We would like to thank the reviewers for their feedback. It improved the manuscript significantly. Please find the response to each reviewer below as has already been uploaded shortly after the review. After our response, we have adjusted the manuscript and conducted the extra simulations. We have performed new simulations of the last glacial cycle using the 3D rheologies and we have conducted extra simulations to test the coupling method. All the figures are renewed and we have add new figures in the revised manuscript and revised supplementary materials. Also many parts of the text are clarified. The data behind the new results is uploaded in a second version under the same doi. The changes can be found in the tracked changes file of the manuscript and the supplementary materials.

We look forward to your response.

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 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.

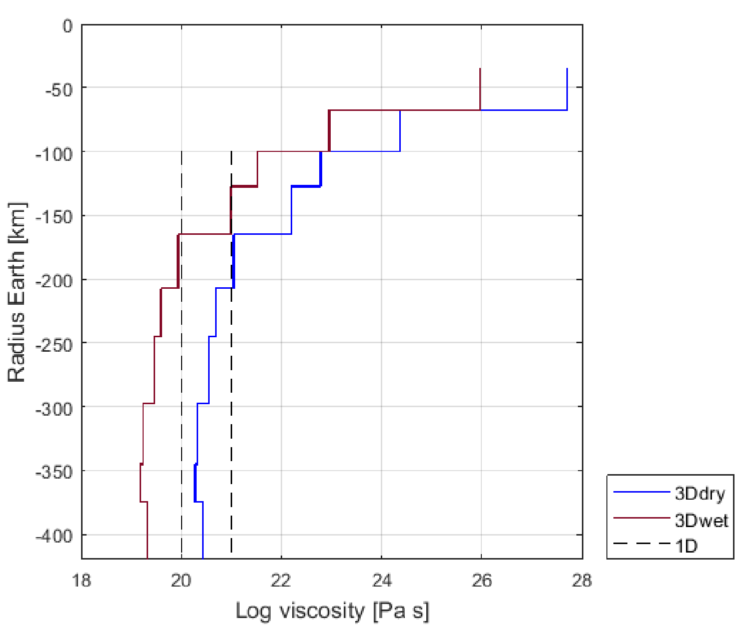
Line 226. Table 1, change crust to lithosphere (as crust is a compositional layer of the Earth).
We will call it the top layer as this layer can represent lithosphere and mantle.

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.

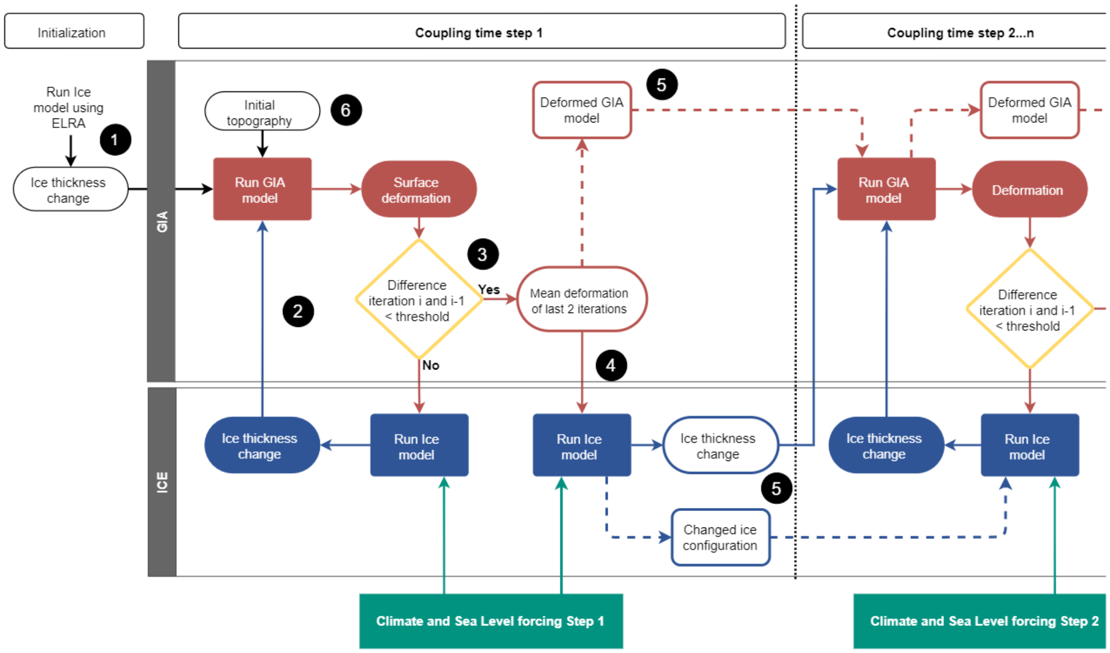
Line 289-290. "Therefore, the rheology …", this sentence is implicit in the previous sentence so it can be removed.
We will do so.

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.

Review of '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.

This manuscript documents the development of a sophisticated coupled model which robustly represents feedbacks between ice sheet dynamics and solid Earth deformation, accounting for spatial variations in Earth rheology. I am aware of only one other model that has the capacity to coherently represent these processes, which can act to stabilise a marine-grounded ice sheet and hence must be considered in reconstructions and projections of Antarctic ice sheet change.

The design and implementation of the model appears to be robust, and it is used to carry out a set of well-designed experiments, the results of which are clearly documented and summarized. I commend the authors on committing to release the code and the data once the manuscript is published. However, the description of how the model works is very confusing, justifications for model choices are not always rigorously presented, and there is some inconsistency in terminology which leads to ambiguity.

This is an important piece of work which has the potential to move the field forwards in terms of our ability to model coupled processes relevant to the development of the Antarctic Ice Sheet, but the current version of the manuscript requires significant revision to improve the clarity and hence impact of the study.

We would like to thank Pippa Whitehouse for the valuable and in depth review. Please find below in blue our answers to the comments. Line numbers refer to the originally submitted document.

Main points

Definition of Glacial Isostatic Adjustment (GIA): there is some inconsistency in the use of this phrase. In some places it is used to describe the deformation of the bed in response to ice loading (e.g. line 53), in other places it is used to describe a model that solves the sea-level equation, i.e. a model that calculates changes to the gravity field and hence sea surface, as well as the bed**.** This leads to some confusion when describing the capabilities of the model (also see next point).

We understand the confusion. We will not use the term 1D GIA-sea level models but only use 1D GIA models to represent the bed deformation in response to ice loading, and explain explicitly in lines 65-66 that most 1D GIA models also solve the sea level equation which we don't do in this paper. We will add Whitehouse et al., 2012 and remove Larour et al., 2019 from the references for GIA models that also solve the sea level equation.

In line 90-91 it is not clear whether only Gomez et al. (2018) include relative sea level or all 3D GIA models include relative sea level We will therefore remove "including relative sea level"

We will clarify the capabilities of our 3D GIA model by adding the following sentence in line 107:
"The 3D GIA FE model does not solve the sea level equation but the viscoelastic model does account for the effect of self-gravitation of the mantle deformation. GMSL from the NH ice-sheets is prescribed."

Definition of sea level and ocean loading: it is not clear whether the model solves the sea-level equation; if it doesn't, then it is not clear how the ocean loading component of the model is defined. Much of the confusion stems from a lack of clarity about what you mean by the term 'sea level' – does this phrase refer to sea surface height (defined by the height of the geoid) or water depth (defined by the height of the geoid and the seafloor)? You say that you neglect spatial variations in sea level (e.g. line 109, 192) – does this statement relate to spatial variations in sea surface height? (you clearly do model variations in water depth because you model the bed deformation). Line 175 implies that the model has the capacity to solve the sea-level equation, but I don't think this is implemented here – why not? Lines 188-191 attempt to describe how the ocean load is applied but the terminology is not defined clearly – what is the difference between 'global ocean loading' and 'the load of relative sea level'? – and consequently, it is not clear how the contribution from far-field ice sheets is handled or how the 'Sea Level forcing' (green box, figure 4) input is defined.

The sea level is the sea surface elevation. In lines 109 and 135-141, we mention that we neglect spatial variations in sea level and that we only take temporal variations in global mean sea level (GMSL) into account. We take the temporal variations in GMSL into account only in the ice model (to compute basal melt). That is why the green box in Figure 4 (referring to the sea level forcing which is the GMSL) has an arrow only to the simulation of the ice model and not to the GIA model.

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 clarify this 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 water depth is only implicitly mentioned in the manuscript because the term SL – Hb in equation 2 refers to the water depth because SL refers to the sea level and Hb refers to the bedrock elevation, both relative to where the sea surface elevation is defined as zero. Minus Hb is therefore the depth between the seafloor and the sea surface of elevation zero. The water depth is spatially variable because the bedrock elevation is spatially variable. In the original manuscript, we don't use the term "water depth" to not cause confusion.

Concerning the GIA model, we don't take sea level into account at all. We will change "surface load" to "ice load" in the paragraph of lines 178-187 to prevent confusion about the loading. We will also clarify the description of the ocean load test (starting at line 188):

How does the coupling work? When you first describe the ice and GIA models you mention that the 'bedrock elevation is updated' in the ice model (line 147) and a 'change in surface load' is applied in the GIA FE model (line 184). However, at this point, it is unclear how these inputs are defined. In the first case, it is unclear what ice load history was used to determine how the bed should be updated, and in the second case, it is not clear how the ice load is chosen for the GIA FE model. It later becomes clear that these inputs are defined by the 'other' model, and what you are describing is part of the coupled model, but this is not clear until page 12. It would be useful for the reader if you could include a summary of how the coupling process works earlier in the manuscript.

We understand that this is unclear. We will change the first paragraph of the method section (starting line 116) to:

“The coupling method that we present in this paper can be applied to any ice-sheet and GIA model, as long as the models have to possibility to restart at certain selected time steps. We applied the coupling method to the ice sheet model ANICE and the 3D GIA FE model, which are introduced in section 2.1 and 2.2. The coupling method alternates between the ice-sheet model and the GIA model for a given time step, where the ice-sheet model uses the bedrock deformation computed by the GIA model and the GIA model uses the changes in ice thickness computed by the ice-sheet model. Section 2.3 discusses the interpolations that are necessary to feed the ice-sheet model output to the GIA model and the GIA model output to the ice-sheet model. Finally, we describe the coupling method in detail in section 2.4.”

Coupling time step: what is the coupling time step, does it vary over the course of the glacial cycle? Is it the same for all experiments? The abstract states that the coupling time step is 500 years, but I think it actually varies within every model run. Information about this is ambiguous for much of the manuscript – clarify this earlier to avoid confusion. Also look out for instances where it is unclear whether something is implemented at the start of a time step or during a time step.

We will clarify this throughout the text. The coupling time step is the time period over which the ice sheet model and GIA model exchange ice thickness and bedrock elevation during a fully coupled transient experiment.

We will add the following sentence in line 18 of the abstract to clarify the magnitude of 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.”

We will rephrase the sentence in line 98 to clarify the meaning of coupling time step:

“We consider the coupling time step of Gomez et al. (2018) as 40 kyears.”

In line 106, we will remove “over time” and add which time step is used in which phase of the glacial cycle.

We will add the following information to the beginning of section 2 (after the text shown in the former answer):

“The models are coupled at a coupling time step that varies during a glacial cycle. During the glaciation phase, the coupling time step is 5000 years and during the deglaciation phase, the coupling time step is 1000 and 500 years. The size of the coupling time step is further discussed in section 2.4.2.”

Model resolution: I was surprised to see that the GIA model uses a finer grid than the ice sheet model because Earth deformation typically varies over longer length-scales than ice sheet dynamics. You test two grid sizes for the GIA FE model and decide to use the coarser grid because the ‘difference in deformation is insignificant' (line 201). Do you think it would be feasible to use an even coarser model, thus further reducing the computation time?

The resolution tests that we have done are conducted using a parabolic ice cap and are not done using a realistic ice history from the ice model. The choice of resolution for the GIA model is therefore independent on the resolution of the ice model. We understand that from the main text it seems that we only test on two different resolutions. The text in the supplemental materials describes the test in detail using 4 different resolutions. The error of using a coarser resolution than 30 km is less than 10 centimeters over a time step of 1000 years on a total deformation of about 171 meters so a coarser resolution could be used without increasing the error much. However, a coarser resolution does not lead a significantly shorter computation time. We therefore chose a resolution of 30 kilometers and not coarser. We will add the following in the main text in line 119 to clarify the test:

"For the sensitivity test, the GIA model is loaded with a parabolic ice cap for 1000 years using 4 different spatial resolutions, respectively 70, 55, 30 and 15 kilometers. The details of the test are described in Fig. S.2 in the supplemental materials."

Justification for model choices: various tests are stated to have been carried out to determine optimum choices for the coupled model, but the results are not always documented very clearly. Lines 188-191: there is no quantitative documentation of the results of tests carried out to determine how to apply the ocean load.

The differences in deformation between including and excluding ocean load on the GIA model were very small and are therefore not visualized but we will quantify the differences.

Line 383: you state that you tested the impact of using different coupling time step lengths, but I could not find the results of this documented anywhere.
We will add the following sentences in line 384:
"Using timesteps of 1000 years during the glaciation phase did not lead to significantly different results than using time steps of 5000 years. Shorter time steps during the deglaciation phase is possible but will lead to a large increase in computation time."

This section on coupling time step length (section 2.4.2) comes between two sections concerned with the number of iterations per time step (sections 2.4.1 and 2.4.3) – these sections would make more logical sense if they were adjacent, or even combined, especially given that you eventually do not use the convergence criterion described in section 2.4.1.
We agree and will move section 2.4.2 (the size of the coupling time step) before section 2.4.1 (convergence of the coupling time step).

The results of the tests described in 2.4.3 would benefit from being shown in a figure.
We will create a figure to show the difference between running a full glacial cycle with multiple iterations and only 1 iteration.

Ice shelves and ice shelf melt: the term 'ice shelf' is used incorrectly in many places – the Ross and Filchner-Ronne Ice Shelves are floating, but many references to these features appear to assume they consist of grounded ice (the embayments where they are located will have contained grounded ice during the Last Glacial Maximum).

We will replace the "Ross and Filchner-Ronne Ice Shelves" by "Ross and Filchner-Ronne embayments".
Separately, the description of how ice shelf basal melt is defined within the ice sheet model is unclear – it appears that sea level change plays a role (e.g. lines 133-136, 442-443, 485-486) but the assumptions behind this are not explained.
In calculating basal melt, only the global mean ocean temperature anomaly is taken into account, according to the approach proposed by Pollard and DeConto (2009) and not a temperature field. We also assume that the shape of the shelf and the distance to the open determine how much ocean water can flow, also taken from Pollard and DeConto (2009). This leads to relatively more melt at the calving front and less melt at the grounding line. However, from observations we know that this is not realistic. Last, we use a linear relation between ocean temperature and melt, taken from Martin et al., (2011). Improved method of basal melt calculations exist. However, we do not aim to reconstruct the best glacial cycle in this paper. Our aim is to compare the impact of different rheologies of the solid Earth. Since the computation of sub shelf melt is the same in all experiments, we are still able to compare the results. A detailed comparison with observations would require more than an improved meltwater parameterization.

We will adjust the text about sub shelf melt at lines 132-135 to include the most important assumption: "The position of the grounding line and GMSL determine whether ice is grounded or floating, thus whether the ice experiences sub-shelf melt or not. A combination of the glacial-interglacial parametrization by Pollard and DeConto (2009) to scale the global mean ocean temperature beneath the shelf, and the ocean temperature-based formulation by Martin et al. (2011) are used to compute sub-shelf melt. This parametrization assumes a linear relation between sub-shelf melt and ocean temperature. Changes in ocean circulation are not taken into account."

Climate forcing: it is not clear how the ice sheet model is initialized or what climate forcing is used. A figure is included in supplementary material (note there is an error in the caption) but data sources for surface temperature and eustatic sea level are not given, and it is not clear whether the 'surface temperature' is Antarctic-specific.
We will change the sentence in line 125-126 to:
"Atmospheric temperature and global mean sea level (GMSL) act as the main forcing for the ice-sheet model, as is shown in Fig. S.1, and are the result of previous ice volume reconstructions using ANICE and benthic isotopes forcing (Boer et al., 2011)".

The reference to Laskar in the caption of figure S.1 is indeed incorrect if that is what is meant by 'error in the caption'. We will clarify the information about supplemental figure S.1:
"Fig. S.1 shows the sea level and temperature forcing for the coupled model simulations. This forcing is the results of previous simulations of de Boer et al. (2013) where ANICE was used to reconstruct global ice volume and the continental mean temperature at the northern hemisphere. Those simulations used the LR04 benthic δ18O stack of 57 deep-sea sediment records as forcing (van de Wal., 2011). Possible output a past surface-air temperature and global mean sea level over time."

Additional details are needed to describe how precipitation, and hence mass balance, are defined in the past (lines 126-127).
We will add to lines 126-127 that the present day precipitation field is taken from ERA40. In Antarctica, precipitation is barely influenced by GIA and precipitation barely influences ice dynamics so we don't discuss it in more detail.

Earth model: do you need to represent the crust and the mantle separately in figure 1? How is the lithosphere defined?

With the word elastic crust we actually meant to refer to the elastic top layer so that would be the lithosphere. We will change the word crust in the figure to lithosphere.

The model description (line 205/table 1) refers to layers representing the crust and upper mantle, but the previous sentence (lines 203-204) and the results refer to the lithosphere; it would be useful if you could explain how you are defining/representing the lithosphere.
In the table, 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 effective lithospheric thickness is therefore spatially variable and follows from the effective mantle viscosity. If the viscosity in a region is so high that viscous deformation in one of the top layers is negligible over the entire cycle, the region can be considered to be part of the lithosphere (e.g. van der Wal et al., 2013; Nield et al., 2018). This 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).”

Review of previous work: “Another approach to compute GIA…” (line 62) – a model that ‘computes GIA’ is often assumed to be one that solves the sea-level equation. However, in this paragraph I think you discuss two different types of models – ones which only solve for bed deformation (using the SGVE approach) and ones which use the SGVE approach to solve the sea-level equation. Check that references are listed in appropriate locations, e.g. Whitehouse et al. (2012) do solve for sea-level change, but Larour et al. (2019) only model the elastic response to surface loading.

We will remove Larour et al. from the list and switch Nield et al. (2014) and Whitehouse et al. (2012) to the description of 1D GIA that does include the sea level equation.

Also, consider including a reference to the work of Coulon et al. (2021) somewhere in the introduction. Coulon, V. et al. (2021). Contrasting response of West and East Antarctic Ice Sheets to glacial isostatic adjustment. *Journal of Geophysical Research: Earth Surface*, **126**(7), e2020JF006003.

Thank you for this suggestion, we added an extra sentence at the end of the paragraph about ELRA: “To partly overcome this limitations Coulon et al. (2021) included regions with different relaxation times in the ELRA model to capture the main patterns of spatial variability in the relaxation time scale.”

Reporting results: key findings are nicely summarized in the text but I recommend including some plots showing differences in bed deformation or uplift rates as well as differences in ice thickness.
We will include a figure showing differences in bedrock elevation at the same time steps as figures 7 and 8 showing the ice thickness. Present day timeframe is not shown because the bedrock elevation difference between using different rheologies is close to zero due to the iterations over the glacial cycle. The bedrock elevation at 20 ka is higher when a 3Ddry rheology is used compared to using both of the 1D rheologies. This is caused by the feedback effect because a lower viscosity in the 3Ddry rheology leads through faster deformation which results in a smaller increase in ice thickness compared to using a

1D rheology. This results in a smaller ice thickness at LGM when a 3D rheology is used compared to a 1D rheology. The differences in bedrock elevation between both 3D rheologies is significantly smaller.

Also, rather than commenting on the volume of the modelled present-day ice sheet (line 482) (by definition, modelled present-day bed topography is nearly identical in all the simulations, so the motivation for comparing modelled ice thicknesses at this time is unclear), it may be interesting to comment on the total magnitude (or rate) of ice volume change between the Last Glacial Maximum and present for the various models. Do any of the models simulate grounding line re-advance?
Thank you for this suggestion, we will include the following sentences at the beginning of the paragraph: "Figure 9 shows that the ice volume decreases faster in the deglaciation phase for simulation with higher viscosity in West Antarctica. The 1D21 decreases faster than the 1D20 rheology dues to the slower uplift in West Antarctica as shown in Figure 7"

Even though the modelled present-day bed topography is nearly equal, there are still differences in ice volume, thickness and extend due to a different ice dynamic history. Thus we think it is still interesting to compare the modelled results at present day. There is no grounding line re-advance in the simulations.

In various places you talk about a model 'underestimating the ice volume' or 'underestimating the stabilizing effect of GIA' – such statements imply that you know what the correct result should be, which is rarely the case, e.g. lines 71, 497, 500-501, 518-519.
Indeed, we do not know the correct result, but we do know that the 3D mantle rheology is more realistic than the 1D rheology. In the text, we will clarify that we consider these statements to be relative to the more accurate 3D model.

Also, it is not always clear what time you are referring to when you report results, e.g. lines 20-21, 494-496, 513-516.
Thank you for pointing this out, we will add the time scale to these results.

Grammar: I recommend carrying out a thorough check for grammar – in a few places the phrasing makes the meaning of the text ambiguous.
We will do so.

Minor points that require clarification
General: make sure it is clear you are talking about mantle viscosity (as opposed to ice viscosity)
We will change the word "viscosity" into "mantle viscosity" throughout the full text.

General: make sure it is clear whether you are referring to a coupling time step, or a time step that is internal to the ice model or the GIA model
We will add the word "coupling" to the time step in lines 162 and 165. We will also clarify the internal time step of the GIA model in the first paragraph of section 2.2 by adding the following text:

"The surface loading is applied to the GIA FE model on a variable time step, hereafter referred to as the loading time step. Each loading time step is divided in a variable number of increments for numerical integration inside the finite element model. The size of each subsequent increment is determined based on how fast the computation of the deformation converges. In this study, each loading time step is divided in approximately 30 increments so that the nonlinear solution path can be followed."

Line 18: define ‘FE’
We will add the definition of FE (finite element).

Line 45: “…apart from the effect on the grounding line” – the processes that are subsequently described will also affect the position of the grounding line because they affect water depth.
We intend to outline the difference between the direct effects on the grounding line and the indirect effects. We will change the sentence of line 45 to: “There exist other GIA feedbacks on the ice sheet evolution apart from the direct effect on the grounding line.”.

Line 47: “meltwater flux towards the ocean” – not clear what this is describing
We understand that lines 47-50 are confusing. The meltwater flux towards the ocean is the meltwater expulsion towards the ocean due to a decreased accommodation space for melt water. As this only affects far field sea level it’s a higher order effect of GIA on ice sheet dynamics. We will remove it from the text to avoid confusion.

Line 48: “A decrease in sea level…enhances uplift” – explicitly link this to a decrease in surface load
We will do so.

Line 49: “GIA could flatten the bed slope” – only in some cases, disagrees with information in fig. 1
Line 50: be more explicit about how GIA “reduces the height change of the surface of the ice sheet”

Thank you for this comment. We will clarify these sentences like this:

“Second, GIA could steepen or flatten the bed slope dependent on the topography. A flattened bed slope decreases the rate of basal sliding and ice deformation and therefore decreases the ice flux and ice velocity towards the shelfs (Adhikari et al., 2014). 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.”

Lines 58-59: include a reference to help the reader understand the implications of the final sentence
We will add the reference to Wu and Peltier (1982) where the inverse relaxation time is shown in figure 2. The fact that the ELRA does not include the size dependency of the Earth’s response to ice loading follows from the fact that there is one relaxation time.

Line 123: which spatial resolution do you use in this study, and do you model multiple ice sheets simultaneously, or just Antarctica – it is not clear from this text, although later in the paragraph the text appears to be specific to Antarctica
We will add the sentence: “For this study, ANICE is used to simulate the Antarctic ice sheet evolution with a resolution of 40x40 km.” in line 125.

Line 139: “increase in sea level is reduced” – local ice loss will cause a decrease in local water depth
Thank you, we will replace “increase in” by “near field”.

Line 144: “adjusted to include” – do you include deformation from the GIA FE model instead of the usual deformation calculated by ANICE, or in addition to it?
We have reformulated this sentence into:

“For this study, ANICE is adjusted to use the bedrock deformation computed by a GIA FE model at coupling time steps of 500, 1000 or 5000 years instead of computing the bedrock deformation using the ELRA method”

Line 149: units of terms in eq. 1 do not match; final term needs a multiplier with the units of time – something that indicates how far through the coupling time step this particular ANICE time step lies.
Thank you for noticing this. We will change “dt” to $\Delta t_{coupling}$ and added Δt_{ANICE} to the equation. We also replaced Hb by b for clarification.

$$b_t = b_{t0} + \frac{db}{\Delta t_{coupling}} \cdot \Delta t_{ANICE} \, , \qquad (1)$$

where b_t refers to the updated bedrock elevation at the ANICE time step, b_{t0} refers to the bedrock elevation at the beginning of the coupling time step, $\frac{db}{\Delta t_{coupling}}$ refers to the total deformation of one coupling time step computed by the GIA FE model divided by the length of the coupling time step in years, and Δt_{ANICE} refers to the ANICE time step.

Line 153: I think deformation will be fastest at the start of a time step, and hence linear interpolation of this exponential process will under-estimate the deformation near the start of the time step.
Yes this is correct and is wrongly stated in the text. We will correct this in the text.

Line 171: what is the effect of including self-gravity?
We will quantify this and include the results of the test in the manuscript.

Lines 175-176: additional information is needed for the reader to be able to understand what is being described in the final sentence of this paragraph – I think these are the only mentions of the sea-level equation and rotational feedback. What do you mean by “can later be used”?
We are referring to the capabilities of the model that could be used in future studies. We will change the last sentence into:
“For future studies, the same iteration over each loading time step could be used to solve the sea level equation (Wu, 2004; Blank et al., 2021) and rotational feedback as done in Weerdesteijn et al. (2019).”

Line 178: make it clear at the start of this paragraph that the ‘surface load’ comprises an ice load and an ocean load, and always be clear which you are talking about.
We agree. Throughout this paragraph we will change ‘surface load’ into “ice load” since, for this study, no ocean load is applied as explained in response to the comments in the beginning of this rebuttal.

Line 180: “water dumping due to local bathymetry” – describe what this process entails
The changes in relative sea level entails this process but we will remove that part from the sentence as it is too vague.

Line 183: does ‘SL’ refer to the height of the sea surface or the local water depth? I think it is the former, which motivates the question: what is the reference elevation for ‘sea level’ and ‘bedrock elevation’. Note: ‘Hb’ refers to an elevation, which must be defined relative to something, whereas Hi,AF and Hi refer to thicknesses – consider using different letters for absolute and relative quantities.
SL is the sea level relative to present day sea level. The reference elevation for SL and bedrock elevation is present day sea level. Minus Hb is therefore the water depth where there is ocean.
We will add “relative to present day sea level” to the description of SL and Hb.

Thank you for this suggestion We will change "H_i" into "H" and "H_b" into "b".

Line 193: this is the only mention of viscosity in this section; it would be useful to include a little more information on the role of viscosity within the GIA FE model.
We will add the following sentences in section 2.2, starting line 159:

"Each element of the model gets assigned a dislocation and diffusion parameter from which the mantle viscosity can be computed based on, among others, the applied stress from surface loading. Section 2.2.2 discusses how these parameters, and the viscosity are computed."

Line 198: in what way is the grid irregular?
We understand that this part of the sentence is confusing at this point in the text, and it is also unnecessary to mention it here since it is better phrased in lines 203-204. We will change this sentence into:
"The horizontal grid has a high resolution region over Antarctica, which is visible in Fig. 2."

Line 200: "increases the computation time…" – computation time of what?
We will add that this is the computation time of the GIA mode.

Line 206-207: refer to table 1 to help the reader understand what is being described here.
Thank you for the suggestion, we will do that.

Lines 208-209: text about ice loading/unloading is opposite to what is shown in the figure and described in the caption
We will correct it in the text.

Line 218: "The chosen viscosities…" – refer to table 1 to help the reader understand that these viscosity values are assigned to two different layers (rather than two different experiments)
We will do that.

Line 219: consisted > consistent
Corrected

Line 222: does viscosity depend on stress? If yes, this should be mentioned in the introduction
We will add the following sentence in line 61 of the introduction:
"GIA is mainly determined by the thickness of the elastic lithosphere and the viscosity of the mantle, which is among others dependent on the grain size and water content of the mantle and to a lesser extent on the stress in the model."

Lines 308-311: the method used to re-grid information from the ANICE model to the GIA FE model is unclear, e.g. when you say 'the closest grid point is selected' – which grid does this refer to?
The closest selected grid point refers to the grid point in the coarse grid. We will clarify this in the text.

Lines 321-323: rather than talking about passing the 'total deformation' to the ice sheet model, it might be clearer to first state that the net deformation calculated by the GIA FE model is divided into linear increments, and then explain that this time-varying model of bed deformation is used as the input to a re-run of the ice sheet model for this time step

We will change the description of step 2 into:
"Next, subtract the final bedrock elevation of the coupling time step from the final bedrock elevation of the last timestep and interpolate this linearly to obtain deformation at the time steps of the ice-sheet model."

Lines 347-348: 'incremental change less than 0.5 mm/yr' – does this refer to the mean incremental change, or does the incremental change in all elements need to be below this threshold?
Thank you for notifying this. We refer to the mean incremental change over each coupling time step but actually in the model, the threshold is 2 mm/year for all individual grid cells. We will clarify this in the text.

Line 349: does the number of iterations needed also depend on the earth model?
Yes, we will add that to the text.

Line 365: "This is within the uncertainty range of the GIA FE model" – I don't understand this statement; is it a statement about the accuracy of the numerical code, the uncertainty of the input variables, or the accuracy (precision?) of sea-level records?
We will clarify this and adjust the text as follows:
"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 367: groundling > grounding
We corrected this.

Lines 398-399: I cannot picture what is being described here, what is the relevance of 8 kyears?
It would be useful to include figures (perhaps in supp. material) documenting the results described in this paragraph; the findings are a fundamental part of your argument for only using one iteration.
We will clarify this by adding the following sentences to the text:
"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 m of ice thickness. There are two outliers at 8 ka. The absolute maximum difference is 1365 m in ice thickness at one ice sheet grid cell, and 1045 m at two different grid cells in our simulations."
We will also visualize these differences at 8000 years.

Line 404: it is a little confusing to find that the threshold approach described on line 324 and shown in figure 4 is not actually used to produce the main results. When you say '1 iteration is used', do you mean that the GIA FE model and the ice sheet model are only run once for each coupling time step, or does it mean that you only iterate around the loop once, i.e. each model is run twice?
Lines 408-409: make it clear that the simulation which took 27 days is the one where multiple iterations were permitted (this is not clear because a few lines earlier you state that all results in the remainder of the paper only used 1 iteration)
We understand the above mentioned lines are confusing. We will add to the text that that run iterates 3 times per coupling time step. We will also move the announcement of using 1 iteration to the end of the paragraph and add the following text at the end of the paragraph:
"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."

Line 414: subduction > subsidence
We will correct this.

Line 414-415: not clear how bedrock elevation affects ice shelf melt (note: ice shelves are floating)
This sentence is incorrect. We will replace "ice shelves" by "the ice sheet".

Line 417-418: are you referring to bed topography or ice sheet topography?
We will change "topography" into "bedrock topography".

Argument needs more careful explanation because the only difference between the simulations is the rheological model, i.e., by definition, all differences in model output are due to differences in rheology.
Lines 114-118 are adjusted as follows:
"The bedrock elevation at last glacial maximum is higher for a larger mantle viscosity is used since there is less subsidence during the glaciation phase. In that case, the ice sheet in West Antarctica will melt less and less bedrock uplift will occur during the deglaciation phase . Thus, the differences in melt during the deglaciation phase for different rheologies could be caused not by the direct effect of different rheologies on uplift, 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 since the model is constrained using the observed bedrock topography at present."

Line 434: extend > extent
We will correct this.

Line 454: "bedrock subsides approximately 500 meter less" – is this a mean or a maximum value?
We will add to the text that the bedrock subsides maximum 500 meter less.

Line 510: "an accuracy of 2 mm/yr" – what quantity is being modelled here?
We will add to the text that it is 2 mm/yr bedrock deformation.

Line 512: "difference in ice thickness of up to 2500 meter" – refer to a figure
We will refer to figure 7.

Line 514-515: "The difference in ice thickness…is 12 times larger…" – differences in ice thickness will be spatially variable across the continent, how did you determine this result?
We will add to the sentence that we used the maximum differences.

Figure comments
Figure 1: where is the sea surface? Does it vary between the initial and final times depicted here?
We will add to the caption:
"The sea level itself is not applied as load on the GIA model and the global mean sea level is prescribed forcing on the ice-sheet model. The sea level is for this reason not shown in this figure."

Figure 2 caption: 'until' and 'above' are ambiguous when describing latitudes.
We will rephrase this sentence and change it to:

“The grid has a higher resolution area of 30 by 30 km at latitudes between -90 and -60 degrees, and a lower resolution area of 200 by 200 km at higher latitudes than -60.”

The sign of the deflection is counter-intuitive and opposite to what is shown in figure 3. Is it possible to reverse the labelling on the colour scale in this figure so that, e.g., red = downwards = negative?
We will reverse the labelling.

Figure 4: what is the difference between the dashed and solid lines?
We will add the following explanation to the caption:
“The solid lines refer to the flow of input and output. The dashed lines connect the blocks of running the model to show that the saved model of the previous coupling time step is used to restart the model in the next coupling time step.”

Should the dashed line of ‘deformed 3D model’ come out of the ‘mean deformation of last two iterations’ shape? In the various labels, how is ‘GIA model’ different to ‘3D model’?
This is indeed inconsistent in the figure. We will replace “3D model” by “GIA model” and we will change the dashed line so that it comes from the ‘mean deformation of last two iterations’ block.

Figure 5: you plot bedrock difference to demonstrate the convergence of the iteration process, but the actual threshold used to determine when the iterations converge is defined in mm/yr – it would be useful to include a plot that quantifies this.
We will add to the text and in the caption that the deformation threshold is 10 meter for this coupling time step (2 mm/year over 5000 years).

Also, state what earth model is used in this figure.
We will state this in the text and the caption.

Figure quality: figures are blurry, hard to see if multiple grounding lines are plotted on a single figure.
Sorry for that, we will replace the figures by high quality figures.

We would like to thank Volker Klemann for his constructive feedback. Please find our answers to the comments in blue. Line numbers refer to the originally submitted document.

Review of egusphere-2022-1328

by Calcar et al.

Calcar present a novel approach for coupling a dynamic ice sheet model with a GIA model. For this they apply ANICE and 3D GIA FE model developed by Wu et al. Both models are established model compartments and suitable for modelling ice dynamics and solid earth deformations, respectively in view of glacial processes covering a glacial cycle.

The authors focus on a new coupling strategy regarding the coupling interval in time at which surface mass change and vertical surface deformations are exchanged between the two compartments. Furthermore, they discuss aspects of spatial and temporal resolution when coupling earth and ice-sheet models.

Further advantages of a time domain code are summarized at the end where they highlightthe flexibility of their approach.

The main conclusion is that a coupling interval of 500 to 1500 yr is sufficient in case dynamics of the system during this interval is iterated. In order to improve efficiency theyconclude that 2 iterations should be sufficient.

For this, they have to assume that the GIA process proceed on such large time scales, although it is known that ice dynamic processes, which impact the mass balance of Greenland or West Antarctica, can proceed on significantly shorter time scales. Accordingly, the authors should specify, why it is sufficient to consider 500 yr as a lower limit in this study. Also the response time of the applied 3D earth model due to two to threeorders of magnitude lower viscosities than 10^{21} Pa s, might be less than 100 yr. This means,the interplay of a short-time ice-dynamic process of may be 100 yr with the solid earth- dynamic response of 100 yr might be masked out with such a coupling interval. During the 500 yr time interval, the solid earth would relax almost completely, and the interaction during the relaxation process could not be resolved (see alternatively also Points 14, 23 in the details). I understand that the coupling between the two model compartments generates a bottle neck in exchanging the data, but it is not clearly presented what the concrete problems inthis coupling are. So, if one could solve some of the technical aspects, would it be possibleto reduce the coupling interval further? For instance, Konrad et al. 2015 considered a coupling interval of 20 yr and, doing so, did not consider further iterations during this interval.

We understand the point raised. The processes of GIA feedback can occur on much shorter timescales than 500 years at regions where the mantle viscosity is relatively low. We will include in the conclusion of the manuscript that the GIA feedback could occur faster when a shorter coupling time step of 500 years were to be used. This would further stabilize the ice sheet. However, we also believe there is a misunderstanding about the update of the deformation in the ice-sheet model within coupling time step, which we will clarify in the text.

The coupling time step is 500 years but bedrock elevation is interpolated linearly over the coupling timestep and the bedrock elevation is updated yearly in the ice-sheet model. This is of course an approximation but it captures the shorter term variations to first order. Furthermore, the internal time step of the GIA model is variable and is, when needed, as short as 10 years to capture the nonlinear GIA response to ice loading.

It is possible to reduce the coupling time step and it possible to restart the coupled model at any time and run the coupled model using different time steps. We will add the following sentence in the text in line 184:
"**Shorter time steps during the deglaciation phase is possible but will lead to a large increase in computation time.**" However, the computation time particularly plays up at glacial-interglacial time scales where the computation time is currently 5 days. Simulating the 3D GIA model for 5000 years takes approximately 40 minutes, whereas simulating the GIA model for 200 years still takes approximately 20 minutes. Reducing the time steps from 500 years to 250 years doubles the number to time steps over that period in the glacial cycle but does not lead to a significant reduction in computation time. Shortening the coupling timestep does therefore lead to very long computation times. However, on shorter timescales than glacial cycles, for example projections, using a coupling timestep of 10 years is feasible. We will add this to line 533 in the text.

There are studies that coupled on decennial timescales, like Konrad et al. (2015) who used coupling time steps of 50 years, but those simulations are performed on much shorter total timescales and restricted to the use of 1D GIA models, as we will clarify better in the introduction (see answer to comment 7). Those studies do also not update the bedrock elevation with a yearly timestep, but assume that the bedrock elevation is constant until the next coupling time step (we will discuss this in more detail section 2.4.1 about the size of the coupling time step). We therefore believe that our approach is an improvement on existing literature, and it has potential for future studies to experiment with even shorter time steps, if computation time allows.

Concentrating on these aspects of the study, I rate this study between minor and major revision. I strongly recommend to elaborate on shorter coupling intervals. Furthermore, why is a crude coupling interval of 500 yr necessary? What is the bottle neck in the coupling? Can this problem be reduced? Some are details would help here.

With regards,

Volker

Klemann

Details:

1. L. 50: You can cite here already van den Berg et al., 2008, https://doi.org/10.1029/2007JB004994.

2. L 59: You can also add here, that the effect of regional sea level change due to gravitation is not considered in ELRA.

3. L 82: 'The only model that coupled 3D GIA [...]' why past tense, as the model still exists.

4. Throughout the paper I would replace years and kyears by yr and kyr, as kyears is a mixture.

   We will adjust comments 1 to 4 accordingly.

5. With respect to units I also wonder if a center dot follows general type writer conventions.

   We will check this.

6. ~ L 100: Although the VILMA - PISM coupling is not published as peer review, there exist already presentations regarding this project, e.g., https://doi.org/10.5194/egusphere-egu21-8050. You could mention that there is an ongoing discussion on how to couple viscoelastic solid-earth and ice-sheet models.
   We agree that there are other ongoing thought or efforts but prefer not to refer to an abstract, but we will add the following to the text in line 87:
   "Whitehouse et al. (2018) emphasizes the importance of coupled 3D GIA – ice-sheet models to study regions with a low mantle viscosity and there are ongoing efforts to develop an efficient coupling method on a high temporal resolution using a 1D GIA model (Han et al., 2021)."

7. In the introduction you concentrate on 3D FE codes, but with regard to coupling with time-domain codes, Konrad et al. (2015) did this also. As your discussion focuson the coupling in the time domain, you should also mention his approach. Therein,he coupled without internal iteration but with a time step which is defined by the Maxwell-time. In his case, he chose 20 yr for a standard upper mantle viscosity.

   We will add the following sentence at the end of the paragraph in line 101:
   "There are coupled 1D GIA – ice-sheet models that use shorter coupling time steps of tens of years, but those models simulate projections and hence consider a much shorter time scale than the glacial cycle (Konrad et al., 2015; DeConto et al., 2021)"

8. L 136: "GMSL is similar throughout Antarctica", I think you mean the far field effectof northern-hemispheric GIA is similar around the Antarctic coast. GMSL by definition is spatially constant.

   Yes you are correct. We will adjust this sentence to:
   "Although the effect of the northern hemisphere ice sheets on GMSL is significant, the

effect of the AIS itself is most important for regional sea level variations" (Gomez et al., 2020)."

9. L 152: The inaccuracy of linear interpolation is clear especially for time steps at the order of the relaxation time of the loading process. Assuming 500 yr as minimum time step, in this regard is rather long.

   Please find a detailed answer above in the general comment section.

10. L 185: 'applied linear change [...]', you could mention here that also the time step in the viscoelastic model is much shorter than the coupling interval.
    Indeed, we see the need of clarification of the internal time step of the GIA model. Somewhat earlier in the text, in line 161, we will include a better explanation of the internal time step of the GIA model. We will add the following:
    "The ice loading is applied to the GIA FE model at each coupling time step. When running the GIA model, each coupling time step is divided in a variable number of increments. The size of each subsequent increment is determined based on how fast the computation of the deformation converges. In this study, each coupling time step is divided in approximately 30 increments so that time integration is sufficiently accurate"

11. L 197: Is the Earth's core not excluded from the solution domain?

    To clarify this, we will add the following sentence to line 198 in the text:
    "The core is included in the model only through boundary conditions to most importantly provides buoyancy force on the mantle (Wu et al., 2004). "

12. L 218: You could separate also in the text the transition zone and the lower mantle, while reading I was puzzled by the statement and could only resolve this looking atthe table.
    Nice suggestion, thank you. We will change "crust" into "top layer" and "upper mantle 1" into " transition zone".

13. L. 298ff: Is mass conservation considered in the applied interpolation algorithms.

    Yes, we will add that to the text.

14. The authors state, that they can choose the coupling time step freely. May be there isno demand for a shorter time step, but in order to represent Grounding-line dynamics it might be of interest what happens for shorter coupling intervals. For instance a WAnt viscosity in some regions of < $10^{1\#}$ will result in a response time ofless than 100 yr, accordingly 500 yr timesteps seem to be too large in order to represent the feedback mechanisms discussed. this would be interesting especially at periods of strong variability like during strong ice mass changes or during meltwater pulses. This would also be of interest regarding the discussion of Fig. 5, where locally, alternating signs appear.

The feedback mechanisms are captured also with a time step of 500 years because the internal timesteps of the ice-sheet model, and GIA model is much smaller. But smaller coupling time steps would indeed be very interesting to test with this method. However, if the coupled model captures short term GIA effects is not only dependent on the coupling time step but also on the sensitivity of the grounding line migration to changes in topography and ice dynamics. The sensitivity of the grounding line is dependent on how grounding line migration is modelled in the ice-sheet model and different ice-sheet models use different approaches. ANICE assumes a full grid cell to be grounded or shelf, whereas some other models can consider a fraction of the grid cell as grounded ice. Using another ice sheet model in this coupled model with this method could reveal significant differences when the coupling time step is decreased. The advantage of this coupling method is that it is possible to apply it any ice-sheet model as long as the model has a restart function. We will add this explicitly to the final paragraph of the manuscript (line 532).

In this paper, we want to focus on presenting the new coupling method and coupled model, and the sensitivity of the Antarctic ice sheet to 3D rheologies but this would be interesting for future studies with a more suitable ice sheet model.

15. L 406ff: Some more details regarding the considered architecture of the two model codes would help here. Also an analysis which model needs what amount of time. My impression from the given numbers is, that the solid earth part dominates here. Alsoit is not clear if the 51 coupling intervals represent one glacial-cycle integration or already the whole iteration procedure of 3 to 4 integrations through the last 40 kyr. From what is stated here, you conclude that only one iteration is reasonable to apply?

    We will clarify that the computation time of the GIA model is about 40 minutes to simulate 5000 years and of the ANICE about 6 minutes. The computation time of ANICE reduces significantly when the timestep is shorter but not for the GIA model. We will clarify that in the text. We will also clarify in the text that the 51 coupling time steps are for one glacial cycle.

    We will clarify that we only use 1 iteration by adding this text to the end of the paragraph:
    "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."

16. Furthermore I wonder, whether the number of necessary iteration steps -- at the moment they amount to 293/51 $\simeq$ 6 ? -- depend on the chosen coupling interval. What happens if they reduce to 250 yr for example? such an experiment I strongly suggest.

Three iterations are needed to determine whether the deformation has converged or not. Shortening the coupling time step does not reduce the computation time per time step much and still 3 iterations are needed. In the current set up, there are 22 time steps of 500 years. These timesteps all require only 3 iterations. Reducing the coupling timestep to 250 will lead to 22 more time steps of 3 iterations. The computation time would thereby increase with about 22 hours. We therefore suggest to decrease the coupling interval when studying shorter time scales than a full glacial cycle.

L 414: 'subduction' -> 'subsidence'?

We will correct this

17. L 429: In the abstract you state three to four iterations.

At line 97, we will clarify that 4 iterations are needed in the method of Gomez et al. (2018). At line 343 and 507, we state that we use 3 to 4 iterations but we will correct this to 4 to 5.

18. Also here, it would be interesting if you present a similar analysis like that you didfor the iterations during each coupling interval.

We assume this is about the glacial cycle iterations. Will provide more details about the glacial cycle iterations like we did for the iterations over the coupling time steps.

19. L 485ff: Does your discussion mean, that you did not consider the sea-level equationin this analysis? If so, you should specify this more clearly from the beginning as the stabilization of the ice sheet through sea level fall is an important direct response to the ice mass loss. And as this is an instantaneous response I wonder how this can be considered in your coupling scheme.

Indeed, we do not consider the sea-level equation in this analysis. We will specify this more clearly in the method section. See also the reply to reviewer Whitehouse.

20. L 494ff: You should also state here that the Antarctic ice-mass variability is dominated by W Antarctica.

We will do so.

21. L 503: I agree, it is the first published study coupling a 3D earth with an ice sheet model, but not the first study published in coupling a solid-earth time-domain code with an ice-sheet model, as it was published by Konrad et al. (2015).

We will include in the introduction that Konrad et al. (2015) and Gomez et al. (2015) coupled a 1D GIA model and an ice-sheet model on short time scales.

22. L 505: Still I am skeptical a bit to state that 500 yr is a short time scale for GIA

feedback. On which assumption do you base this statement, considering that the response times of the Antarctic ice sheet are as long? The solid earth in the 3D case responses regionally much faster. Also the statement only one iteration is enough, depends strongly on the considered process. I can imagine that the gross evolutionof the Antarctic ice sheet might be representable in this way, but with respect to more regional aspects I doubt that such a strategy would be sufficient.

We agree that for regional aspects, the coupling time step should probably be lower. But to simulate regional processes, the resolution of the ice-sheet model should also be much higher than 40 kilometers. The temporal resolution of 500 years is already an improvement on existing literature and it does include the effect of GIA on shorter timescales via the internal time steps of the models. In this paper, we neglect the processes on a high spatial resolution, and we want to focus on the direct feedback of 3D GIA on the full Antarctic ice sheet. In future studies we will explore different ice-sheet models and higher spatial and temporal resolution.

23. L 509: Where is the spatial resolution discussed in the manuscript.

The spatial resolution of the ice-sheet model is mentioned in line 123 and is 40 kilometers. The horizontal resolution of the GIA model is mentioned in lines 201-202 and is approximately 30 kilometers over Antarctica and 200 kilometers globally.

24. L 516: If WAnt is dominant, and the viscosities are about 10^{19} Pa s, what happens if one would use a 1D model with such a small viscosity value?

The ice volume at last glacial maximum would be relatively low compared to the results when using 3D rheologies, but the ice volume at present day might be closer to the results of using 3D rheologies than the 1D20 rheology. This could be an interesting approach to save computation time while approaching a more realistic bedrock deformation but only when one wants to calibrate the model to present, as the ice volume at LGM will be further off then a 1D20 or 1D21 model.

25. L 520ff: That with smaller grid cells the convergence improves, I did not find a discussion for in the manuscript.

That is indeed missing in the method section. We will include the following in line 362 in the manuscript:
"Decreasing the spatial resolution would allow smoother transitions between grounded and floating ice and thus an improvement of the convergence. However, the ice-sheet model is limited to a 40-kilometer resolution."

26. In Figure 4: The climate and sea level forcing appear to come from outside the system, but sea level change is one output of the GIA model. I understand that for the moment, you have not considered this, but you should indicate at least that for

state of the art modeling the relative sea level is part of the GIA models.

We will add in line 340 the following sentence: “However, the GIA FE model used in this study does not solve the sea level equation whereas that should be included in the GIA FE model and added to the coupling scheme for state of the art modelling.”