Review Maryam Yousefi

The manuscript "Simulation of a fully coupled 3D GIA - ice-sheet model for the Antarctic Ice Sheet over a glacial cycle" by Caroline J. Van Calcar et al. model the influence of GIA feedback on evolution of the Antarctic Ice Sheet over the full glacial cycle from last interglacial to present.

This study uses state-of-the-art approaches and models such as incorporating the lateral heterogeneity in the mantle structure using a recent seismic model of Lloyd et al. 2020 to develop two different 3D Earth structures assuming a composite rheology and applying a dynamic coupled GIA-ice sheet model with variable coupling time steps. Therefore, the results and methodology will have a significant and excellent contribution to the community. However, it needs more clarification and major revisions to be considered for publication.

We thank Maryam Yousefi for the valuable and detailed review, and for all the textual suggestions for improvement. Please find below in blue our answers to the comments. Line numbers refer to the original manuscript.

- Some aspects of the applied methodology are not clear and need further explanation. One important aspect is the GIA feedback and the results of the GIA model that is used for the coupling approach. Throughout the manuscript the authors use the term "deformation" for such model output, while the GIA signal is a combination of gravitational and rotational effects as well. Therefore, the surface deformation is not the only factor that affects the ice evolution, but also the changes in gravity field (geoid) and consequently the sea level which essentially defines the topography. This needs to be clarified if (and why) the applied method has ignored such effects.

Indeed, the GIA causes deformation and gravitational effects and rotational effects which can affect sea level and we recognize it was not clear what was included in our simulation. We take the main processes into account, namely deformation induced by changes in ice loading, and we include the self-gravitational effect induced by deformation on deformation itself. To make more clear what is included we will change "surface load" to "ice load" in the paragraph of lines 178-187 and we will also clarify the description of the ocean load test in lines 188-193. We did include the effect of self-gravity on bedrock deformation in the GIA model. We neglect the rotational effect on bedrock deformation, as mentioned in line 176.

Concerning ice dynamics, we include the direct effect of GIA via the bedrock elevation. A prescribed global mean sea level is used in the simulations and we acknowledge that it is a drawback that the gravitational effect of changes in ice mass and the rotational effect on sea level are not taken into account in the ice model. To make this more clear, we will remove the sentence about spatial variations in sea level in line 109 because at this point in the text, this sentence seems to be only confusing. Instead we will mention it in the method section where we can explain it in detail (lines 135-141). We will add the following in line 139 to justify our decision not to include spatial variations in sea level:

"De Boer et al. (2014) studied the differences between using ANICE with a gravitationally self-consistent sea-level, and with global mean sea level. At last glacial maximum, the ice volume of the AIS is lower when including regional sea level due to the increased regional sea level due to increased gravitational attraction of the growing ice sheet leading to a small reduction in grounded ice. During the deglaciation, the differences in ice volume are small. The spatial variation caused by Northern Hemisphere ice volume changes over a glacial cycle is smaller than the spatial variation in regional sea level by Antarctic changes and is therefore considered a second order effect and not yet included in this model."

- The approach to infer the viscosity field is still not clear (Line 230-290). A detailed description is required on how the absolute viscosity values (the term stated in Line 281) are inferred from seismic anomalies.

The effective viscosity (the term stated in line 281) is described in equation 4. The parameters are described in equations 5a and 5b. One of the parameters is temperature and the derivation of temperature from seismic anomalies is extensively explained in Ivins et al. (2021) and Goes et al. (2000). We will clarify the text at this point and include an explanation of the method used to calculate temperature from a seismic model.

- The elastic thickness of the lithosphere considered for the 1D models differ from that of the 3D models, the former is set to 100 km and the latter is set to 35 km (Line 285). Please explain the reason for choosing these two different values. The lithosphere thickness is an important parameter particularly where there is localized loading and deformation, as a thicker lithosphere can have a damping effect on the GIA signal. So, to have a fair comparison, this parameter should have an equal value (or very close values) in both 1D and 3D settings. Therefore, at least one additional set of simulations is required where the elastic thickness of the lithosphere is set to 35 km in the 1D models. The associated model results should be revised based on this simulation. Furthermore, as mentioned in the previous comments, 35 km is not a good representative of the lithosphere thickness across East Antarctica. So, a sensitivity analysis with a thicker lithosphere (e.g., 100 km as set in the 1D models) in the 3-D simulations would be beneficial.

We recognize that we were not clear how the lithosphere was defined in the 3D model. The top 35 km is defined as fully elastic, but the effective lithosphere thickness varies depending on the effective viscosity. Thus the 35 km is a minimum thickness of the lithosphere. We think it is one of the benefits of this model that the lithospheric thickness is spatially variable in the 3D models, derived from seismic observations, and fixing the lithospheric thickness would make the 3D model less realistic . We therefore think that the comparison 1D/3D is the most valuable as it is now. To make this more clear we will make the following changes:
In figure 1, we will change the word "crust" to "lithosphere".

In table 1, we will not refer to the "crust" but to the "top layer" and we will change "upper mantle 1" into "transition zone" as this layer is partly lithosphere and partly mantle, dependent on the dislocation and diffusion parameters. In the text, we will add the following sentence in line 22: "The lithospheric thickness is therefore spatially variable and follows from the dislocation and diffusion parameters. The effective mantle viscosity determined by these parameters will lead to a thicker effective lithosphere than 35 km in most of Antarctica. Thus, the second model layer partly consists of lithosphere and partly of upper mantle. In the 1D model, the lithosphere is prescribed at 100 kilometers thick which is similar to the lithospheric thickness used in Gomez et al. (2018)."

- The model outputs that are presented in the result section are based on only one iteration over the coupling time step, as the maximum differences are flagged as the outliers, and it is declared that the absolute mean of the maximum differences is 2.4 m. However, based on Fig. 5, there seems to be a significant difference between changes in the ice thickness and bed elevation of the second iteration and those of the first iteration. Also, the comparisons that are provided in section 2.4.3 are not clear that belong to which simulations. Therefore, this section requires more explanation and clarification with supporting figures in the supplementary section. Furthermore, based on the provided reasoning and Fig. 5, it is not convincing that only 1 iteration is sufficient to achieve the convergence criteria. In addition, if the results are based on only one iteration, section 2.4 (including Fig. 4) and elsewhere in the manuscript needs to be revised to declare that only one iteration per coupling time step is performed. Otherwise, it would be misleading for the reader.

The differences shown in figure 5 are less than 10 meter on a total of 150 meter deformation over 5000 years which we consider small compared to other uncertainties resulting from uncertainty in the GIA model inputs. We will add a new figure to show these differences at 8000 years BP. We could reduce the uncertainty by iterating However, that would also increase the runtime. Extensive testing showed that it is more efficient to choose a sufficiently small coupling time step rather than to iterate multiple times per coupling time step.

The coupling method as visualized in figure 4 includes the iterating process because the number of iterations needed depends on the chosen coupling time steps, the change in load over time and the Earth structure. For these simulations, we have chosen sufficiently small coupling time steps considering the change in load and the different Earth structures in the simulations. We therefore only need to iterate 1 time. However, changing the Earth structure or the period of interest requires new testing. We therefore include the full method, including the iterating process, in figure 4.

Following your suggestion, we will better emphasize in the text that only 1 iteration is used by adding the following text at the end of section 2.4.3:
"Considering the insignificant improvement and long computation time of multiple iterations, only 1 iteration is used for results in the remainder of the paper. This means that for each coupling time step first the ice model is run using the deformation over the former coupling time step, next the GIA FE model is run with the new ice load from the ice model and finally, the ice model is run including the new deformation of the GIA FE model."

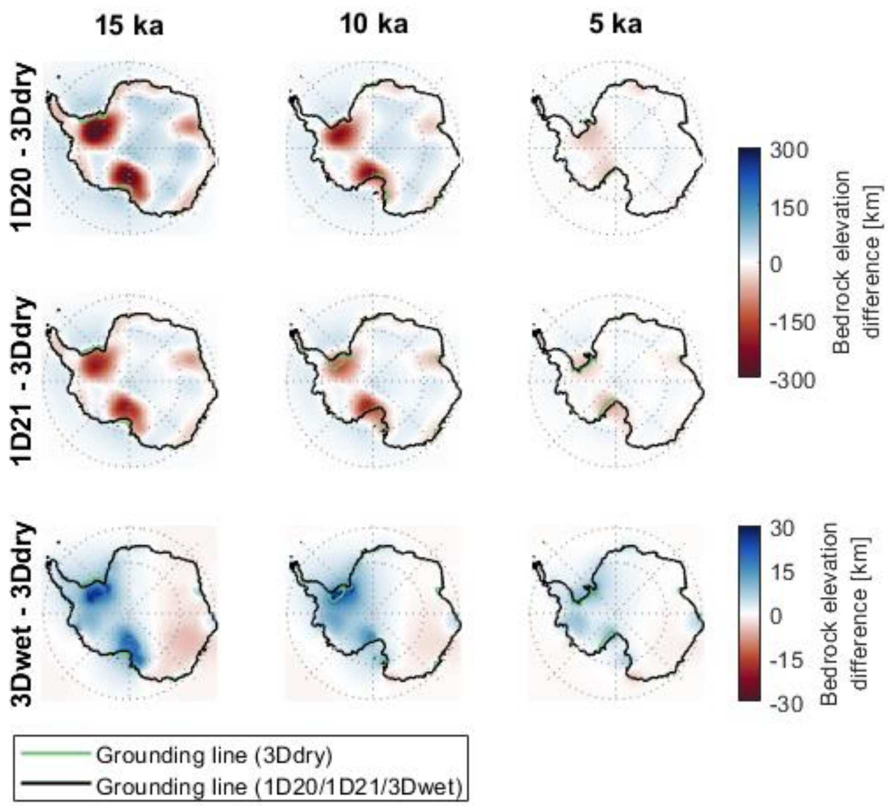
- The result section can be developed further to include detailed discussion about different aspects of the model results, particularly when compared with other studies that performed GIA-ice sheet coupling approach. There is lack of model comparison with observational constraints, some constraints that can be considered here include: present-day (grounded) ice elevation and grounding line position, surface exposure age data, and relative sea-level records. As mentioned, while the similarities between the model results of this study and other coupled GIA-ice sheet studies are considered, there is lack of investigation of the mismatches, data-model comparison enables the authors for performing a better evaluation in this regard.

In this paper we present the coupling method and study the sensitivity of the coupled model to different mantle rheologies. Comparing model results at present day to observations is only valuable if the ice-sheet model is calibrated to present day conditions. However, this calibration is different when different Earth structures are used. That means that parameters in the ice-sheet model differ per simulation, which is not desirable for a sensitivity test regarding GIA. It would be a large step forward to simulate a glacial cycle calibrated to present day observations for future studies, this is a very large task that is also not performed in other studies where coupled models are presented (Gomez et al., 2018; Konrad et al., 2015; deConto et al., 2021). We agree that the differences with other coupled GIA-ice sheet studies are important. Therefore we will add a new simulation that is similar to the earlier 3D GIA – ice sheet model

(Gomez et al. 2018) which applied coupling after 40 kyr time step, as suggested in the following review comments.

Furthermore, the current plots do not adequately support some of the provided information/numbers within the text.

We are not sure what plots are referred to here. For example, the numbers in lines 444-445 are supported by figure 6, the numbers in lines 462-464 are supported by figure 7 and the numbers in 473-474 are supported by figure 8. We assume you refer to comment on line 454 and we will include a figure showing bedrock elevation differences between using different Earth structures, as shown below.



- As the final remark, the dynamic coupling is introduced as a feature element of the modelling in this study in comparison to other studies with coupled simulations (e.g., Line 337-340). However, its implications are not explored thoroughly. It would be interesting to see how the results differ from the case when coupled GIA-ice sheet model is done alternately at once over the entire simulation time in order to highlight its impact.

Thank you for this suggestion, this is indeed useful to show the effect of a key aspect in our model. We will perform a simulation where the coupled GIA-ice sheet model is simulated at once over the entire simulation time and analyze the differences. We will present the results in the new manuscript/supplementary materials.

specific comments

Line 17 in abstract. " … on a high temporal resolution …", since a combination of temporal resolution is used in the manuscript from 5000-500 years I would suggest not using the term "high temporal

resolution" and please provide an accurate statement accordingly.
We will add the following sentence in line 18 of the abstract to clarify the coupling time step:
"The feedback effect is taken into account on a high temporal resolution where the coupling time step varies between 500 and 1000 (in the glaciation phase) and 5000 years (over the deglaciation phase) over a glacial cycle."

Line 19. Please be specific about the applied seismic model.
We will add the following to the sentence in this line:
"a regional seismic model for Antarctica embedded in global seismic model SMEAN2."

Line 21. Please be specific about the region(s) where these maximum differences occur.
We will include the regions in the text.

Line 26 in introduction. " …. is the response of the solid Earth …", one important aspect of GIA is its effect on the gravity field of the Earth which is essentially tied to the definition of sea level (and so the bedrock elevation). Therefore, solid Earth does not reflect this point adequately. Please revise this sentence accordingly.
The gravity field is inherent on the solid Earth so the response of the solid does reflect this effect as well. Also, this sentence is a quick introduction to what GIA is and the effect of gravity is a secondary effect (its a result of a change in surface load) and is discussed later in the introduction and in the method section.

Line 34-36. " … causing a local shoaling of water and an outward movement of the grounding line to position p3 (Fig. 1). As a consequence, the GIA feedback slows down migration of the grounding line (…) and acts as a negative feedback (e.g. Konrad et al., 2015)". The relation between ice flux, water depth and the ice thickness need to be clearly stated here as the reason behind the stabilizing effect of the GIA and the readvance of the grounding line.
We will split this sentence and explain the relation more explicitly:
"Due to a decreasing ice thickness, and thus a decreasing ice load, the Earth's surface experiences a direct instantaneous elastic uplift and a delayed uplift of the viscoelastic mantle of the Earth, represented by the dashed brown line. The uplift of the bedrock causes a local shoaling of water, decreased ice flux towards the ice shelves, and an outward movement of the grounding line to position p3 (Fig. 1)."

Also, is there a reason that the final sentence and its associated reference is not followed immediately after the previous sentence with a combined list of references?
We will combine the references at the end of the sentence.

Figure 1. Change Elastic "crust" to Elastic "lithosphere" as the latter also includes the part of the upper mantle that is brittle in addition to the crust.
Thank you, we will change this.

Line 45-48. The gravitational effect of the GIA impact the grounding line migration and the ice retreat, the phrase mentioned "apart from the effect on the grounding line" is confusing and does not apply in this case. Please revise accordingly.
We will clarify this sentence and change it into:

"There exist other GIA feedbacks on the ice sheet and grounding line evolution apart from the direct effect on the grounding line via the bedrock elevation"

Line 50. Please clarify how the final feedback "Finally, .." differ from the process illustrated in Figure 1 and the beginning of the introduction section?
We will clarify this feedback and add the following:
"Finally, GIA stabilizes the ice sheet as it reduces the surface elevation change of the ice sheet caused by surface melt in a warming climate. The reduced lowering of the surface elevation thereby suppresses melt rates."

Line 65. "Some 1D GIA-sea level models also account for relative sea level change", please clarify how these differ from the 1D models that account for gravity field perturbations and displacements as mentioned in previous sentence.
We will add "by solving the sea level equation" to this sentence.

Line 65-66. The models and references cited here are referring to the studies rather than different models. For example Nield et al., essentially uses Whitehouse et al., 2012 GIA model and similarly DeConto et al. and Gomez et al. uses a similar GIA model. So, this is confusing whether the authors are using examples for different studies or different computational methods. If latter, there are some references that can be referred to as the first generation of the 1D GIA models that should be used. Please clarify.

We meant to refer to 1D GIA studies so we will replace "some 1D GIA-sea level model" by "Some 1D GIA studies".

Line 68. The relevance of the reference "Geruo et al., 2013" is not clear here, please clarify the reason for choosing this reference.
Geruo is the reference for the global average lithospheric thickness. We will also include Gomez et al., 2018 as a reference.

Line 70. "although for the Eurasian ice sheet, … (van den Berg et al. 2008)", the relevance of this sentence to previous sentence is not clear and also the cited reference does not include such conclusion. Please clarify and also mention which page and paragraph this statement is mentioned in van den Berg et al. 2008.
The statement is taken from the conclusion of van den Berg but at this point in this context it is not relevant. We will replace the sentence in lines 68-72 by:
"Additionally, ELRA neglects the size dependency of the Earth's response to ice loading (Wu and Peltier, 1982), larger ice sheets respond to deeper Earth characteristics and smaller ice sheet respond to shallower Earth characteristics. ELRA models also ignore the effect of self-gravitation of the Earth and the ice sheet. The present-day ice surface elevation resulting from a coupled 1D GIA – ice-sheet model with a mantle viscosity of 1021 Pa s can be achieved with reasonable accuracy by the ELRA approach with a relaxation time of 3000 years, but the accuracy for other relaxation times is not known."

Line 103-104. "from the previous interglacial", please indicate clearly the temporal coverage with respect to the present time.
We will adjust that.

Line 109. “In this study we neglect the spatial variations in sea level.”, how is sea level defined here? This makes a confusion as the GIA model is essentially referred to as a “sea-level solver”. Please clarify this and add more description.
We will remove the sentence about spatial variations in sea level in line 109 because at this point in the text, this sentence seem to be only confusing. We think it is better to mention it in the method section where we can explain it in detail (lines 135-141).

Line 122 in method. “individually or simultaneously on different equidistant grids for each ice sheet”. How does simulation on different grids differ from the term individually mentioned here? Please rephrase this sentence for more clarity.
We will rephrase this into:
“The ice-sheet model ANICE is a global 3D ice-sheet model allowing to simulate the AIS, Greenland ice sheet, Eurasian ice sheet and North American ice sheet separately or simultaneously (de Boer et al., 2013). Each ice sheet can be simulated on different equidistant grids.”

Line 123. Does the usage of the term “typically” mean that the horizontal resolution can be adjusted, e.g., to higher resolution over a given region? If there is an option for adjusting the grid resolution, what is the justification for choosing a 40-km grid resolution over AIS and not 20 km? Are there any technical difficulties involved? Please clarify.
We will remove the word “typically” to not cause any confusion. Changing to another grid resolution does require new interpolations of input fields and the running time would be very long. Adjusting the grid size in parts of the domain is not an option in this (and most) ice flow models.

Line 136. Indicate here that the model does not take into account this regional sea-level variations.
We will create a separate paragraph to discuss this topic by separating lines 121-135 and 135-141 and adding the results from a test from de Boer et al. (2014) as discussed above in the general section of this review.

Line 136-137. By stating “similar throughout Antarctica”, does this mean the effect of the NH ice sheet on the evolution of Antarctica? If so, this effect has been recognized to be noticeable by the study “Antarctic ice dynamics amplified by Northern Hemisphere sea-level forcing”, Gomez et al., Nature, 2020. Please clarify. Line 137. “The effect of the AIS itself on regional sea level is more important”, what aspect is considered here when stating “more important”, as the change in regional sea level provides feedback to AIS and this is the foundation of the coupling approach which is considered to be quite important. Line 140. “the effect of regional sea level variations is a second order effect compared to the GMSL variations …..”. What is the justification for this statement? Line 136-141. “The effect of the northern … yet included in this model”. This part seems to include information that are not necessary and can be removed.
This part is essential information as this section explains why we don’t include the effect of regional sea level on ice dynamics.

Gomez et al. (2020) is a better suitable reference, we will include it and clarify the sentences concerning the NH ice sheets and the effect on regional sea level. We will adjust the sentence in the following way: “Although the effect of the northern hemisphere ice sheets on GMSL is significant, the effect of the AIS itself is most important concerning regional sea level (Gomez et al., 2020).”

We will clarify the last sentence of this paragraph stating that we don’t include regional sea level effects. It is therefore also not the foundation of the coupling approach presented in this paper. We will adjust

the last sentence in the following way:
“However, the variation in GMSL over a glacial cycle is bigger than the spatial variation regional sea level and is therefore considered a second order effect and not yet included in this model.”

Line 147. “at time steps of 1 year”, is 1 year the computational time step of ANICE? Please mention this temporal resolution of the ice sheet model at the beginning of this section where the spatial resolution of 20 km and 40 km are noted.
We will do that.

Line 159. “it computes bedrock …. on a spherical Earth”, what are the assumptions of the Earth model here? Does the model assume it as an incompressible material? If so, please add this information. Also, what is the assumption for the rheology of the Earth?
We will add the following:

We include material compressibility by using a Poisson ratio of 0.28. However, the effect of change in density required for full compressibility is not included as in e.g. Wang et al. (2008)

Line 11. “over the full glacial cycle”, indicate the time window of this study.
We will change it to “over the past 120000 years” (we assume you are referring to line 170).

Line 174. Wu et al. (2004) demonstrate that achieving the solution to include self gravity below 1 per cent error requires 4-5 iterations. Please quantify how much the lower number of iterations affect the accuracy of the results.
In the simulation of Wu et al. (2004), each iteration runs the sea level equation and the self-gravity. More iterations were needed for the SLE. We will quantify the effect of self-gravity in the paper by adding the results of a test with the number of iterations of the self-gravity.

Line 175. “The same iteration within each time step …”, what is the purpose of this, please clarify and also state that whether this has been performed in this study or not.
We will clarify this as follows:
“For future studies, the same iteration over each coupling time step could be used to compute the sea level equation that was included in the original model (Blank et al., 2021) and rotational feedback (Weerdesteijn et al., 2019).”

Line 190-194. Add relevant references and relative plots/results for justification of the statements.
We will clarify the results of this test in the text. We will also refer the added explanation of regional sea level in the method section of ANICE, as explained above in the general comment section of this review (de Boer et al. (2014) studied … not yet included in this model).

Line 196-197. Is the lithosphere thickness considered as a constant value? Please provide information about the applied lithosphere thickness value/model.
We will change all the mentions of “crust” into “lithosphere”. Furthermore we will clarify the information about the lithosphere thickness from line 223 as described above in the general comment section of this review.

Line 201. “Since the difference in deformation is insignificant, …”, the maximum difference of the performed test is associated with a viscosity of 10^{20} Pas. This is while there are regions of very low

viscosity beneath western AIS. It would be useful to see the similar graph for a lower viscosity of e.g., 10^{18} Pas. Also, the information about the radius of the applied load in the test is not provided in the description of Fig. S2, please add this information.
We will include the radius in the description. The runtime of the 1D model with a viscosity of 10^{20} Pas is almost 10 minutes. We performed the same simulation using this resolution with a 3D rheology and the runtime was 42 minutes. The test you are suggesting is interesting, but it won't change the choice of resolution because the increase of resolution is very expensive in computation time.

Line 218. Cite table 1. Line 218. The order of the details is making confusion. I would suggest to bring the details according to the depth, as in table 1, starting from the lithosphere, so one would not need to wonder about the viscosity values considered for the upper parts of the mantle above 210 km of depth.
We will do so.

Line 220. Whie considering a thin lithosphere is appropriate for the western section of AIS, the eastern region is characterised by thicker lithosphere. A sensitivity test is required to explore the effect of considering a thick lithosphere on the results.
We will clarify the lithospheric thickness in the model, as described above in the general comment section of this review.

Line 221. "..with specific dislocation and diffusion creep parameters..", the assumption of a composite rheology should be noted in section 2.2 (see comment of Line 159).
We will do so.

Line 226. Table 1, change crust to lithosphere (as crust is a compositional layer of the Earth).
We will call it the top layer as this layer can represent lithosphere and mantle.

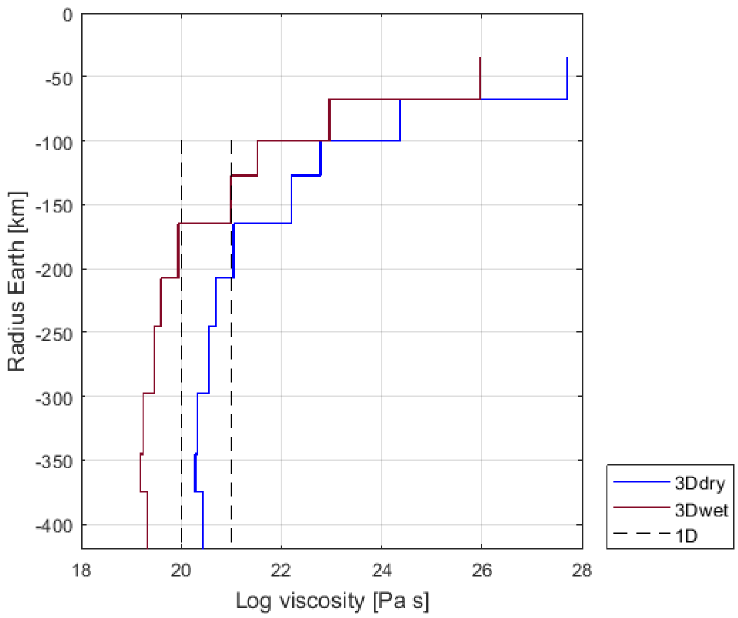
Line 251. If A is a constant, it should be mentioned here.
We will do so.

Line 254-255. Which seismic models? move this information that is mentioned later to this sentence.
We will move the reference to Lloyd et al. to this sentence.

Provide details about approach 3 in Ivins et al., 2021, if provided it is not clearly linked in the following sentences.
We will provide a short explanation about this approach in the text.

Line 272-274. It would be useful to have a figure in the supplementary material showing the viscosity profile for the two models, 3Ddry and 3Dwet, at some locations in e.g., Amundsen Sea sector, Antarctic Peninsula, etc.
We will include viscosity profiles as shown in the figure below for multiple locations, respectively at the Siple coast, in the peninsula and in the centre of East Antartica. We will indicate the locations in figure 3. The figure below shows the viscosity profile at the Siple coast for the 4 different rheologies for each layer in the GIA model, assuming a pressure of 1MPa. The viscosity of the 3Ddry model is approximately 1 order of magnitude higher than the viscosity of the 3Dwet model. At depths below 170 km, the 3Dwet viscosity is lower than the 1D20 viscosity. The 3Ddry viscosity stays higher than the 1D20 viscosity at all depths, but is lower than the 1D20 viscosity at depths below 220 km. It should be noted that the response of the bedrock to changes in ice loading does not depend on the local viscosity, like shown

here, but on the viscosity of the whole region where the change in ice load occurs.



Line 282. "…assuming only a temperature profile and not a viscosity profile.", it is not clear what assumption is made here.
We will change the part of the sentence into:
"without the need to assume a background viscosity profile."

Line 230-290. Please cite Table 1 where there are numbers pointing to the values in this table.
We will add a reference to table 1 where appropriate.

Line 289-290. "Therefore, the rheology …", this sentence is implicit in the previous sentence so it can be removed.
We will do so.

Line 301-302. What are considered as the ANICE output here? The topography and the ice loading? Please specify.
We will specify that the ANICE output is the change in ice thickness over the coupling time step.

Line 310. "Furthermore, the ice thickness is linearly interpolated …", this is confusing which method is used for interpolation of the ANICE output on the GIA grid, as in Line 306 it is stated that the quadrant method is used for gridding from a coarser ANICE grid to a somewhat finer grid of the GIA FE model. Please clarify.
We will add that the input for the GIA model is defined on a regular grid of 0.25 degrees latitude and longitude. This is then linearly interpolated to the irregular grid of the GIA FE sphere.

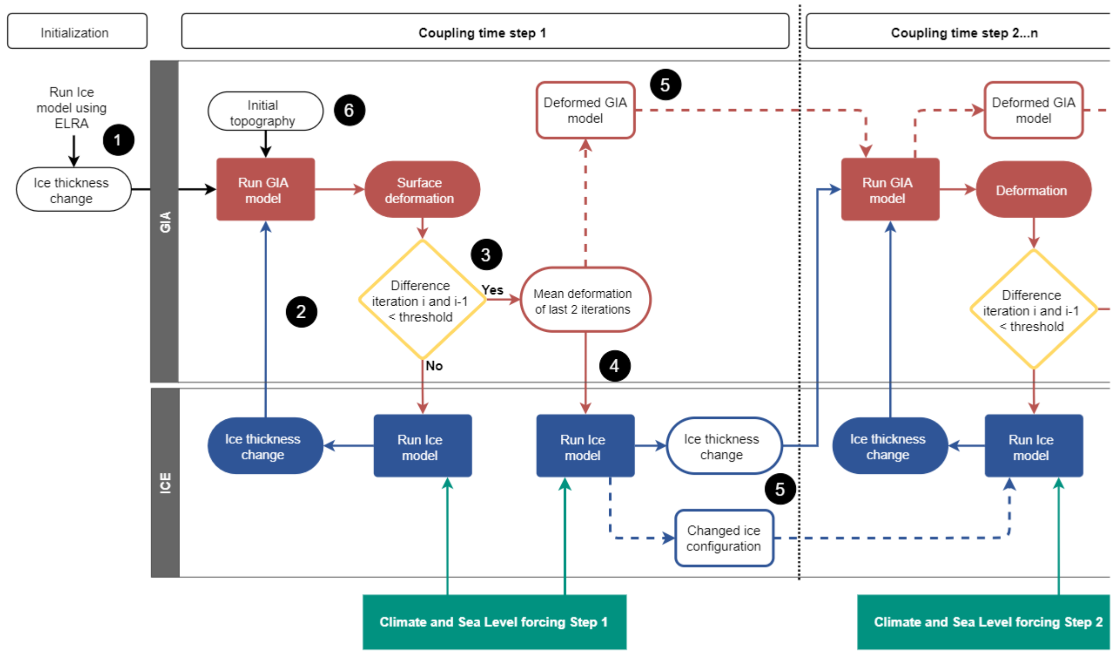
Line 298-311. This section (section 2.3) can be placed in the supplementary material and a sentence can be added in the coupling section to mention that the GIA and the ice model outputs are generated on different grids and the corresponding interpolation method is described in the supplementary section.
We will do so and add a sentence about the interpolation in line 315.

Line 312-345. In my opinion, instead of explaining the coupling approach for each coupling time step, first the big picture of the modelling can be described, including the coupling scheme. This is because the current explanations of the model make some confusion that will be resolved later but would be better if the steps are clear as the reader goes through the manuscript. For example, in GIA modelling, the difference between the observed modern topography and the predicted one is used to update the initial topography, and this is done in an iterative process. This is mentioned later (lines 342-343), but it would be much clearer if the entire modelling scheme is shown in the figure and included in the bullet points.

We will the iteration over the glacial cycle as bullet point 6 with the following text:

"Apart from iteration during a coupling time step there is another iteration in the model. This is introduced because there is a mismatch with present-day topography. Similar to GIA studies when solve the sea level equation we iterate."

We will also include the change of initial topography in the scheme. Please find the new scheme below.



Line 335. Figure 4. Following my previous comment, as there are n steps involved, the figure cuts just after coupling time step 2. I would recommend revising the figure so that it shows the entire performed approach including the following time steps (or the final, n^{th} time step) after time step 2 and the iteration for the convergence of the present-day topography.

Presenting more steps in the scheme would complicate the figure further. We will change "step 2" into "step 2…n" as the last step is no different from step 2. We will make clear the coupling within a time step as it is new, whereas the iteration over the glacial cycle is similar to other studies.

Line 315-316. And also in Lines 145 and 187. " …. developed that alternates between the models per time step of 500 to 5000 years.", from the statements it is not clear that the model alternates between these coupling time steps, it may give an impression that the model is performed for each of these

coupling time step. So, please revise the associate sentences accordingly. In addition, please provide a short sentence of the criteria used for choosing the time step.
The model does not alternate between the coupling time steps but between the models. We will add an overview of the coupling approach in the beginning of section 2 (starting at line 117). We will change section 2.4.1 and 2.4.2 so that the criteria for choosing the time step is discussed right after the coupling method.

Line 349. Fig 5 can be moved to the supplementary section.
We believe this is very helpful for the reader to understand how the coupling works. Given that the other reviewers didn't argue for this, we prefer to maintain the figure in the main text.

Line 348-349. For that given rheology? Is the number of iterations also dependent on the assumed rheology (e.g., regions with lower viscosity experience larger GIA signal upon ice load change)?
Yes, we will add that to the text.

Line 350. Mention the associated Earth model (e.g., 1D21 rheology).
We will do so.

Line 347-350. I would recommend starting the paragraph with a general statement, e.g., the number of iterations per coupling time step to converge is dependent on the rheology and the size of the ice load. Our simulation shows that for a given rheology, the 1D21 model, The coupled model requires three iterations per coupling …. or something like this.
Thank you for the suggestion, we will follow your suggested order.

Line 365-366. "the uncertainty range of the GIA FE model based on uncertainties from the rheological model such as background temperature and seismic velocity …", using "such as" here do not seem a proper link here. I would suggest the usage of other terms such as associated with, etc.
We will rephrase the whole sentence to:
"This uncertainty is less than the effect of the uncertainties of the input parameters such as background temperature and seismic velocity (e.g. Blank et al. 2021) and accuracy of paleo sea level records."

Line 379-385. These sentences can be reordered for the purpose of clarity. Here is my recommendation: First bring up the point that "The convergence of the coupled model depends on the length of the coupling time step, since smaller time steps increase the number of grid cells converging to zero." Then mention that there are other factors than the length of the time step that affect the convergence: "The convergence is also highly dependent on the change in deformation and ice thickness such that the time steps need to be chosen sufficiently small to have nearly linear changes in ice thickness and bedrock elevation." Then declare the disadvantage of smaller time steps: "On the other hand, a large time step is desirable to limit …"
Thank you for the suggestion, we will do so.

Line 389-390. "but their method assumes a constant topography during one coupling timestep which requires smaller timesteps than the coupling method presented in this study.", what does it mean by "a constant topography" in the study of Han et al., 2022? As stated in section 2.4, a total deformation from GIA model is passed to the ice sheet and the next coupling time step, which seems a similar concept as the coupled simulation applied by Han et al. Please clarify. Also, Han et al. (2022) suggested 200 years as the shortest and preferred coupling time interval for glacial-cycle simulations. Please revise the

sentence. Considering the 0.2 kyr as their preferred coupling time interval, how do you justify the selection of the 500 year coupling time interval?
We notice that preferred 0.4 kyr accounts for another period and not for the deglaciation phase. We will adjust the text to clarify the difference in our approach to the method used by Han et al. 2022:
"Han et al. (2022) showed that coupling time steps of 200 yr are optimal for the deglaciation phase in their coupled 1D GIA – ice-sheet model, but their method assumes a constant topography during the coupling timestep, which is not the case here, and the topography is updated only at the end of each time step. In our simulation, the topography changes linearly during the coupling timestep and is updated every year. In addition we run the ice-sheet model twice per coupling time step, whereas in the method of Han et al., (2022) this is only once per coupling time step. The method of Han et al. (2022) therefore requires smaller coupling timesteps between GIA and ice-sheet model than the coupling method presented in this study."

Line 398-401. "The absolute maximum …" it is difficult to follow these sentences, Are the two numbers associated with the absolute maximum difference in ice thickness between the 1-iteration and multi-iteration simulations? Please clarify. "the absolute mean of the maximum differences …. Is 2.4 m", To which parameter this number belong?, "The maximum difference in ice thickness at present-day …", how much is the difference and where it occurs?
We will clarify in the text that it concerns the difference between the converged simulation and the simulation with only 1 iteration. We will also include a figure to visualize the numbers mentioned. We will adjust the text as follows:
"The maximum deformation and ice thickness differences between the converged simulation and the 1 iteration simulation vary per time step. The absolute mean of the maximum differences at all grid cells over all time steps is 2.4 meter of ice thickness. There are two outliers at 8 kyears before present. The absolute maximum difference is 1365 meter in ice thickness at one ice sheet grid cell, and 1045 meter at two different grid cells in our simulations."

Line 414. The term "subsidence" would be a more appropriate choice here.
We will adjust that.

Line 414. "Ice shelfs in West Antarctica will melt less … due to the higher bedrock elevation", any reference?
This was a mistake, ice shelves should be ice sheet. We will adjust the sentence as follows:
"The ice sheet in West Antarctica will melt less and less bedrock uplift will occur during the deglaciation phase when a stronger rheology is used due to the higher bedrock elevation."

Line 416-418. "Differences in ice sheet evolution during the deglaciation phase are then mainly caused by a different topography at last glacial maximum rather than differences in rheology.", It is difficult to follow why the previous sentence leads to this conclusion. Also, the relevance of this statement to the following sentences are not clear. Please clarify.

Lines 114-118 are adjusted as follows:
"The bedrock elevation at last glacial maximum is higher in case a rheology with a larger mantle viscosity is used since there is less subsidence during the glaciation phase. Due to the higher bedrock elevation at last glacial maximum, the ice sheet in West Antarctica will melt less and less bedrock uplift will occur during the deglaciation phase when a stronger rheology is used. The differences in melt during the deglaciation phase between using different rheologies is then not caused by the direct effect of different

rheologies on uplift rates, but by the difference in bedrock elevation at last glacial maximum. The direct effect of different rheologies on ice dynamics during the deglaciation phase can be isolated if the model is constraint using the observed bedrock topography at present."

Line 432-500. The results section can be presented in another way, by categorizing the subsections based on different time intervals. For example, one subsection is assigned to LIG to LGM, another subsection covers the last deglacial retreat, either from LGM to present day or this can be divided into LGM to late Holocene, and late Holocene to present day. This approach facilitates investigating the model outputs.
We have used this approach when analyzing all the results and we chose to focus on presenting the new method and model by showing the most outstanding results in this paper, which are the results of the deglaciation phase.

Line 444. In "At present day, the ice is up to 1 km thinner around the grounding ….", this information cannot be inferred from the figures provided, so it is suggested to provide a zoomed map of the places where such information are provided. Also, a figure can be added as "data-model" comparison where the present-day observed ice thickness and grounding line position is compared to the model results.
Line 451-501. As mentioned in earlier comments of the result section, the model outputs provided in this subsection can be compared to observational constraints, such as the modern ice thickness, to better investigate the efficiency of the developed 3D models.
As mentioned above in the general comment section of this review, we do not aim to simulate present day ice thickness and grounding line position as close to observed as possible since that requires a different method, but moreover a tedious initialization of the ice-sheet model, which is at the heart of state of the art ice sheet models, but not resolved and therefore not easily available for the type of applications presented here. It would be very interesting work for a future study.

We will improve the quality of the figure. Other than that, the light red is visible in figure 6h.

Line 438. "These simulations also allow to study the differences between ..", this sentence seems that do not follow the flow of the text and can be removed.
We will do so.

Line 454-454. Any statement should be cited to the associated figure, if not provided, one should be generated to support the statement within the text.
Line 454. "In the 1D simulations, the bedrock subsides approximately 500 meter less", the same comment as the previous one, the statements should be supported by appropriate plots.
We will provide a figure with deformation rates.

Line 458-459. "During the deglaciation phase, the Ross and Filchner-Ronne Ice Shelfs retreat fast due climate warming, similar to other studies of the AIS evolution suggest (e.g. Albrecht et al., 2020).", As mentioned earlier in the general comments of the result section, beside the similarities, the differences in the model results should also be investigated. As an example, there are some discrepancies on the timing of the thinning around ASE and Ross embayment, some studies suggest earlier deglaciation while in the study referred here the major deglaciation occur after 10 ka (though the more appropriate referencing is the part 2 of Albrecht et al., 2020, https://tc.copernicus.org/articles/14/633/2020/). So a more detailed comparison and discussion is required.
We present a study where we address the full coupling of a GIA and ice sheet model. Addressing the

timing of deglaciation is probably partly controlled by these processes but for a much larger part by the timing of the climate forcing to the ice sheet model, which is outside the scope of this paper.

Line 464. “Using a 3D viscosity leads to a difference in grounding line position of up to 500 km and a difference in ice thickness of up to 1.5 km at present-day”, this statement cannot be inferred from Fig. 7. Revise the plot accordingly. Also, “up to 500 km”, in which region?
We will add that we refer to the Siple coast and we will add a scale of 1000 km.

Line 470. Figure 7. the comparison should include all the models involved, particularly the two different estimated 3D rheologies, i.e., also add the 3Dwet results: 1D20-3Dwet and 1D21-3Dwet.
The difference in ice thickness between the two 3D rheologies is 12 times smaller than the differences between the 1D and the 3D rheologies. Visualizing differences in ice thickness between the 1D and 3D rheologies require a color scale in which differences between the two 3D rheologies are not visible. Visualizing 1D20-3Dwet and 1D21-3Dwet will therefore look exactly the same as the provided figures of 1D20-3Ddry and 1D21-3Ddry. We thus chose to show only the difference of 1D rheologies with the reference model 3Ddry and discuss the differences between the 3D rheologies separately.

Line 473-474. “the maximum difference in grounding line position is approximately 40 km (Fig. 8.g)”, in which region? This statement cannot be inferred from the plot.
We will improve the quality of the figure to it is not shown blurry and we will add the regions where this occurs to the text.

Line 490. Figure 9. change the plot based on the unit km^3.
We will do that.

Technical corrections
Thank you for providing these detailed corrections, we will correct them all.

Line 14 in abstract. “Most studies assume a relatively **high** laterally homogenous response time of the bedrock”. I would recommend using other adjectives instead of “high” that are used in reference to the “response time”, such as slow or long.

Line 17. Please revise the sentence “The feedback effect into account …” as it seems that the word “takes” is missed.

Line 18. Please change FE to finite element

Line 21. Change “…, to differences in ice thickness …” to ““…, and differences in ice thickness …”

Line 31 in introduction. Put “,” before respectively.

Line 42. “the dashed brown the new bedrock surface”, the word “is” is missing.

Line 59. Change Earths to Earth or Earth’s

Line 62. “Another approach …”, the verb should be singular. Revise accordingly, e.g., Another approach to compute GIA is using …

Line 82. “The only model that coupled 3D”, a past tense is used here while in some other places the present tense has been used. Please be consistent time wise when referring to a study.

Line 106. If FE stands for finite element, it has not been introduced before. Please indicate the full name of the method where first appeared in the text.

Line 112. I would recommend rephrasing of “as 3D Earth structures” as: “in comparison to 3D Earth structures“.

Line 114. Chane to “This method … ”

Line 140 in method. “sea-level” variations

Line 161. Can be written as: “…. based on ABAQUS is its flexibility as its grid size…”

Line 162. “and FE models operate in the time domain …” I would suggest to make this part as a separate sentence, otherwise the whole sentence is long and more difficult to follow.

Line 219. Change to consistent

Line 252. In Tx,y, the x,y indices should appear the same as the equation (as subscripts)

Line 279-280. “who obtained viscosity by scaling seismic …” and “background viscosity can be obtained from …”, using the term “obtain” in these sentences give the impression that the viscosity values are determined or tuned rather than being modelled. I would recommend using alternative terms such as model, estimate, infer, etc.

Line 284. “two experiments …”, I would recommend to rephrase this sentence for clarification, something like: “Two experiments are performed using a 1D rheology with two different upper mantle viscosity profiles: 10^{20} Pa.s (hereafter referred to as 1D20) and 10^{21} Pa.s (hereafter referred to as 1D21). These values are consistent with the lower and upper boundaries… . The elastic lithospheric thickness is the same for both experiments and is set to 100 km. “. A general comment: please keep the sentences short so that it will be easier for the readers to follow.

Line 359. It may read better:” In this case, both ice thickness and deformation at these … “

Line 364. The coupled model “converges” within an acceptable ….

Line 365. No need for comma after the GIA FE model.

Line 365-367. I recommend to move “accuracy of paleo sea level records” before “the uncertainty range of the GIA FE model” for clarity. So, the sentence reads: “This is within the accuracy of paleo sea level records and the uncertainty range of the GIA FE model …”.

Line 369-371. These two sentences can be merged as one single sentence, something like: To decrease this uncertainty, the average deformation of the last two iterations is used as the final deformation to simulate ANICE for the final iteration of a given time step.

Line 386. “ice sheet is slowly increasing till LGM,…”, increasing in what aspect? Extent? Volume? Please specify.

Line 398. Also everywhere else in the manuscript: change meter to “m”

Line 399. And elsewhere in the manuscript. Change kyears to kyr, kyr before present can be written as ka for simplicity

Line 420. “If they are not, it is assumed that initial topography is in error.”, this is implicit in the previous sentence and can be removed.

Line 426. And also Line 429. It seems that there is an extra parentheses in the subscript of $H_{b,ALBMAP)}$

Line 434. Change to “extent”

Lin2 449. e-“h”?

Line 460. Grounding line

Line 470. Figure 7 (and also Fig. 8). Indicate the depth associated with the 3-D model viscosity map.