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.

**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.

   A couple sentences were added at the tail end of the introduction to better frame the research goals of the manuscript.

   “Part two of this study presented below aims to quantify the evolution of the AIS with a specific focus on GIA and sea-level change by properly exploring uncertainties in the glacial system. By applying a history-matching methodology, bounds are generated which define uncertainty ranges on AIS, GIA, and sea-level change that illustrates the limitation of simply focusing on a few best fitting models with direct consequences on how we understand the PD AIS. As part of the history-matching analysis, a sub-ensemble of AIS simulations are chosen to represent the Antarctic component and its respective uncertainties within the global ice sheet chronology GLAC3 for future analysis.”

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.

The manuscripts that were cited as submitted or in preparation now have a doi and are in press. The GSM description paper was submitted on Sept 20th 2024, a pre-print is available with a permanent DOI at https://doi.org/10.5194/gmd-2024-175. Part 1 of this study is in press and a pre-print can be found at: 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.

It is challenging to talk about GIA and ice sheet processes in isolation given they are a coupled system. The text was revised to consolidate the majority of the GIA description to a single paragraph (see below). This manuscript only provides an overview of the model description and provides the necessary information to understand the GIA component, resolution, initialization, and ensemble parameters. As stated in the paper, we recommend that the reader look at the complete model description paper for more detail:

Tarasov, L., Lecavalier, B. S., Hank, K., and Pollard, D.: The glacial systems model (GSM) Version 24G, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2024-175, in review, 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 coupled to a glacial isostatic adjustment 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). The Earth model rheology has a standard Preliminary Reference Earth Model (PREM) density structure (Dziewonski and Anderson, 1981) and an ensemble parameter-controlled three-shell viscosity structure defined by the depth of the lithosphere, upper and lower mantle viscosity. A total of three ensemble parameters defines the uncertainties in the viscosity profile of the solid Earth which directly impact GIA. Specifically, 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, however, our GIA component is asynchronously coupled to the ice sheet component. Considering GIA operates on longer 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. However, upon completing the simulation, a gravitationally self-consistent solution is computed using the AIS simulation as part of the global ice sheet chronology GLAC3. 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."

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?

   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). Therefore, another ice sheet modeller could leverage their ice sheet model of choice to achieve a history-matching analysis. This manuscript is already exceeding lengthy, hence why we rely on citations and opted to exclude an exhaustive model description and data scoring methodology section. An accepted pre-print for part 1 which includes a description of the history-matching scoring and sigma thresholds can be found at: https://doi.org/10.5194/tc-19-919-2025. Furthermore, the complete details of the history matching implementation is a whole paper on its own and an asset was provided for additional context. The results and discussion section details the misfits shown in Figure 2 and 3. As per the methodology section: "Our implausibility threshold for inconsistency is a simulation-data misfit score component value of between 3-σ and 4-σ of the total uncertainty (internal discrepancy, external discrepancy, and data uncertainty; see Table S1 in Lecavalier and Tarasov, 2025)."

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 introduction and model description regarding the GLAC3 global ice sheet chronology model to provide some more context. However, the work presented in Lecavalier and Tarasov, (2025) and in this study is the Antarctic component that

is applied in the GLAC3 model. The GLAC3 global ice sheet chronology and its applications to global sea-level change is best reserved for another publication.

"As part of the history-matching analysis, a sub-ensemble of AIS simulations are chosen to represent the Antarctic component and its respective uncertainties within the global ice sheet chronology GLAC3 for future analysis."

"However, upon completing the full transient simulation, a gravitationally self-consistent solution is computed using the AIS simulation as part of the global ice sheet chronology GLAC3."

**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

Corrected.

"A large variety of ice loading histories and Earth rheologies are evaluated against the available data. Data-model comparisons are shown against a subset of the AntICE2 database which directly constrains relative sea-level (RSL) change and GIA. This illustrated significant spatial variability in Antarctic RSL and GIA. The uncertainties affiliated with these inferences are large given the limited number of observational constraints which results in 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?

This is specified in part 1 of this study (Lecavalier and Tarasov, 2025):

“Here we present the data-model comparison of the full ensemble, the NROY AN3sig sub-ensemble, and a highvariance subset (HVSS) selection from the AN3sig subensemble, with the latter being integrated within the GLAC3 global ice sheet chronology for future analysis. A HVSS of 18 simulations was extracted from the NROY AN3sig subensemble to showcase some glaciologically self-consistent simulation results. The simulations that make up the HVSS were selected based on maximizing the normalized multidimensional distance between metrics and scores for simulations in the NROY sub-ensemble. A few reference simulations with minimized scores for key data types were also included in the HVSS, such as the overall best-scoring simulation, best-scoring simulation against ice core data, and best-scoring simulation for marine paleo extent data. The HVSS simulations are shown against the LIG and LGM metrics of interest in Fig. S9 in the Supplement.”

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?

We deem revisions are unnecessary since 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 enventual unloading event since many scenarios can yield the same uplift rate.

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 score across all the 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 score across the paleo data types (joint score based on the paleoH, paleoExt, paleoRSL data type scores). Rather than revise the text, the word “joint” was dropped from the text when speaking of data-model scores to be more succinct and avoid confusion.

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

Restructured the conclusion 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 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 bound 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. 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 global GLAC3 ice sheet chronology. The NROY sub-ensemble AIS chronologies represent the Antarctic component in the GLAC global ice sheet chronology. This research enables the upcoming evaluation of global RSL predictions and the Antarctic far-field sea-level contributions during the last interglacial, LGM, and deglacial melt water pulses. The AIS NROY sub-ensemble chronologies are constrained by near-field observations. Evaluating the updated global ice sheet chronology against far-field RSL observations would in turn constrain the AIS NROY sub-ensemble by said far-field data, potentially ruling out additional AIS simulations that are currently in the NROY sub-ensemble. This future work could leverage 3D Earth GIA models to formally evaluate lateral Earth structure and its impact on far-field and near-field RSL predictions."

**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 which would likely confuse the reader. Additionally, it would be misleading to show ensemble mean, min, max, and 2sig ranges alongside reference simulation results since individual runs are glaciologically self consistent and ensemble statistics are not, so a proper unloading attribution like you describe would not be possible.

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.