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.

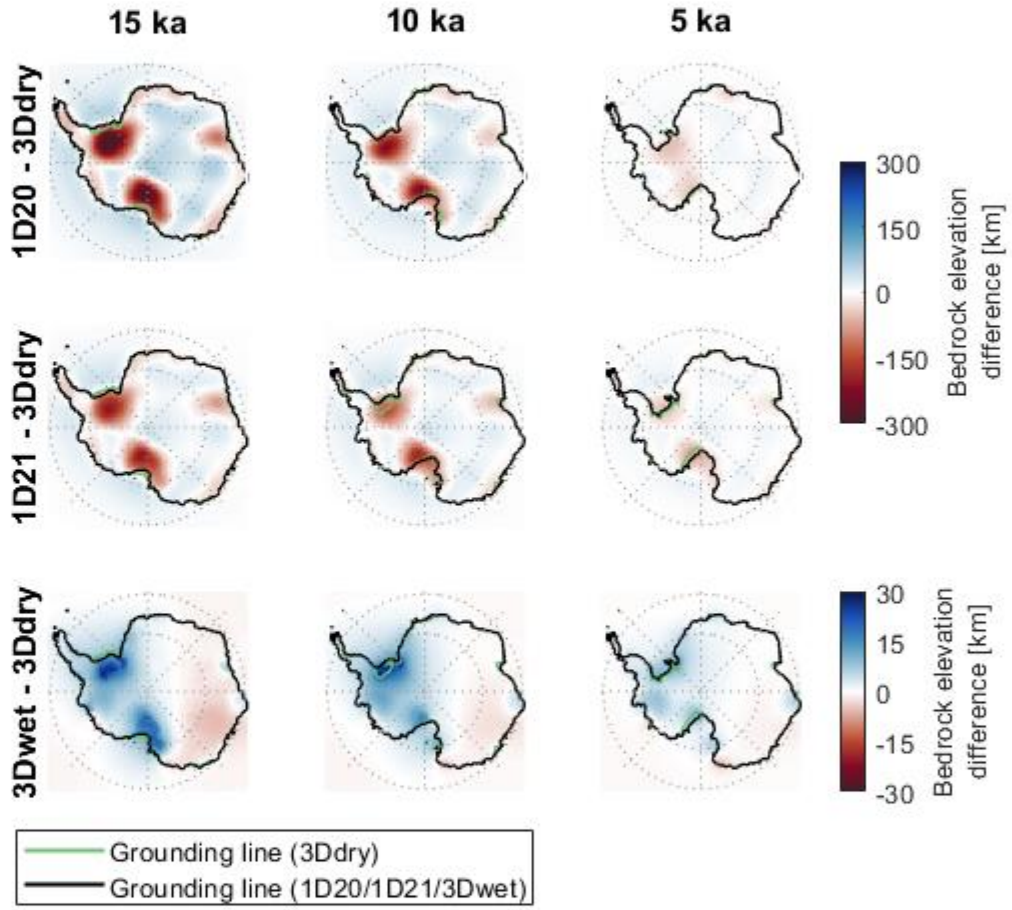
We will remove Larour et al. from the list and switch Nield et al. (2014) and Whitehouse et al. (2012) to the description of 1D GIA that does include the sea level equation.

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 the figure below in the supplemental material. The figure shows 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.