Review of Swierczek-Jereczek et al.

By Caroline van Calcar

Swierczek-Jereczek et al. present a new GIA model, FastIsostacy, based on the Fourier collocation method that can include lateral viscosity and lithospheric thickness variations in the mantle. The new model is compared to the existing 3D self-gravitating visco-elastic Earth model Seakon. They show a maximum error of 0.2 over a glacial cycle when FastIsostacy is used compared to Seakon. Although the error is not negligible, FastIsostacy has the potential to be coupled to ice sheet models because the runtime is very short and the model is open source.

The manuscript is well written. The introduction provides a great overview of current existing methods used in GIA models. The second part of the introduction, "FastIsostasy in the model hierarchy", provides a clear overview of the different GIA models. Table 1 also includes which numerical scheme is used for each type of GIA model, but the numerical scheme are not explained in the text of the section "FastIsostasy in the model hierarchy". For this manuscript, the FDM/FCM and the numerical scheme of Seakon are particularly important and should be described in more detail.

The method section explains quite well the details of the new method developed but should elaborate more on the effect of simplifications in FastIsostasy in order to reduce computational cost compared to Seakon. Line 503 states that tuning can be done easily but doesn't explain what tuning would exactly be required. Also, line 537-539 states that the difficulty of creating meaningful ensembles is decreased but even though different viscosity fields are available, it is not shown how FastIsostasy performs using different viscosity fields. It is necessary to discuss the implication of the use of effective viscosity, the characteristic wavelength, and alfa. Equation (6) suggests that the alpha is selected to improve the fit to a 3D model, which means the results depend on a particular 3D GIA model. Are alpha and W fixed for all comparisons? That results in conclusions that are dependent on this choice, which should be emphasized. Tests for different alpha and W are required to have robust conclusions on the accuracy of FI3D.

FastIsostasy is presented in line 533-534 as a model that can greatly reduce the error of bedrock displacement compared to ELRA and ELVA and that is useful coupled to an ice sheet model due to the short computation time. However, there are no results presented in this manuscript that compare the performance of FastIsostasy with the most widely used GIA model in ice sheet modelling, the ELRA model and the laterally varying ELRA model so there could also be no conclusion about the reduction of the eror of FastIsostasy compared to ELRA. It is therefore not shown whether FastIsostasy is an improvement on what already exists. The focus of the paper should therefore be changed and the introduction rewritten with less focus on coupled ice sheet – GIA models, or a comparison with ELRA should be shown.

In line 361 the authors justify an error of 0.2. However, the error should ideally be smaller than the error introduced by different parametrizations. In some cases this error could be in the order of a hundred meters, which is significant and could have a large effect on ice dynamic models. In comparison, 1D GIA model benchmark study show much lower errors. Furthermore, from figure 8b it can be seen that the error between FastIsostasy 3D and Seakon 3D after 8 kyear is larger than the effect of 3D rheology itself. In that case, differences between FastIsostasy and global GIA models are outside of the range of parametric uncertainties, which contradicts the conclusion in line 534-535. The conclusions on the

performance of FastIsostasy should therefore be more considerate of the large error rather than accept them compared to an arbitrary standard, especially since the values hold for certain choices of the resolution.

Specific comments

Line 3-4: The impact of 3D GIA on ice sheet dynamics has only been shown for glacial cycles and not yet for projections. This sentence is suggesting that it has been shown. Please include in this sentence that the impact has only been shown over a glacial cycle.

Line 6: An iterative coupling scheme is required when simulating a glacial cycle but it hasn't been studied yet whether iterations are required to simulate projections. Projections have been performed without an iterative coupling scheme using a 1D GIA model and there are no published projections using a 3D GIA model. The need for an iterative coupling scheme is therefore not an argument why 3D GIA models are not used in ice sheet models. I would suggest to, instead, include that 3D GIA models are not used in ice sheet modelling because the effect of 3D GIA is not known, 3D GIA models are computationally expensive and the coupling scheme is complex to apply.

Line 12-13: Please include the value of error here instead of mentioning that the agreement is very good.

Line 15: The Fortran version is not provided yet, according to the data availability section. I suggest to include in this sentence that it will be provided.

Line 44-47: The impact of 3D GIA over a glacial cycle doesn't necessarily mean that the impact is also large over projections of a much shorter time scale. In multiple places in the introduction, the distinction between what has been studied over glacial cycles and what has been studied over projections is not clear. There are studies that show a significant effect of using 3D GIA compared to 1D GIA over a glacial cycle using a coupled ice sheet – GIA model (for example Gomez et al., 2018 & van Calcar et al., 2023) and from recent history till present day using a GIA model with a prescribed ice history (for example Blank et al., 2021). However, in this manuscript, results from Gomez et al. and van Calcar et al. are presented as if they show the impact of 3D GIA in projections as well, which is not the case. There are studies that show the importance of 3D GIA in projections using uncoupled models, such as Yousefi et al. (2022) but this study is not referenced in the manuscript. Currently, there are no publications on coupled ice sheet – 3D GIA models used for projections. This distinction should be made more clear throughout the introduction and the references to Yousefi et al. and Blank et al. should be added.

Line 47: Include that sea level contributions from the basins are 19.2 and 3.4 m at present day.

Line 58: Include references of the 3D GIA models that you are referring to.

Line 62-64: Whether or not the ice-sheet modelling community is well aware of the how important 3D GIA is, is subjective. There are only a few studies showing the importance of 3D GIA over a glacial cycle and in projections and there are no published studies simulating projections using coupled ice dynamic – 3D GIA models. It can therefore be argued how well informed the ice sheet modelling community is up to this point and how well aware they could be without so many studies. I suggest to only mention that 3D GIA models are computationally expensive and complex to couple to an ice sheet model.

Line 81: It is worth mentioning that there might be no asthenosphere at certain locations in Antarctica, and that ELRA includes that mantle, but that does not weigh against the confusion that it could cause to change a name that has been used in numerous papers since 1996. I suggest to leave the name as it is.

Line 86: Add the constant “flexural rigidity” and “lithospheric thickness” in the text, as these are other important parameters in the ELRA model.

Line 101-102: To improve the readability, provide a short explanation about the difference between a viscous channel and a viscous half space.

Line 109-112: Include that 1D GIA models also include the buoyancy effect of the core on the mantle and the mantle on the lithosphere.

Line 118: Include reference A et al. (2012), and Huang et al. (2023) for the finite element method.

Line 119-121: The referenced models in this sentence (Gomez et al. and van Calcar et al.) are coupled ice sheet – GIA models, which require a much longer simulation time than 3D GIA models by itself. Since this section is solely about 3D GIA models, a simulation time of weeks is not applicable.

Line 123-124: The 3D GIA model in van Calcar et al. uses timesteps varying from approximately 1 to 1000 years, depending on the ice loading and the deformation rate, so the lower limit of the timestep of 3D GIA models is not accurate. Furthermore, it is not clear why it is relevant in this context that GIA models sometimes have a larger timestep than ice sheet models.

Line 126-139: The manuscript mentions two regional models specifically (Coulon et al., 2021 & Weerdesteijn et al., 2023). However, it is not clear why these two are picked out, since there are multiple other 1D and 3D GIA regional models (Nield et al., 2018; Book et al., 2022). I suggest to move line 126-129 to the section about LV-ELRA, and line 129-135 to the section about 1D GIA models. Also explain why Coulon et al. and Weerdesteijn et al. are mentioned specifically, and not other regional models. Some other important references are missing, such as Book et al. (2022), who used a similar method as this manuscript for a regional model focused on Thwaites glacier, and Kachuck et al. (2020).

Line 136-137: The available GIA models have a runtime acceptable for modelling ice sheets over glacial cycles, the runtime is only not acceptable to perform ensemble studies with a wide parameter space. Please include this nuance in the manuscript.

Line 137-138: Could you define what is meant by “complexity gap” since there are regional 3D GIA models.

Line 155-159: To improve readability, include a sentence to explain why a placeholder field is used and what the pseudo-differential operator represents.

Line 168-169: Add whether the viscous half space have a variable or constant thickness.

Line 180: Clarify in the text whether R is computed at each time step.

Line 248: Please include why it is required that the far-field displacement should be zero.

Line 307: It is not clear what “in-place” means.

Line 340: To improve readability, include reference to Spada et al. (2011).

Line 415: Given the negligible maximal difference in displacement between the 1D GIA models of Spada et al. (2011), a maximal difference of 0.16 between FastIsostasy and the 1D GIA models of Spada et al. is relatively large. Also, purely based on this idealized test, it cannot be stated that FastIsostasy can replace 1D GIA models. This is also shown by figure 8, showing a maximal error of about 0.8 around -4000 years between the SK1D and FI1D, which is relatively large for a benchmark test.

Line 421-422: Please include the reference to the chosen viscosity.

Line 438-439: The error of FastIsostasy compared to Seakon can be different when a realistic ice load with a realistic Earth rheology is used. Whether FastIsostasy can be used in regional ice sheet models should therefore be concluded based on test 4 as well and should not be stated based on only test 3.

Line 460-461: Could you quantify the error tolerance and adaptive time stepping.

Line 472: Please include the results of this test in the manuscript and quantify what is meant with "better results".

Line 479: Quantify the offset in the forebulge and the implication of leaving the forebulge out of the presentation of the results.

Line 502: Define what is meant by "worst case".

Line 502: Define which region is meant by "near field".

Line 505: The pattern of the rotational feedback is described as "a subtle dipole separated by a great circle" but when one doesn't know what the pattern of rotation looks like, the description is not so clear. It could be described as a gradient from east to west outside of the grounding line.

Line 512: It would be useful to include what the runtime would be when a higher resolution is used.

Line 515: The timestep of the GIA model used in van Calcar et al. (2023) is dynamic and is about 1 year when the deformation rate is high. The convergence of the ice-sheet and GIA histories are there to reach a present day bedrock topography when simulation a glacial cycle. Those iterations would be needed by any ice sheet model coupled to FastIsostasy as well when a glacial cycle is simulated. The iterations are therefore not related to the time step of the GIA model. This should be corrected in the text.

Line 517: Include the resolution of Seakon.

Line 520: It is unclear what is meant by "much richer".

line 533-534: It should be stated more explicitly when FastIsostasy performs better than 1D GIA models, namely between -22 and -10 kyr of the glacial cycle.

Line 541-542: Clarify what is meant by "it minimizes the misrepresentation of the GIA feedback".

Line 560: A discussion should be included that compares the conclusion of this paragraph with literature that does compare incompressible and compressible models, such as Huang et al. (2023). Is this increase in viscosity consistent with literature? Describe the limitations of increasing viscosity instead of including compressibility.

Technical corrections

Line 20: impacting > altering

Line 169/Footnote 1: API is not defined.

Line 225: Define F.

Line 242: Define ODE

Line 268: A0 is not defined.

Line 276: SLC is not defined.

Line 365: Define parameters.

Line 501: t = -14 kyr > t = -16 kyr

Figure and table comments

- Table 1: includes a description of the rheology, but it is not clear what is meant by Maxwell-like.
- Table 2: Please include a short description of the parameters in the caption.
- Figure 4: To improve readability, include the definition of variables in the caption.