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 earthdeformations, 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 highlight the 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 they conclude 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 three orders 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 focus on 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 effect of 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 at the 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 is no 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 of less 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 did for 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 equation in 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 evolution of 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."