that means a limitation of the used forcings or solid-Earth models and parameter ranges).

Overall, the paper structure is mostly clear and easy to follow with just some points where the text could be improved, sometimes by rewriting confusing paragraphs, sometimes by clarifying some technical parts. Below I make some general remarks with suggestions to improve the overall state of the paper before it can be published, provide technical/editorial suggestions line by line, and finally comment on how to improve some of the figures presented.

I hope the authors find my comments useful, and I look forward to seeing a revised and improved version of this manuscript.

General remarks

1. The introduction adequately provides the background necessary to contextualise the paper, but it lacks a proper ending pointing the reader to what research question(s) the study aims to address. Please add a final paragraph or a couple of sentences framing how the present study fits into the picture provided, and what its goals are.

   Addressed with the following text:

   "This study is the second part of a two-part study, and should be considered in conjunction with part one which analyzed history matched ice sheet evolution and fits to non-GIA data constraints. (Lecavalier and Tarasov, 2025). 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."

2. As per TC's guidelines, papers that are submitted or in prep (i.e., not yet available and without a DOI) cannot be cited. This needs to be rectified before the manuscript can be published. I suggest acting on it now instead of waiting for the same issue to be pointed out by the typesetting or copy-editing teams.

   All the cited papers that were submitted or in prep listed in the manuscript now have a DOI. The manuscript has been updated with this information. The GSM description paper now has a permanent DOI at https://doi.org/10.5194/gmd-2024-175. Part 1 of this study is published: https://doi.org/10.5194/tc-19-919-2025. The Tarasov & Goldstein (2021) study can be found at: https://doi.org/10.5194/cp-2021-145.

3. Considering I am no GIA expert, and that this paper is likely targeted at paleoglaciologists and ice sheet modellers as well, I personally feel that the GIA model description part is quite confusing and a bit unstructured, and could be improved. It would be beneficial to this manuscript if the authors invested some time in improving the flow of the model description section (especially the last two paragraphs), rearranging some of the sentences to make the sequence of information presented more logical (e.g., not going back and forth between the GIA and ice sheet components) and adding some clarifications to the more technical terms (e.g., PREM structure). I believe such changes would provide a much better context for the results, and aid the non-GIA experts who would likely be interested in this paper.

   The model description section was heavily revised to address this point though we still retain a separate paragraph describing the ensemble parameters given the central role they play in history matching:

   "The GSM consists of comprehensive ice dynamic, climate forcing, and glacial isostatic components which are described in Tarasov et al. (2025) and Lecavalier and Tarasov (2025). To summarize the GSM includes: Hybrid SIA-SSA ice physics; with a subgrid grounding line ice flux parameterization; dual power basal drag for hard and soft bed sliding; ice shelf hydro-fracturing and restricted ice cliff failure; ocean temperature dependent sub ice shelf melt; subgrid ice shelf pinning point scheme; and a climate forcing representation with 14 ensemble parameters and fully coupled 2D energy balance climate model. An illustration showing the key components of the GSM is found in Figure S1 of Lecavalier and Tarasov (2025).

   GIA models simulate the response of the solid Earth due to present and past changes in surface loading from the redistribution of ice, water, and mantle material. The two primary inputs to a GIA model are a global ice chronology and the Earth rheology. The GIA model products will henceforth be referred to as GIA inferences which include past and PD bedrock deformation, geoid and RSL estimates. 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). 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. Three ensemble parameters specify the lithospheric thickness and viscosity of the upper and lower mantles. The lithospheric thickness, upper mantle viscosity, and lower mantle viscosity can respectively vary 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. 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). 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. 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.

As detailed in the accompanying study (Lecavalier and Tarasov, 2025), the Antarctic configuration of the GSM consists of 38 ensemble parameters. 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). This represents the most comprehensive exploration of parametric uncertainties across the entire Antarctic glacial system of any study to date. A given simulation is defined by a parameter vector which consists of chosen values for each ensemble parameter. In this study, the GSM simulates AIS changes over the last 2 glacial cycles to minimize initialization uncertainties propagating into the last interglacial start of our history-matching interval. The GSM relies on several eustatic global sea-level forcing time series (e.g. Lambeck et al., 2014; Lisiecki and Raymo, 2005) when performing joint ice sheet and GIA calculations."

4. The authors offload most of the explanation regarding scoring the simulations to two other papers: One that is "in prep", and another that is an exceedingly lengthy pre-print which was never accepted for publication. The "in prep" manuscript is provided as part of the review process, which is much appreciated (I actually found it very interesting and look forward to seeing it eventually published). Still, it is very much in preparation, and I could only get a general grasp of how the scoring was done. Considering that details

regarding the scoring are not the focus of the manuscript under review, and "in prep" manuscripts cannot be cited, I would only ask that the authors explain slightly better why NROY simulations (or the entire ensemble, actually) do not bracket some observations, as evident in Figs 2 and 3. Is it because by choosing e.g., 3.5 or 4sigma means the "allowed variability" is actually larger than the ensemble variability itself? And what does the sigma refer to? Is it simply the standard deviation of the metric(s) being shown in the graphs?

The text was revised to include the following:

"Our implausibility threshold for inconsistency is a simulation-data misfit score component value of between 3-σ and 4-σ of the total uncertainty:

$$I = \frac{|d_i - E - \mu_{int} - \mu_{ext}|}{\sigma_{em} + \sigma_{struct} + \sigma_{obs}} \quad [1]$$

The implausiblity (I) includes the data-model residual ($d_i - E$) as well at the total internal and external discrepancy bias (μ_{int}, μ_{ext}) and all uncertainty sources: emulator (σ_{em}) structural (σ_{struct}), observational standard deviation (σ_{obs}) (see Table S1 in Lecavalier and Tarasov, 2025 for values, and Tarasov and Goldstein, 2021 for motivation). The implausibility threshold for each data type (σ in eq.1) is applied to the corresponding data-model score component. In other words, a NROY simulation must be NROY for each data type."

However, an implausibility threshold of 4sigma is consistently used for the RSL scores:

"given that the model struggles to bracket a few observations in this data class, which resulted in ruling out nearly all simulations if imposing a 3σ threshold across all data types."

At some RSL (9301, 9603, 9604) and GPS sites (8411, 8426, 8502, 8616), the data is not bracketed by the full ensemble, meaning any choice of implausibility threshold (3.5 or 4 sigma) would not yield any passing simulations that are consistent with the data (excluding considerably expanded structural uncertainty contributions). This suggests that the model is not exhibiting an adequate range of responses given the current accounting of model uncertainties in the GSM. This is discussed in Section 4.1 and 4.2:

"Given the full ensemble does not achieve the necessary amplitude needed to capture the observations at Windmill Island regardless of the range of Earth rheology considered in the history-matching analysis and Earth model sensitivity analysis, the discrepancy is likely due to the ice load chronology and/or a non-linear Earth rheology."

Also:

"This suggests the climate forcing or basal conditions may lack adequate regional degrees of freedom to produce a sufficiently larger ice load in the region, and subsequent deglaciation timing to reach the observed sea-level high-stand in the paleo RSL data."

However, at other RSL (9401) and GPS sites (8406, 8405, 8701), the full ensemble brackets the sea-level high stand or vertical land motion but upon imposing the implausibility thresholds, the NROY simulations fail to achieve the appropriate amplitude (e.g. reach the suggest 30 m sea-level highstand at site 9401). This suggest that the model is able to produce the adequate range of responses but upon imposing the implausiblity thresholds, all simulations that showed the adequate response failed to be broadly consistent, within several standard deviations, across the entire AntICE2 database. This is discussed in Section 4.1 and 4.2:

"The NROY sub-ensemble brackets the sites except for the highest sea-level observations at Terra Nova Bay (9401). The region is topographically complex with subgrid valley glaciers that are poorly resolved in the GSM. This is a recurring challenge performing a data-model comparison to paleoH data in the region which can manifest in an inaccurate ice unloading history. Moreover, this region of the Transantarctic Mountains has an anomalous low viscosity zone in the upper mantle which has consequences on the viscous response to past load changes (Whitehouse et al., 2019). The NROY HVSS Earth model sensitivity analysis demonstrates that by lowering the upper mantle viscosity in this region, a more rapid viscous response to ice unloading can reach the peak observed RSL at Terra Nova Bay."

"Tier-1 and tier-2 GPS observations that are not bracketed by the simulations tend to misfit both the full ensemble and NROY sub-ensemble at 3 distinct sites 8426, 8504, and 8502 in or near the Amundsen Sea sector. The Amundsen Sea sector has an anomalous low viscosity zone in the upper mantle which is not differentiated in the spherically symmetric GIA model. The HVSS Earth model sensitivity analysis does demonstrate that by considering a low upper mantle viscosity, elastic-corrected GPS predictions are captured at site 8406, 8411, 8504, 8616, and 8701 (Fig. S2) which are regions with inferred anomalously low viscosity structure. As the upper mantle viscosity is decreased by several orders of magnitude, this can significantly increase or decrease the amplitude of the GIA response depending on the temporal proximity of the unloading event. None of the HVSS Earth model sensitivity simulations capture the GPS bedrock trends (-4 mm/yr at site 8426, and 19 mm/yr at site 8502; Fig. S2), even though such amplitudes are attainable at other sites. Alternatively, the elastic corrections applied to the GPS data could be underestimated, particularly given their full uncertainties are ill-defined with its limited reliance on the input contemporary mass balance estimates (Martín-Español et al., 2016; Sasgen et al., 2017). Negative vertical land motion at 8426 suggests regional loading not represented by the elastic correction and/or GSM simulations. This could be attributed to increase precipitation or ice being advected to the region which thickens the ice column in the late Holocene. Conversely, 8502 with its exceedingly high elastic-corrected uplift rate indicates significant mass loss in the late Holocene. A large quantity of regional ice mass loss can be linked to ocean forcing and margin retreat of marine-based ice overlying soft till during the late Holocene. This suggests that the GSM might have insufficient degrees of freedom in the regional climate forcing and basal environment to produce a sufficiently late ice load scenario to reconcile these remaining discrepancies."

5. The GLAC3 chronology comes totally out of the blue, being mentioned only in the abstract and conclusions. All I can gather is that it stems from the NROY ensemble, but no other context is provided. It would be worth contextualising it and saying why it is relevant, so the reader can appreciate how the NROY ensemble relates to it.

   Additional remarks have been added in the text to provide some more GLAC3 context:

   "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."

   "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."

   "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."

Line-by-line comments

L29-34: This feels more like a sequence of bullet points written in-line instead of proper text. Please rewrite and give it a proper flow for the reader, as it is hard (even if still possible) to follow the implications of one to another

Addressed with the following revisions:

"This displays significant spatial variability in Antarctic GIA. The limited number of observational constraints contributes to wide inferred RSL bounds with max/min ranges up to 150 m during the Holocene."

L37: Please add a comma after "that" so the sentence actually states that it was your study that adequately explored the uncertainties, and not the previous studies.

Corrected.

L58: There's an extra ":" at the end of the line

This preceeds a list of different GIA models.

L63: Is the author's last name really "A"? I could not find it in the reference list

Error with reference manager, it was corrected.

L128-129: "ensemble parameter controlled three shell viscosity structure": some hyphenation needs to be done here so the reader can properly understand what is going on...

Corrected.

L186: Either "Antarctica" or "the Antarctic"

Corrected.

L195: A full stop works better than a comma after "matching"

Corrected.

L263: It is not clear which criteria were used to choose the HVSS. What counts as "High Variance" in this subset?

Addressed with the following revisions:

"A high variance 18 member subset (HVSS) of simulations were selected from the NROY sub-ensemble according to key metrics of interest, such as the AIS grounded ice volume during the Last Glacial Maximum (LGM) (Figure S7 in Lecavalier and Tarasov, 2025). Each metric of interest (last interglacial 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."

L323: Please change "Although" for "However"

Corrected.

L397: There's an extra "is" that does not make sense in this sentence

Corrected.

L438-440: It would be useful for the reader if this sentence was discussed more in terms of climate than "degrees of freedom", i.e., what kind of atmospheric, ocean, and basal conditions not captured in GSM would be necessary to fit the vertical motion estimates at sites 8426 and 8502?

Several factors could help address remaining data-model discrepancies, we can't point to a single aspect but it can be attributed to the limited range of forcings, processes, and feedback in a given region based on the existing degrees of freedom represented in the model through its ensemble parameters and boundary conditions. It is a non-unique problem to fit GPS and RSL data, therefore it is more important to talk about the range of scenarios a model can produce rather than simply state that we needed more precipitation over a site to increase the initial loading for an eventual unloading event since many scenarios can yield the same uplift rate. The text was partly revised to the following:

"Negative vertical land motion at 8426 suggests regional loading not represented by the elastic correction and/or GSM simulations. This could be attributed to increase precipitation or ice being advected to the region which thickens the ice column in the late Holocene. Conversely, 8502 with its exceedingly high elastic-corrected uplift rate indicates significant mass loss in the late Holocene. A large quantity of regional ice mass loss can be linked to ocean forcing and margin retreat of marine-based ice overlying soft till during the late Holocene. This suggests that the GSM might have insufficient degrees of freedom in the regional climate forcing and basal environment to produce a sufficiently late ice load scenario to reconcile these remaining discrepancies."

L480: What is the difference between the minimum score and the joint minimum score? Is the GPS score not included in the former? If so, please clarify that in the text.

For a given simulation, it is scored against each data type in the AntICE2 database. The NROY sub-ensemble consists of simulations that are below the sigma thresholds on each of the data type scores in AntICE2. Within the NROY sub-ensemble, we identified the run (RefSim1) which has the minimum of the maximum score across all primary data type scores, we identified the run (RefSim4) with the lowest misfit score to the GPS data type, and we identified the run (RefSim5) which has the minimum of the maximum score across the paleo data types (paleoH, paleoExt, and paleoRSL). The text was revised to clarify this point. Additionally, the word "joint" was dropped from the text when speaking of data-model scores to be more succinct and avoid confusion.

"The reference simulations are all in the NROY sub-ensemble, where RefSim1 has the minimum of the maximum score across all the primary data types in AntICE2, RefSim4 has the minimum GPS score, and RefSim5 has the minimum of the maximum score across all the paleo data types in AntICE2."

L515: I believe it should be "reliance on three reference..."

Corrected.

L562: Here you state that the ensemble comprises 9,292 simulations, whereas in L16 and L255 it is stated 9,293. Please double check which one is correct

Corrected typo, should be 9293.

L571-579: I struggle to see how this paragraph fits in the Conclusions section. It reads much better without it, but I do understand that this relevant information. I'd suggest the authors to either rewrite it, or to move this to the previous section, making the appropriate changes so it fits in the text. This is related to my general comment #4

As recommended, the conclusion was restructured to improve flow.

"In this study a sub-ensemble of Antarctic GIA inferences is presented based on a history-matching analysis of the GSM against the AntICE2 database. The fully coupled glaciological and GIA model was used to generate a full ensemble consisting of 9,293 Antarctic simulations spanning the last 2 glacial cycles. BANNs were trained to emulate the GSM for rapid exploration of the parameter space via MCMC sampling. Simulation results were scored against past relative sea level, PD vertical land motion, past ice extent, past ice thickness, borehole temperature profiles, PD geometry and surface velocity. The full ensemble of simulations broadly brackets the AntICE2 database with a few outstanding data-model discrepancies likely attributed to model resolution, 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 likely many subgrid pinning points that can help stabilize an ice shelf and grounding line. The scores were used in the history-matching analysis to rule out simulations that were inconsistent with the data given observational and structural uncertainties, thereby a NROY sub-ensemble (N=82) that bounds past and present GIA and sea-level change was generated.

Given that our history matching accounts for data-system and system-model uncertainties to a much deeper extent than any previous AIS study, the NROY sub-ensemble provides the most credible bounds to date on actual Antarctic GIA and last glacial cycle ice sheet evolution. As such, our analysis demonstrates that previous Antarctic GIA studies have underestimated the viscous deformation contribution to PD uplift rates due to past ice sheet changes across several key regions. This is particularly the case in the Amundsen sector, an area currently undergoing significant mass loss, which has a large range of viable PD GIA estimates. Our NROY set of chronologies will therefore facilitate more accurate inference of the PD mass balance of the AIS, including for vulnerable marine-based regions.

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. Future research will prioritize a history-matching analysis using a higher horizontal resolution Antarctic configuration of the GSM, the integration of additional observational constraints such as the age structure of the ice inferred from reflective isochrones in radiostratigraphic data, and a 3D Earth viscoisty GIA emulator (Love et al., 2024) to better represent lateral Earth structure."

Figures

Figure 1: Please add to the caption what the abbreviations in the legend mean (paleoExt, paleoH, paleoRSL). In the text, only paleoH is explained

Corrected.

Figure 4 and all others in similar style: It looks like the grounding line shown is that of present day. I would recommend changing to that of one of the reference simulations, so the figures can better illustrate the solid-Earth response to changes in ice loading/unloading

We show the present day grounding line to georeference key features relative to present. It enables a better comparison across figures since the individual NROY sub-ensemble simulations exhibits a wide range of present day grounding line differences relative to present day. We opted not to show ensemble mean, min, max, and 2sig ranges alongside a reference simulation result since individual runs are glaciologically self-consistent and ensemble statistics are not, so a proper unloading attribution like you describe would not be possible. However, the reference simulations in Figure 5d/e/f and 6d/e/f have been updated to also include their PD simulated GL.

Figs 4 and S3: What is the significance of a RSL value where ice is grounded? If nothing, wouldn't it be clearer to mask out values where the ice is grounded in all ensemble members for each of the time slices? I would imagine this can be addressed in combination with a solution to my comment above.

RSL is the distance between the sea surface elevation and bedrock relative to present-day. The sea surface is located on a equipotential surface of the Earth's gravitational field i.e. geoid. Therefore, it has value to show inland RSL values since it also indicates the past geoid elevation inland which represents the past reference elevation with respect to sea level.