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.

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).

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.

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.

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.

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?

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. 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. 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. The results of the tests described in 2.4.3 would benefit from being shown in a figure.

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). 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.

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. Additional details are needed to describe how precipitation, and hence mass balance, are defined in the past (lines 126-127).

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

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. 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.

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. 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?

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. 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.

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

Minor points that require clarification

General: make sure it is clear you are talking about mantle viscosity (as opposed to ice viscosity)

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

Line 18: define 'FE'

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

Line 47: "meltwater flux towards the ocean" – not clear what this is describing

Line 48: "A decrease in sea level…enhances uplift" – explicitly link this to a decrease in surface load

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"

Lines 58-59: include a reference to help the reader understand the implications of the final sentence

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

Line 139: "increase in sea level is reduced" – local ice loss will cause a decrease in local water depth

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?

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

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

Line 171: what is the effect of including self-gravity?

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"?

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

Line 180: "water dumping due to local bathymetry" – describe what this process entails

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: 'H_b' refers to an elevation, which must be defined relative to something, whereas $H_{i,AF}$ and H_i refer to thicknesses – consider using different letters for absolute and relative quantities

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

Line 198: in what way is the grid irregular?

Line 200: "increases the computation time…" – computation time of what?

Line 206-207: refer to table 1 to help the reader understand what is being described here

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

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)

Line 219: consisted > consistent

Line 222: does viscosity depend on stress? If yes, this should be mentioned in the introduction

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?

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

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?

Line 349: does the number of iterations needed also depend on the earth model?

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?

Line 367: groundling > grounding

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

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)

Line 414: subduction > subsidence

Line 414-415: not clear how bedrock elevation affects ice shelf melt (note: ice shelves are floating)

Line 417-418: are you referring to bed topography or ice sheet 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

Line 434: extend > extent

Line 454: "bedrock subsides approximately 500 meter less" – is this a mean or a maximum value?

Line 510: "an accuracy of 2 mm/yr" – what quantity is being modelled here?

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

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?

Figure comments

Figure 1: where is the sea surface? Does it vary between the initial and final times depicted here?

Figure 2 caption: 'until' and 'above' are ambiguous when describing latitudes. 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?

Figure 4: what is the difference between the dashed and solid lines? 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'?

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. Also, state what earth model is used in this figure.

Figure quality: figures are blurry, hard to see if multiple grounding lines are plotted on a single figure

Pippa Whitehouse, January 2023